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**Ida-Bagus Putera Parthama**

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Larry A. Leefers
Major professor

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# QUANTITATIVE MODELS
# FOR TEAK FOREST MANAGEMENT IN INDONESIA

By

Ida-Bagus Putera Parthama

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## ABSTRACT

## QUANTITATIVE MODELS FOR TEAK FOREST MANAGEMENT IN INDONESIA

By

Ida-Bagus Putera Parthama

This study provides a prototype of a quantitative approach for management of large-scale timber plantations in Indonesia. Focusing on teak plantations in Java, a package of quantitative models has been developed consisting of (1) a set of growth and yield models and (2) harvest scheduling models. The growth and yield models were integrated into a computer routine that can be used to project future yields of a given teak stand under different management regimes or rotation ages. This computer routine was applied to Cepu Forest District in Central Java, which was selected as a model forest for the development of the harvest scheduling models. The harvest scheduling models were formulated to maximize total net present value (NPV) over a 120-year planning horizon subject generally to non-declining even-flow (NDEF) constraints. Stands comprising the selected forest district were aggregated into stand-types, and the outputs of the harvest scheduling models were hectares of each stand-type allocated to three rotation ages (i.e., 60, 70, and 80 years) or no management. Other outputs included harvest flows over time and the total NPV.

The harvest scheduling models were formulated in two versions. The first version is deterministic and treats yields as known with certainty. This version was formulated as a linear programming (LP) problem, and different sets of constraints were used to examine management options. For comparison purposes, one model resembles the current management strategy. Outputs of these LP models indicated that the current single 80-year rotation-age management incurs a substantial cost in the form of foregone NPV; total NPV was nearly doubled when shorter alternative rotation ages were provided. The highest NPV was given by a model that includes multiple rotation ages and allows periodic harvest volumes to increase without an explicit upper

bound. Models that restrict the increase to a certain upper bound or allow periodic harvest volumes to decrease resulted in lower NPVs. All models tend to allocate a major portion of the forest to the shortest rotation. Furthermore, without any NDEF constraints, harvest flows over time fluctuate erratically. Imposing NDEF constraints regulates the harvest-flows, but reduces total NPVs.

The second type of harvest scheduling model incorporates risk of not achieving a NDEF condition due to non-deterministic yield predictions. This version was formulated using chance-constrained programming (CCP). CCP accounts for the risk by incorporating the associated variances of yield predictions into the models, and requiring the NDEF requirement to hold up to a certain probability, but not with probability one. A strict NDEF condition was not feasible with CCP formulation. Several CCP models with different NDEF requirements were examined, and feasibility was achieved by allowing periodic (i.e., decadal) harvest volumes to decrease by a maximum of 10%. CCP models resulted in different hectare allocations. Under specific constraints, they produced higher total NPVs relative to the deterministic models, but resulted in less smooth harvest-flow trajectories. An important advantage of including the risk factor in the model is having some degree of assurance (e.g., 95%) that the projected periodic harvest volumes (hence, harvest flows) will materialize if the model outputs are implemented.

In general, this study has demonstrated the applicability of a contemporary forest management technique to forest plantations in Indonesia. It was also shown that the technique considerably reduces limitations inherent in the conventional management approach currently practiced on teak plantations in Java. This finding provides a basis for not using the current teak forest management as a model for forest plantation management in Indonesia. Instead, the approach proposed in this study is recommended as a prototype for developing similar packages of quantitative models for other species in other regions of Indonesia. Possible model improvements are suggested. They include: using finer levels of spatial and temporal aggregation, incorporating other relevant constraints and other sources of risk, and refinement of the growth and yield models.

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# CHAPTER ONE:

# INTRODUCTION

## 1.1. General Background

The forest products industry has emerged as a significant sector of the Indonesian economy. It has been consistently one of the country's leading export sectors, second only to petroleum. Export earnings from forest products were about 16% of the country's foreign exchange earning in 1992, and an average of about a half-million jobs were created annually during the 1984-1989 period (Ministry of Forestry/MOF 1989, 1993). In addition, the industry has also been instrumental in the socio-economic development of several regions of Indonesia.

The industry's source of raw material is almost entirely Indonesian tropical rain forests. An outlook study indicates that, due to degradation of timber potential and losses of forest area to other land uses, Indonesia's annual timber production from tropical rain forests is predicted to decline from the current level of 33 million cubic meters to 25 million cubic meters by year 2000, and to only 21 million cubic meters by 2030 (MOF 1991). On the other hand, the total processing capacity of wood manufacturing plants has reached 45 million cubic meters per year (MOF 1989). Thus, there is an alarming possibility of a widening discrepancy between timber supply and the industry's raw material requirement. If the forest products industry is to remain a significant contributor to the national economy, timber shortages must be prevented.

Given no alternative timber sources, a pragmatic solution of timber shortages would be an increased exploitation of the tropical rain forests. However, this is not a favorable solution for various reasons. It is well known that the alleged excessive exploitation of tropical rain forests in developing countries is a primary concern in the growing global environmental conservation movement. The most recent movement is the eco-labelling campaign which advocates boycotting any product for which production involves environmentally detrimental processes. Being a country which extensively utilizes its tropical rain forests, Indonesia has been frequently a major target of criticism. Any increase in the exploitation of the tropical rain forests inevitably will further undermine Indonesia's credibility and exacerbate the situation. A major implication is that, increased exploitation eventually will create a hot-bed for marketing of Indonesian forest products, which can be very damaging to the forest products industry[1].

Recognizing this potentially impending situation, the MOF has launched a program for establishing large-scale industrial timber plantations called the HTI (*Hutan Tanaman Industri*) program. The ultimate goal is to create alternative timber sources and eventually reverse the present situation. A major portion of the national timber supply would be harvested from sustainably and economically managed timber plantations, hence alleviating the pressure on the tropical rain forests. Several timber plantations have been and are being established by state corporations under the MOF. By creating a favorable investment atmosphere, private companies (especially wood manufacturing enterprises) are expected to be the major participants. By 1994, 1.5 million hectares of timber plantations should have been established with a 1999 target of 4.4 million hectares (MOF, 1993).

A likely obstacle to the long-term goal of the HTI program is the lack of forest management techniques and instruments necessary for bringing the plantations into sustainable and profitable production. At present, forest plantation management in Indonesia still embraces a neoclassical normal-forest oriented technique which has some fundamental limitations. This particular technique (discussed in detail in Chapter Two) is not sufficient for attaining modern forest management objectives such as sustainably maximizing profits, and therefore, is not suitable for the management of HTI plantations. Moreover, no study on assessing the applicability of modern forest management techniques has been undertaken.

The lack of reliable management techniques is addressed in this study. Specifically, the purpose of this study is to contribute to the accomplishment of the HTI program by providing a prototype of a quantitative management technique appropriate for the management to large-scale

[1]A fresh illustration is a recent advertisement "incident" that occurred in London. Environmental groups including the Greenpeace and Down-to-Earth organizations successfully demanded that the Independent Television Commission (ITC) blackout an advertisement by the Indonesian Forestry Community (Anonymous 1994).

timber plantations. Beyond supporting the HTI program, this study is a significant breakthrough toward improving forest management in Indonesia in general. As noted by Suryohadikusumo (1992), the current Minister of Forestry, Indonesia urgently needs to adopt more advanced forest management techniques, especially techniques for forest resource planning, in order to increase and sustain the country's gain from its forest resources.

### 1.2. Forest Management: Selected Concepts and Situation in Indonesia

The focus of this study is on devising a package of mathematical models for the management of large-scale timber plantations in Indonesia. Forest management, however, has many facets, and different kinds of mathematical models are needed for each facet. To outline the facets covered in this study and to specify the type of mathematical models developed, a review is necessary of some relevant forest management concepts and the related prevailing situation in Indonesia.

The Society of American Foresters (1958) defines forest management as "[t]he application of business methods and technical forestry principles to the operations of a forest property." Within this broad definition, forest management encompasses virtually all activities involved in the process of producing goods and services from a forest land. This study adopts a more recent definition which restricts forest management to the decision-making aspect of the entire process; i.e., forest management is "... the study and application of analytical techniques to aid in choosing those management alternatives that contribute most to organizational objectives" (Leuschner 1990).

Forests may be managed for multiple objectives but frequently timber production is the primary objective. With regard to timber production, many forests are managed to achieve and maintain some form of a sustained yield condition. The two common managerial interpretations of this condition are either a "long-term sustained-yield" or alternatively a "non-declining even flow" of yield (Leuschner 1990). Long-term sustained-yield refers to a level of annual or periodic timber production that a particular forest can produce perpetually under a certain management intensity.

A non-declining even flow (NDEF) condition is achieved when timber production in any subsequent years or periods is continuously maintained to be at least equal to previous volumes.

Forest management can be stand-level or forest-level (Clutter et al. 1983, Leuschner 1990). With stand-level management, stands comprising a forest are treated as independent management units, and the overall management objective is attained by optimally managing each individual stand. Conversely, forest-level management considers the entire forest as a single entity, and the management of each individual stand is coordinated to attain the overall management objective. Stand-level management theoretically should lead to the highest total production or revenue because the overall output is the sum of the maximum outputs of every individual stand. However, since individual stands are managed independently, it is difficult or often impossible to attain and maintain any of the sustained yield conditions mentioned earlier. In contrast, forest-level management controls the flow of production over time; imposing this condition often requires a portion of the forest not to be managed under the most efficient management strategy, resulting in lower total production. In Indonesia, the General Forestry Plan (MOF 1986) implies that all forests should be managed under the principle of maximum and sustained yield. Thus, it is required by law that the management objectives of any forest must include attaining and maintaining some form of a sustained yield condition. As a result, all forests in Indonesia are managed with the forest-level approach. The economic trade-off of this approach, which may be substantial, is often tolerated due to the necessity of maintaining relatively stable timber production and of continuously creating job opportunities.

The core of forest-level management is harvest scheduling: determining the portions of the forest to be harvested in spatial and temporal context in order to attain overall management objectives. Accordingly, a component of the package of mathematical models developed in this study is a set of harvest scheduling models. Main inputs in harvest scheduling are projections of timber yields per unit area under different management options throughout the planning horizon. An appropriate instrument for generating these inputs is a set of mathematical growth and yield models. In Indonesia, yield projection instruments currently available for some selected species are conventional normal or empirical yield tables which are not adequate for mathematical harvest scheduling purposes. Therefore, mathematical growth and yield models constitute the other component of the package developed in this study.

At the present, forest plantations in Indonesia are dominated by teak plantations in Java; they make up approximately 40% of the total existing forest plantations (Ingram et al. 1989). As a result, this study focuses on this species and the harvest scheduling models are developed for a selected teak forest district in Central Java. Nonetheless, the general modeling framework is intended to be a prototype for developing similar packages of mathematical models for other species in different regions of Indonesia. Another reason for focusing on teak plantations in Java is to examine the limitations of the conventional management technique currently applied to these plantations. Management of these plantations has been generally considered a success and more importantly, may be proposed as a model for forest plantation management in Indonesia. By examining the limitations of the prevailing technique and drawing comparisons to a more modern alternative technique, this study provides important information for justifying whether teak plantation management in Java is sufficient as a model for forest plantation management in Indonesia. On the other hand, this study will also determine if the management of the teak plantations themselves need improvement.

### 1.3. Study Objectives

This study focuses on achieving the following objectives:

1. To develop a set of growth and yield models for teak plantations in Indonesia and to integrate the resulting models into a computer routine that can be used to generate information necessary for forest management planning, particularly harvest scheduling;
2. To develop mathematical harvest scheduling models for a selected teak forest district in Java, which maximize total net present value (NPV) and ensure a non-declining even flow (NDEF) condition over a specified planning horizon; and

3. To examine the limitations of the forest management (harvest scheduling) technique currently applied to teak plantations in Java.

An important specification of harvest scheduling models involves the treatment of risk caused by non-deterministic model inputs. Based on how these non-deterministic inputs are treated, harvest scheduling models fall into two broad categories: (1) deterministic or excluding risk, and (2) non-deterministic or including risk. Sources of non-deterministic inputs include: natural hazards due to fire, insects or diseases; unpredictable behavior of prices and costs; and errors in yield projections. In the context of teak forests in Java, another source is timber theft.

One of the harvest scheduling models (Objective 2) is devised to include risk due to errors contained in timber yield predictions resulting from spatial and temporal aggregations. Hence, a final objective of this study is:

4. To examine the effect of incorporating risk due to non-deterministic timber yield projections on harvest scheduling outputs.

Risk due to other sources are excluded for a combination of reasons, including data unavailability, historical observations (e.g., relatively constant prices and costs), and inherently stable biological characteristics of teak plantations (e.g., low susceptibility to fire hazards).

### 1.4. Organization

Chapter Two presents an extended description of teak plantations in Indonesia including a brief overview, the silvicultural system, and the standard management. A literature review on the subjects of harvest scheduling and growth and yield modeling is presented in Chapter Three. Information in these two chapters provides the basis for devising the modeling framework and methods described in Chapter Four. Chapter Five and Chapter Six present the resulting growth and yield models and harvest scheduling models, respectively. Finally a summary, conclusions and recommendations are offered in Chapter Seven.

## CHAPTER TWO:

## TEAK FORESTS IN JAVA

Some relevant aspects of teak forests and their management in Java are provided in this chapter. A general overview is provided in the first section. The second section briefly describes the silvicultural management of the plantations, followed by detailed descriptions of two forest regulation techniques in the third section. Some limitations of these two techniques and a brief discussion relating teak forest management in Java to the HTI Program is given in the last section.

### 2.1. A General Overview

Teak (*Tectona grandis*, Linn F.) is one of the most valuable tree species in Indonesia. Combining superb physical and mechanical properties with a beautiful appearance, teak wood is an excellent raw material for a wide range of wood products, from furniture and housing components to wood carving and household instruments. In the past, when teak wood was relatively inexpensive and abundant, it was used for building ships (Peluso 1992).

Teak has been considered indigenous to Indonesia, but some believe it was brought from India centuries ago (Gyi 1992). At the present, teak forests in Indonesia are mainly monoculture plantations covering about one million hectares almost entirely located in Central Java and East Java provinces. Less extensive teak forests are also found on Lombok, an island in the West Nusa Tenggara Province, and on Muna, an island in the South Sulawesi Province (Hamzah 1975). This geographical distribution is shown in Figure 2.1.

Java's teak forests have been exploited for centuries. Large-scale exploitation first took place in the early decades of the 18$^{th}$ century following the arrival of the VOC or the Dutch East Indian Company (Kartasubrata 1992, Peluso 1992). Planned management, however, was not initiated until 1855 when several professional German foresters were hired to prepare management plans for some forest districts in Central Java. These German foresters introduced the concepts of sustainability and the normal-forest, upon which the management of the teak forests has been based


*Figure 2.1.* Geographical distribution of teak forests in Indonesia. (Derived from: Hamzah 1975, MOF 1991 and Perum Perhutani 1993).

ever since. Historically teak forests in Java have always been managed by the state, either directly or by a state-owned enterprise. Today, the teak forests are managed by Perhutani, an autonomous state corporation which also manages some two million hectares of non-teak forests in Java.

The entire forest under the responsibility of Perhutani is divided into three regional units, namely, Unit I Central Java, Unit II East Java, and Unit III West Java. Each regional unit is further divided into forest districts of varying size (30,000 - 100,000 hectares). In total there are 51 forest districts, about half of which are exclusively teak forest districts. Forest districts are self-contained management units operating on individual long-term management plans prepared by regional planning offices. Only in certain aspects such as international marketing are forest districts centrally coordinated. For planning purposes, forests under Perhutani's control are divided into sustainability units. A sustainability unit is an area between 4,000 - 6,000 hectares, usually confined within natural boundaries, for which a long-term sustainable management plan is devised. A forest district may be constituted by a number of sustainability units, and therefore a forest-district management plan is usually an integration of several sustainability-unit management plans.

The management goal, as mandated by law, is to produce goods and services for the people and support government programs in socio-economic development. Perhutani's general management plan (Perum Perhutani 1990) implies that in fulfilling this mandate Perhutani should follow the following strategies:

(1) to apply economically sound management,

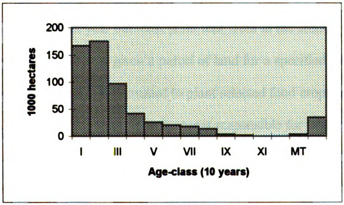
(2) to maintain the sustainability of the forests, and

(3) to participate in the effort of alleviating the poor socio-economic condition of the surrounding communities (forest villages).

At the operational (forest-district) level, the first two strategies are interpreted as a set of management objectives of (1) attaining the maximum profits and (2) maintaining relatively stable timber production over time.

Java is one of the most over-populated regions in the world. A chronic problem affecting the socio-economic condition of Java's communities, among others, is the persistently high unemployment rate. Therefore, Perhutani's implementation of the third strategy has been adopting labor-intensive methods at each level of management, hence creating job opportunities for a large segment of the surrounding rural populations which are mostly poor subsistence farmers.

Despite the conflicting objectives (attaining profits versus maintaining a stable timber production and creating jobs), Perhutani has been financially healthy for decades. In 1986, before-tax total profit reached 22 billion rupiahs[1] (Perum Perhutani 1990), while employment totaled 260,000 (UGM 1990). A relevant question is whether Perhutani has been gaining profits in a sustainable fashion. In view of the currently practiced management approach (discussed in the last section of this chapter), the answer to this question may be negative. Perhutani's long-term general plan sets the annual harvest for the period of 1989 - 2008 at 5,000 hectares or 575,000 cubic meters (Perum Perhutani 1990). Meanwhile, the current age-class distribution of the forests is heavily skewed toward younger age-classes (Figure 2.2). Under the current single rotation-age management approach, attaining and maintaining the targeted annual harvest volume can not be continued and subsequently will require harvesting younger age-classes. In other words, current management may not be sustainable.




*Note:* age classes are in 10-year increment (e.g., age-class I covers ages 1 - 10, age class II covers ages 11 - 20 and so forth), MT: over mature stands.

*Figure 2.2.* Age-class distribution of teak forests in Java.

[1] The current exchange rate is approximately $1.00 = Rp 2,100.00. In 1986 the rate was approximately $1.00 = Rp 1,600.00.

## 2.2. The System of Silviculture

The system of silviculture applied to teak forests in Java is characterized by artificial reforestation, a series of thinnings, and clearcutting. This section provides brief descriptions of these silvicultural activities. A great portion of the information is obtained from Gadjah Mada University or UGM (1990), Sabarnurdin (1989), and Simon (1993).

### 2.2.1. Artificial Reforestation

Several different reforestation approaches have been devised. Three main approaches are: the *komplangan* system, the *voorbow* system, and the *tumpang-sari* system (UGM 1990). These systems are similar in the sense that they are all labor intensive and relatively low cost, employing farmers from the surrounding forest villages virtually without any monetary compensation. Briefly these systems can be summarized as follow:

*Komplangan system*: Each farmer is given two separate parcels of land. On one parcel (usually the more fertile) the farmer is permitted to cultivate food crops, while on the other parcel the farmer must plant teak trees.

*Voorbow system*: Each farmer is given one parcel of land on which he/she is permitted to plant food crops in the first year but must plant teak trees in the second year.

*Tumpang-sari* system: A farmer is given a parcel of land for a specified time period (between 2- 4 years). The farmer is permitted to plant selected food crops throughout this period between rows of teak plants. The farmer is responsible for taking care of the young teak trees during the period.

Of these three approaches, *tumpang-sari* has been proven to be the most successful system and is currently the standard reforestation system. Understandably, the *komplangan* system is less successful because farmers must pay attention to two separate parcels, and it is very likely they tend to pay more attention to the one with food crops. In the case of the *voorbow* system, it is irrational to expect farmers to spend a great amount of time in taking care of the teak plantation during the second year.

*Tumpang-sari* was first proposed in 1873 and allegedly was imported from Myanmar or Thailand. Technically *tumpang-sari* is carried out as follows. After land is cleared, teak seeds are planted on 3x1m or 2x1m spacing. Seeds of a leguminous species (*Leucaena leucocephala*) are spread in rows between the rows of teak seeds. This legume is needed for maintaining the soil nitrogen content and reducing soil erosion. The next step is planting hedge plants, usually a prickly shrub species (e.g., *Samanea sapan*), around the teak plantation for protection from animals. This is followed by planting a row of non-teak species surrounding the teak plantation inside the hedge. The purpose of planting this non-teak species is not very clear. According to some Perhutani officials, it is for producing wood needed for temporary construction in the forest. Farmers cultivate their food crops between these activities. The whole period is 29 month, during which there are usually four to five rotations of food crops (Sabarnurdin 1988). During the 29-month period the farmers are also responsible for blank-filling (replanting the seeds that did not grow using either seeds or seedlings), pruning the legume, and tending the young teak trees.

Obviously *tumpang-sari* is very desirable both from cost efficiency and output quality standpoints. For a minimal cost, Perhutani establishes forest plantations on bare lands within a period which can be as short as three years after clearcuttings. Perhutani used to be only responsible for providing the seeds of teak, legume intercrops, hedge plants and the seedlings of non-teak species. Since 1974, as a policy to improve farmers' income, Perhutani also provides seeds of agricultural crops (of superior varieties), fertilizers, and pesticides. *Tumpang-sari* teak plantations are generally well tended because farmers always tend their food crops.

Hutabarat (1990) carried out benefit-cost analyses of *tumpang-sari* using a teak forest district (coincidentally Cepu Forest District) as a case study. Actually he formalized something that was not surprising: *tumpang-sari* is beneficial to Perhutani. *Tumpang-sari* is also beneficial to farmers; any job that creates non-negative incomes should be beneficial to unemployed landless farmers having virtually no other chance of getting alternative jobs. However, Hutabarat found that the pre-1974 form of the *tumpang-sari* was not beneficial to farmers. This conclusion may be due to the assumption that farmers may get alternative jobs, which is questionable. From Perhutani's standpoint, both types of *tumpang-sari* were found to be beneficial.

Originally the size of the parcel allotted to a farmer was 0.5 hectare, which was considered sufficient for supporting the farmer's subsistence living. But due to the rapid increase in rural population, this size has been reduced repeatedly. Today, a farmer would be very lucky if he/she can get more than 0.25 hectare (Simon 1993). This indicates that, as long as there are population pressures and poor landless farmers, Perhutani will always enjoy a labor surplus and be able to cut costs and create employment at the same time.

### 2.2.2. Thinnings

Teak stands are thinned beginning at age 5 years, and thinned every 5 years until 10 years before the clearcut (Perhutani 1993). The main purpose of thinnings is to improve the quality of the stands, and thereby the value of the final timber harvest. Nonetheless, thinnings are also an important source of intermediate revenues. Thinning intensity is based on a density measure as represented by the following relationship between the average distance between trees and the average height of the dominant stand canopy:

$$S = \frac{a}{H}; \quad a = \left[ \frac{100}{\sqrt{2} \Big/ N\sqrt{3}} \right] \tag{2.1}$$

in which $S$ = relative spacing, $H$ = dominant height, and $N$ = number of trees (per hectare).

This relationship, which is credited to Hart (1928) who undertook a thinning experiment on teak plantations in Java, is what today known as the relative spacing or spacing index (see Clutter et al. 1983). From this relationship, Perhutani derived and tabulated the standard after-thinning per-hectare number of trees for each site class at any age. This table is used in practice as the thinning manual, from which the number of trees that must be left in any thinning is obtained.

The compulsory 5-year thinnings makes Perhutani's thinning scheme very rigid. Setyarso (1985) suggests that Perhutani should consider renovating its current thinning method.

### 2.2.3. Clearcuttings

Final harvests are carried out through clearcutting. Before clearcuts, trees are girdled at least two years in advance. The purpose is to reduce timber damage in the felling process; teak trunks often split or break when cut in a fresh condition. Another advantage of girdling is the reduction in water content of the trees, hence reducing the transportation costs. Like other activities, clearcutting is carried out in a very labor intensive fashion excluding any form of modern mechanization. Trees are felled and cut into logs using hand saws, hauled using cows, and loaded onto trucks by humans. Every single piece of each log is documented systematically, making easy tracing of any lost piece. This also aids in recognizing logs coming from illegal cuttings.

## 2.3. Forest Regulation

Management of the teak forests in Java has always been based on the conventional wisdom that maximum and sustained yield is a product of a normal or fully regulated forest. Two normal-forest oriented forest regulation methods have been subsequently implemented. The first method is called the *gecombineerde vakwerk methode* (GVM) which was formally issued in 1938, and was the compulsory forest regulation technique until it was replaced in 1974. The newer method, which is still in use today, is called the Burn's method. A further elaboration on these two methods is necessary in order to examine their limitations, hence providing a justification for examining a more modern quantitative technique. Information presented in this section is based on a critical review on the GVM by Hardjosoediro (1973) and the operational manuals of the two methods, respectively (Anonymous, no year; and the Directorate General of Forestry 1974).

2.3.1. The *Gecombineerde Vakwerk Methode* (GVM)

At the time GVM was devised, natural stands constituted the majority of teak forests in Java. GVM was designed primarily for converting these forests into fully-regulated forests. Hardjosoediro (1973) indicates that conceptually GVM is a hybrid of the classical area-based and volume-based periodic block methods and the Von Mantel technique. However, the relation to those classical methods is truly limited only to the determination of the area and volume allowable cuts in the early stage of the procedure. The relation with the Von Mantel technique is perhaps in terms that yield is estimated at the rotation age. The following summary is intended to provide a better understanding of this particular forest regulation technique. All formulas are prepared by the author based on their corresponding descriptive explanations in the manual.

(1) *Predicting the potential volume of the forest*

GVM starts with determining the budget volume of the forest, that is, the total volume at the rotation age. This quantity is computed using:

$$TV = \sum_{i=1}^{n} l_i v_i \tag{2.2}$$

where

$TV$ = total volume or budget volume (in cubic meters) for $n$ age-classes

$l_i$ = total hectares of age-class $i$

$v_i$ = per-hectare volume of age-class $i$ at the rotation-age.

Volumes of plantation stands are derived from a normal table. For natural stands, the volumes are computed using:

$$V = (Boniteit)^2 \times dn \times f \tag{2.3}$$

where

| | |
|---|---|
| $V$ | = stand volume (in cubic meters) |
| *Boniteit* | = site class (not site index; 1, 1.5, 2, ...6) derived from an age-height graph |
| $dn$ | = a ratio indicating the closeness of the stand to the normal stand |
| $f$ | = factor of exploitation, usually between 6 - 10, dependent upon the topographical condition of the forest, harvesting technique utilized, type of product produced, etc. |

(2) *Determining the annual allowable cut (AAC)*

The AAC is computed both in terms of area and volume. Respectively, the two AACs are obtained by dividing the total area and the total volume of the forest (*TV*) by the rotation age.

(3) *Determining the conversion period*

The conversion period is the number of years required to convert the unregulated (natural-forest) portion of the forest into plantations. It is determined as the average of the area-based and volume-based conversion periods. The area-based conversion period is the total area of the natural forest divided by the area AAC. Likewise, the volume-based conversion period is the total volume of the natural forest divided by the volume AAC. Arithmetically, this is given by:

$$CP = \frac{1}{2}\left(\frac{L_{nr}}{AAC_L} + \frac{V_{nr}}{AAC_V}\right) \tag{2.4}$$

where

| | |
|---|---|
| $CP$ | = conversion period |
| $L_{nr}$ | = total area of the natural forest |
| $V_{nr}$ | = total volume of the natural forest |
| $AAC_L$ and $AAC_V$ | = area-based and volume-based annual allowable cuts. |

(4) *Re-determining the AAC.*

Given the length of the conversion period, the next step is re-determining the area and volume AACs for the first period (first ten years). This time these AACs are obtained respectively by dividing the total area and volume of the natural forest by the length of the conversion period, i.e.,

$$AAC_L = \frac{L_{nr}}{CP} \quad \text{and} \quad AAC_V = \frac{V_{nr}}{CP} \tag{2.5}$$

(5) *Allocating hectares and volume to each period*

Finally, hectares of each age class are allocated to the 10-year periods throughout the rotation. It is unclear how this part should be done quantitatively. It seems that from this point forest regulation is treated as an art instead of a quantitative planning process. According to the example in the manual, total hectares allocated to each period are intended to be as close as possible to the area AAC of the first period, and so is the corresponding total volume. This implies that the first period AACs are applied throughout the rotation, which is difficult to justify because those AACs were computed only for a portion (the natural forest) of the forest and were based on the conversion period. Hardjosoediro (1973) perceives this is a fundamental mistake with an implication endangering a forest's sustainability.

After about a half century of implementation, it was concluded that the GVM was no longer appropriate. Several forests districts were unable to maintain a perpetual timber production level and the targeted fully-regulated forests were far from reality. Massive over-cuttings during the Japanese occupation in the Second World War, extensive forest destruction during the subsequent revolution period, and relentless timber theft have been blamed as the main causes of the failure. To correct this situation, a new technique called the Burn's Method was devised to replace the GVM. Conceptually this new technique is very similar to the former. The major difference is that it allows harvesting below the standard rotation age depending upon the current age distribution of the forest. As a result, the new technique may be an appropriate remedy in the short-run, but is hardly a long-run solution to the problems faced.

2.3.2. The Burn's Method

This new technique is almost identical to the GVM. A few notable differences include:

(1) The total volume used in determining the volume AAC; it is not the total volume at the rotation-age, but rather the total volume at a forest specific mean-cutting-age or MCA.

(2) As an implication of (1), the cutting-ages of each age class may vary, either below or above the standard rotation-age depending on the forest age-class distribution.

(3) The technique involves a procedure called cutting-time testing, which is basically examining whether a resulting AAC will insure a perpetual harvest, and adjusting it if it does not.

In general, the procedure involved can be summarized as follow:

(1) *Determining the MCA*

The MCA of a given forest is defined as the weighted-average age of the forest plus one-half of the standard rotation age. For a forest with *k* age classes, MCA is computed using the following formula:

$$MCA = \frac{\sum_{i=1}^{k} L_i A_i}{\sum_{i=1}^{k} L_i} + 0.5R \qquad (2.6)$$

where,

$L_i$ = total hectares of age-class *i*

$A_i$ = mid-age of age-class *i* (for example 15 is the mid-age of age-class 2)

$R$ = standard rotation-age which is usually 70 or 80 years.

(2) *Determining the budget volume and the AACs*

The forest budget volume is computed using formula 2.2, but $v_i$ is the projected volume of age-class *i* at the MCA instead of the rotation age. The forest volume AAC is computed using this budget volume. Area AAC is computed as usual.

(3) *Testing the volume AAC*

The main objective of the Burn's method is to ensure a perpetual harvest. Accordingly, after defining the area and volume AACs, the Burn's method proceeds with a lengthy procedure called cutting-time testing. This is basically computing the number of years required to harvest the entire forest if the AAC is applied. The computation is carried out for one age-class at a time starting from the oldest age-class. The manual explains this procedure using an example, which can be represented in the following series of formulas:

$$Y = \sum_{i=1}^{n} y_i$$
$$y_i = \frac{V_i}{AAC_V} \tag{2.7}$$

where

$Y$ = total years required to harvest the entire forest

$y_i$ = total years required to harvest age-class *i*

$V_i$ = projected volume of age-class *i* at $MCA_i$

$MCA_i$ is the mean-cutting-age of age-class *i* which is not necessarily the same with the forest MCA obtained in step (1). $MCA_i$ is the midpoint of age-class *i* plus the total $y_i$ of all older age-classes.

If the resulting *Y* is equal to the standard rotation-age (*R*), the volume AAC is considered to be correct and will ensure a perpetual harvest throughout the rotation. Otherwise, if *Y* differs from *R* , the AAC is adjusted by the quantity (*Y/R*) and the entire process of cutting-time testing is repeated. The test is conducted until ($Y = R$ ) is attained.

(4) *Allocating hectares and volume to each period*

This step is carried out in the same fashion as of that in the GVM. However, the budget volume to be allocated is no longer the budget volume obtained in step (2). Rather, it is the sum of all $v_i$ obtained during the process of cutting-time testing; recall that during cutting-time testing the $MCA_i$ of individual age-classes are adjusted.

## 2.4. Limitations of the GVM and the Burn's Method and Relations to the Hutan Tanaman Industri (HTI) Program

### 2.4.1. Limitations

Both the GVM and the Burn's Method inherit the benefits and limitations associated with the concept of a normal or fully regulated forest. Early day's texts (for example Roth (1925) as cited in Davis and Johnson (1987)) list several potential benefits of a regulated forest. One of the most important, and perhaps still relevant benefits, is a stable annual or periodical harvest (in terms of volume, size, quality, and value). On the other hand, there are some fundamental inadequacies associated with any forest management techniques based upon the normal-forest concept. First, these techniques generally assume the existence of an ideal normal forest and attaining such a normal or near normal forest is usually the primary management objective (Ware and Clutter 1971). By definition, a forest is normal if it has and maintains a normal increment, normal growing stock level, and normal age-class distribution (Leuschner 1990). A normal increment is the maximum increment produced by a given species on a particular site. Since it is achieved when the forest is fully-stocked, a normal increment also implies a normal growing-stock. A normal age-class distribution exists when the forest area, adjusted for differences in site productivity, is equally distributed across age-classes. Since a forest with all normality conditions satisfied virtually does not exist, a normal forest is almost purely conceptual.

A fully regulated forest is not necessarily a normal forest. It is defined as one that produces an equal level of production perpetually. Unlike a normal forest, a fully regulated forest is theoretically achievable. However, as noted by Thompson (1966), creating and maintaining a regulated forest incurs several costs: (1) the opportunity cost due to delayed harvests and/or leaving land idle during the conversion period, (2) the cost due to the inflexibility of assuming that the currently determined optimal parameters (e.g., rotation age) will remain optimal in the future, and (3) the opportunity cost represented by more attractive investment alternatives which are not considered because the regulated-forest is considered an end in itself. Thus, in justifying whether attaining a regulated-forest is an economically sound management approach, these costs should be weighed against the potential benefits along with the owner's objective, constraints, and assumptions.

Moreover, the value of a regulated forest either as an end in itself or a means to an end has been questioned in recent decades. Beuter (1982) effectively elaborated on the subject and contended that a regulated forest is of "questionable value" as an end in itself and is not very useful as a means to an end. Clutter et al. (1983) were even more lucid in asserting that achieving a static balanced fully-regulated forest should no longer be part of the goal of today's forest management, because "... the real role of the manager is the intelligent management of *imbalanced* forest structures." These statements imply that a fully regulated forest is no longer a necessary condition for achieving modern forest management objectives such as maximizing profits over a given time period or in perpetuity. Moreover, attaining a regulated-forest is not necessary as an explicit goal of forest management because, as indicated by Beuter (1982), intended or not intended, a regulated forest will materialize in the long run. It is a by-product of long-term forestry planning because of economic and institutional constraints and assumptions imposed in the planning process.

In addition to these limitations, both the GVM and the Burn's Method involve some data manipulations without any clear nor discernible rationale (e.g., the calculation of the mean cutting age). Moreover, in spite of the rigorous cutting-time testing, there is no guarantee that the Burn's method will ensure a stable harvest flow. It remains very possible that, in order to avoid any decline in harvest volume, the total hectares harvested in any given year or period may exceed the previously calculated AAC. Once this takes place, it starts a chain effect over the subsequent periods and the expected fully-regulated forest may never materialize.

Neither one of the techniques ensures the attainment of the maximum total revenues. The use of a single rotation-age is by no mean a revenue-maximizing strategy. It may maximize the total harvest volume if the standard rotation is a volume-maximizing rotation. However, maximizing the total volume and maximizing the total revenue only coincide when the time-value of money is ignored. Thus in general, the Burn's method does not fully accommodate the current management objectives of maximizing revenues and maintaining a relatively constant annual timber production.

2.4.2. Relations to the HTI Program

The fundamental limitations inherent in the Burn's method receives little notice because, as mentioned earlier, Perhutani has been gaining profits for decades. However, a deeper observation would reveal at least two non-ordinary conditions which may have enabled Perhutani to gain substantial profits regardless of the shortcomings in its management approach. First, for decades Perhutani had the luxury of harvesting high quality old-growth forests and second, the labor cost in Java, especially in teak forests regions, has been unusually low. These two advantages, combined with the constantly high price of teak wood, undoubtedly have contributed significantly to Perhutani's financial profits.

Nonetheless some proponents (e.g., Sumitro 1992 and Iskandar 1992), implicitly suggest that Perhutani's financial success and the relatively constant or even slightly increased total area of the teak forests reflect the overall accomplishment of the management approach. Sumitro further implies that this exemplary accomplishment warrants recommending Perhutani's management approach as a model for forest plantation management in Indonesia, which in general also includes the HTI industrial timber plantations. While Sumitro's recommendation is subject to criticism, until another alternative is made available it is very likely that the industrial timber plantations established under the HTI program will be managed similarly to the teak forests in Java.

## CHAPTER THREE:

## LITERATURE REVIEW

This chapter reviews literature on: (1) harvest scheduling and (2) growth and yield modeling. Selected articles dealing with modern approaches of harvest scheduling, (i.e., the application of operation research techniques) are reviewed in the first section. The second section highlights studies proposing techniques for incorporating risk in harvest scheduling models. Chance-constrained programming, a particular technique of optimization under risk, is the subject in the third section. Finally, articles dealing with concepts and techniques of growth and yield modeling are discussed in the last section.

### 3.1. Current Approaches of Harvest Scheduling

In modern forest management, harvest scheduling using operation research techniques replaces the classical and neoclassical forest regulation approaches. One of the most widely used techniques is linear programming (LP). The works by Curtis (1962), Loucks (1964), Kidd et al. (1966), Liittschwager and Tcheng (1966), Nautiyal and Pearse (1967), Paine (1966), and Ware and Clutter (1971) are among early studies pioneering the application of LP for harvest scheduling. Numerous LP-based harvest scheduling software have been developed. The most well known include Max-Million (Clutter 1968), Timber-RAM (Navon 1971), and FORPLAN (Johnson et al. 1986). In addition, there are also several lesser known personal computer LP-based harvest scheduling programs, such as TIMPRO-FORMAN (Hendricks and Harrison 1987), and the spreadsheet-based FORSOM (Leefers and Robinson 1990).

With mathematical programming, harvest scheduling problems are treated as constrained optimization problems. In general, the forest's utility to the owner is maximized subject to various constraints. Given the relatively long time-span in forest management, a common measure of utility is the net present value (NPV) of the forest. Considerations restraining the maximization of the NPV usually include those reflecting management policies and requirements such as a required level of periodic harvest volumes, maximum hectares harvested, and the like.

Several advantages are afforded from handling harvest scheduling problems in a mathematical programming fashion. Selected advantages are listed below.

1. It insures that the resulting harvest schedule is the optimal strategy for attaining the management objective under the imposed constraints.
2. Because the modeling framework involves a critical assessment of the management objectives, identification of alternatives, and specification of the scope and limitation within which the solution holds, mathematical programming helps insure that the right problem is being solved (Rustagi 1976).
3. Mathematical programming provides features for examining the effects of changes in inputs or management constraints, and models can be adjusted as new information becomes available (Rustagi 1976).
4. Mathematical programming enables attaining the benefits of fully-regulated forest (e.g., a a stable timber production over time) without the necessity of forcing the forest to form a specific age-structure (Hoganson and McDill 1993).

Apart from these advantages, Chappelle (1977) observed some practical limitations associated with the application of LP to forestry planning in general. The first limitation is the high data requirement (in terms of quantity and quality) which usually entails numerous assumptions. The second limitation has to do with the necessity of relying on spatial and temporal aggregations in order to maintain a manageable model size, and high level aggregations usually bring about aggregation errors. Furthermore, Chappelle considers the requirement of specifying an objective function as both an advantage and disadvantage. It is an advantage in the sense that the requirement forces planners to assess thoroughly the owners' or decision makers' management objectives. However, it is a disadvantage when the forest is managed for multiple objectives. Treating one of the management objectives as an objective function implies putting less weight to the other objectives which are represented as constraints.

The high-data requirement is factually true, but it should not greatly hinder the applicability of LP, primarily because mathematical programming forestry planning models can be improved incrementally. In terms of model size, to some extent it can be technically overcome through the application of the decomposition method used by Liittschwager and Tcheng (1966) and more recently, by Berck and Bible (1984) and Hoganson and Rose (1984). With regard to the last objection, Rustagi's (1976) notions regarding three alternatives of how a multiple-use resource may be managed perhaps give some clarification. At one extreme, a potentially multiple-use resource may be managed for producing a single output disregarding the other uses. At the other extreme, the resource's multiple uses are literally exploited for producing several outputs without a single output being dominant. In this case, the single-objective limitation noted by Chappelle hampers the applicability of LP. However, it is more common that a multiple-use resource is managed to produce one primary output and several secondary outputs. This justifies putting one management objective as an objective function and treating the others as constraints.

Nonetheless, LP's inadequacy in accommodating multiple objectives has led to the assessment of the applicability of multiple-objective programming (De Kluyver et al. 1980, Mendoza et al. 1987, and Mendoza 1988) and goal programming (Kao and Brodie 1979, Field et al. 1980, and Hotvedt et al. 1982). De Kluyver et al. (1980) used a multiple objective linear programming (MOLP) to formulate an optimal multicriteria harvest scheduling. Likewise, Kao and Brodie (1979) proposed the use of goal programming (GP) for reconciling incommensurate objectives in harvest scheduling (i.e., maximum NPV, perfect regulation, and even-flow of harvest) and conclude that under the given situation GP is superior to LP. Field et al. (1980) and Hotvedt et al. (1980) suggested a complementary use of LP and GP for harvest scheduling, which eliminates LP's limitations when there are conflicting criteria, and avoids possible pitfalls of GP by basing it on the LP solution. The framework starts by formulating the harvest scheduling problem as an LP and optimizing several objective functions serially. Based on the LP solutions, the problem is reformulated as a cardinally-weighted GP model and solved in various forms. Finally, a strategy that best satisfies the decision maker's preferences is selected from the GP solutions after comparing them to the original LP solutions.

In general, GP remains less popular than LP for forestry planning. Leuschner (1990) states that, although theoretically it is heralded as a technique for solving multiple-objective problems, GP still minimizes one objective function and still has many limitations. Dyer et al. (1979, 1983) compare GP with LP from a welfare economic perspective and contend that, in contrast to the LP solutions which are Pareto-optimal, the solutions of GP are Pareto-inferior. Hrubes and Rensi (1981) and Rensi and Hrubes (1983) argue that neither LP nor GP will necessarily produce Pareto-optimal solutions in the public domain due to imperfect markets, wrong price signals, and inaccurate representation of production possibility curves, and therefore, judging the usefulness of GP from the welfare economic perspective is inappropriate. This debate, however, may be of more theoretical interest. From a practical standpoint, perhaps the greatest limitation of GP is the necessity to obtain substantial information from the decision makers concerning their objectives, targets, weights and ordering of preferences.

A popular alternative to LP is binary-search (BS) simulation. Chappelle's (1966) SORAC is considered the first application of BS simulation for harvest scheduling. More recent BS scheduling software includes SIMAC (Sassaman et al. 1972), ECHO (Walker 1976), and TREES (Tedder et al. 1980). LP and BS differ in several aspects. Johnson and Tedder (1983) compare these two techniques and suggest that both have relative advantages but none is definitely superior to the other. Some important advantages of BS include: BS usually costs less per run, BS provides feasible solutions more easily, BS is able to depict the inventory in more detail, and BS can accommodate changes more easily. The main limitation of BS is that the solution obtained may not be optimal; it is only optimal if all predetermined inputs are optimal. Many argue that solutions which are near optimal may be sufficient in practice. However, "near" can be ambiguous and it is generally desired to have optimal solutions. Moreover, because BS depicts instead of solves problems, one special program is usually needed for each specific problem. In this sense, BS is less flexible. Other limitations include: limited number of decision variables (maximum equal to the number of periods), difficulty in incorporating constraints beyond an overall harvest flow, and inability to consider alternatives management intensities. Hoganson and Rose (1984) developed a heuristic that overcomes the last limitation, but still retains the difficulties of handling constraints beyond harvest level. Although in general BS is a viable harvest scheduling tool, LP has received more attention in recent decades. The National Forest Management Act (NFMA) indicates a preference for optimization techniques over simulation, and the U.S.D.A Forest Service currently uses FORPLAN for developing long-run management plans for national forests (Kent 1980).

Johnson and Scheurman (1977) broadly classify the numerous techniques of formulating harvest scheduling problem as a mathematical programming or simulation model into Model I and Model II formulations. In their simplest forms, the two formulations can be presented as follows:

Model I:

$$\max \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij} x_{ij} \tag{3.1}$$

subject to

$$\sum_{j=1}^{n} x_{ij} = A_i \tag{3.2}$$

where:

$x_{ij}$ = hectares of management unit (e.g., stand type or age class) *i* allocated to management regime (activity) *j*

$A_i$ = total hectares of management unit *i*

$c_{ij}$ = NPV of allocating management unit *i* to management regime *j*.

Model II

$$\max \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij} x_{ij} + \sum_{i=1}^{m} e_{iN} w_{iN} \qquad (3.3)$$

subject to

$$\sum_{j} x_{ij} + w_{iN} = A_i \qquad i = -M,0 \qquad (3.4)$$

$$\sum_{k} x_{jk} + w_{jN} = \sum_{j} x_{ij} \qquad j=1,N \qquad (3.5)$$

where

$x_{ij}$ = hectares regenerated in period $i$ and harvested in period $j$

$w_{iN}$ = hectares regenerated in period $i$ and left as part of ending inventory in period $N$

$A_i$ = hectares present in period 1 that were regenerated in period $i$

$M$ = number of periods before period 0 in which the oldest age-class present in period 1 was regenerated

The main difference between the two formulations is rooted in how a management regime is defined. Model I defines a management regime as a set of management activities applied to a management unit or stand-type throughout a planning horizon. In Model II, a management regime is defined as a set of management activities applied to a stand-type from regeneration to final harvest. The implication is that while Model I preserves intact the identity of the original stand-types, Model II allows hectares of different original stand-types to be merged when they are harvested in the same year or period, hence does not preserve the identity of the original stand-types. The impossibility of tracing the origin of any stand-type is often considered a disadvantage of Model II. On the other hand, the flexibility of combining hectares from different original stand-types to form new stand-types is cited as an advantage.

Other important comparisons between Model I and Model II are in terms of the number of constraints and decision variables required. Model I needs fewer area constraints than Model II. If there are *m* stand-types, and the planning horizon is divided into *T* planning periods, Model I needs *m* area constraints, whereas Model II needs $(m + T)$ area constraints. The two models are usually identical in the number of constraints that are not required by the model formulation (e.g., constraints representing harvest flow over time, or total hectares harvested).

The number of decision variables in any LP harvest scheduling model generally depends on (1) the number of stand-types, (2) the number of management regimes, (3) the number of periods in the planning horizon, (4) the minimum and maximum rotations or clearcutting ages, and (5) the initial age-class distribution of the forest (Leuschner 1990). As a result, there is no generalization regarding which model needs a higher number of decision variables. Johnson and Scheurman (1977) provide formulas for computing the number of decision variables needed in Model I and Model II for a given forest situation. To illustrate that the number of decision variables needed is very case specific, Johnson (1977) examines 12 harvest scheduling problems of different forest situations. In one problem he found that Model I requires 33,717 variables while Model II needs only 828 variables. In another example, he found that Model I needs only 339 variables as compared to 939 variables needed in Model II. However, it was also discovered that Model I needs more variables than Model II in 10 out of the 12 problems examined. This may be an indication that Model I has a tendency to increase the number of variables, while Model II can keep it relatively smaller.

### 3.2. Harvest Scheduling: Decision Making Under Risk

The literature of decision theory (e.g., Knight 1921, Raifa 1968) generally categorizes decision making into: (1) under certainty, (2) under risk, and (3) under uncertainty. Decision making under certainty refers to a deterministic situation in which the decision maker is able to specify precisely the outcomes of alternative actions or management options. Clearly this type of decision making rarely exists in reality. On the contrary, when each management option may result in several different outcomes and the decision maker is unsure about which outcome will take place, the situation faced is either under risk or under uncertainty. Risky and uncertain situation are distinguished by the availability of empirical information for generating probability distributions representing the outcomes of each alternative action. If such information is sufficiently available and the decision maker is able to predict at a specific probability level that an outcome will occur, the decision making is under risk. When very little or no such information is available, the decision making is under uncertainty.

In a forestry environment, the majority of management inputs are naturally non-deterministic, making it virtually impossible to predict the output of any forest management option with certainty. However, there is generally empirical information for predicting the range of outcomes of a given management option. For example, it is possible to predict the average and variance of the harvest volume produced by a given stand at a given future age, or to generate a probability distribution associated with the occurrence of forest fires, or to predict a range of future timber prices. Therefore, decision making in forest management, such as harvest scheduling, mostly falls into the category of decision making under risk.

Related to the categorization of decision making is the classification of decision makers with respect to their attitudes toward risk. Generally, decision makers are categorized into those who are (1) risk neutral, (2) risk averse, and (3) risk takers. Texts (e.g., Robison and Barry 1987) describe each of these groups in terms of utility functions. A risk-neutral attitude is associated with a linear utility function with a constant marginal utility, whereas a risk-averse (risk-taker) attitude reflects a concave (convex) utility function representing a diminishing (increasing) marginal utility. A decision maker with a constant marginal utility disregards the probability associated with each outcome, and therefore, is indifferent between two management alternatives with different range of dispersions (probability) as long as they have equal expected values. With a diminishing marginal utility, a risk-averse decision maker always prefers an option which outcomes are less dispersed (with a higher probability) although it may be associated with a lower expected value. Conversely, a risk-taker decision maker is willing to select an option with more dispersed outcomes in order to take a chance on receiving a higher return. In reality, the concave utility function is most rational and it is reasonable to state that most real-world business decision makers are more likely risk averse rather than risk taker or risk neutral.

While risk can not be eliminated, risk-averse decision makers can incorporate risk into their decision analyses. A fundamental drawback of using LP and its variants for handling decision making or optimization problems under risk is that LP is based on an assumption that all model inputs are deterministic. In other words, LP has no feature for incorporating risk associated with the non-deterministic nature of model inputs. Ample techniques of optimization under risk have been developed and several authors have reported some applications in forestry planning.

Hool (1966) applied a combination of dynamic programming and Markov chain approach for incorporating risk in a forest production control model (i.e., temporal and spatial scheduling of management activities to attain prespecified management objectives). In this approach, risk due to the random future states of the forest is accounted by applying the concept of Markov-chains, and prescriptions of production control activities over a planning interval are optimized by dynamic programming. The outputs are prescriptions of optimal production control activities over time for various forest conditions, and the associated expected returns. The applicability of this approach greatly depends on the possibility of generating the probability associated with each future state of the forest. Lembersky and Johnson (1975), Lembersky (1976), and Kaya and Buongiorno (1987) applied Markov decision models for stand-level management planning.

Thompson and Haynes (1971) proposed an approach termed partially stochastic linear programming. They solved a problem concerning least-cost wood procurement scheduling in which the availability of land area is not known with certainty. Their approach involves developing subjective probability distributions for the non-deterministic resource availability, followed by determining the resource availability situation through a Monte Carlo simulation utilizing the distributions. These resulting values were used as the right-hand-side (RHS) quantities of the corresponding constraints in the LP formulation, hence accounting for risk associated with the non-deterministic land-area availability.

Reed and Errico (1985) assessed the application of the stochastic control theory to develop a harvest schedule that incorporates risk due to timber losses caused by random fires. In general, it is supposed that random portions of the area in each age class in a given period are destroyed by fire, changing the state of the forest in the following period. They showed that the stochastic control approach is not practically possible when the harvest scheduling involves harvest-flow constraints. Hence, they solved a deterministic version of the problem (i.e., assuming that fixed portions of the forest are destroyed) and concluded that if the forest is relatively large, the deterministic optimal solution should provide a good approximation to the stochastic optimal solution. The variance of the random variables representing the proportions burnt determines the closeness of the two solutions. A similar approach was applied to incorporate risk due to pest hazards (Reed and Errico 1987). This time, the average annual infestation rate was used to represent the highly random occurrences of pest hazards. By simulating the resulting optimal solution over time, they showed that using the average annual infestation gives a reasonable approximation when infestation intensities are low. Gassmann (1989) showed that the stochastic version of Reed and Errico's (1986, 1987) problems can be solved using a specifically developed computer program which utilizes the Dantzig-Wolfe decomposition principle. It was found that stochastic models tend to give more conservative solutions compared to the deterministic counterparts.

Hoganson and Rose (1987) developed a harvest scheduling model that incorporates risk due to random fire using a multistage recourse approach. This approach is based on the premise that at any given point in time decision makers focus mainly on solving immediate problems. Thus, the harvest scheduling problem is solved by finding the optimal solution for one period at a time. Feedbacks obtained from implementing the optimal solution in previous periods are used as additional inputs in finding the optimal solutions of the following periods.

A harvest strategy that recognizes risk due to random growth was developed by Marshall (1987). Here risk is measured by the deviations between the expected and actual mean annual increment (MAI). A penalty cost based on weighed positive and negative deviations was developed and incorporated into the objective function. In this approach, the problem becomes one of minimizing the total cost.

Several studies addressed the situation when yield estimates are subject to random variations. Pickens and Dress (1988) discussed potential sources of randomness in yield estimates, and described the consequences of using yield estimates that contain error in LP harvest scheduling. One source of error is land aggregation, in which each aggregate is usually treated as if it is a homogenous entity although it is comprised of several non-homogenous lands/stands. Moreover, any management activity assigned to a given aggregate is usually assumed to take place in one point of time. In reality, due to the diversity inherent within each single aggregate, the timing of management activities applied to individual stands may be years apart. Another source of errors has to do with the estimation of multiple yields which are highly correlated. An example is the case when yield estimates must be split into several classes of product such as sawtimber, pulpwood, and firewood. Among their important conclusions regarding the impacts of using stochastic yield estimates in an LP harvest scheduling are: (1) the optimal objective function value tend to be optimistically biased, (2) the dual activities will be biased estimates of the true marginal costs, and (3) solutions generated will usually be infeasible.

A possible approach for incorporating non-deterministic yield estimates into an LP is by using their expected values. Hof et al. (1988) provided a theoretical explanation of this approach. When there is no harvest flow constraint, the problem can be transformed into one with random objective function coefficients but with deterministic constraints. However, the approach is not feasible when the problem involves harvest-flow constraints, in which the constraint coefficients will be no longer deterministic.

Leefers (1991) provided another possible technique. His approach involved creating a number of "sample" yield tables from a yield-estimate database utilizing a variant of the Monte Carlo simulation, hence capturing yield variability. An LP-harvest scheduling model is formulated and solved for each of these yield tables, and the expected value of the optimum is derived from the LP solutions. In essence, this approach reverses the expected-value approach mentioned previously. That is, instead of finding the optimum using the expected value of the non-deterministic yield estimates, the expected value of the optimum is determined using the non-deterministic yield estimates. Using a case model, Leefers demonstrated that, incorporating yield variability in this manner results in a more conservative harvest schedule in the sense that a wider range of rotation ages is adopted and a larger portion of the forest is not managed in the first period.

The harvest scheduling situation addressed in this study is also under risk because of the randomness contained in the yield estimates. This randomness is due to stand aggregation similar to the aggregation situation mentioned by Pickens and Dress (1988). Because the problem involves harvest-flow constraints, the expected-value approach mentioned by Hof et al. (1988) is not applicable. Hof and Pickens (1991) and Hof et al. (1992) mentioned the possibility of using chance-constrained programming for handling this situation.

### 2.4. Chance-Constrained Programming

Chance-constrained programming (CCP) is one of three main approaches of optimization under risk. The others are stochastic linear programming and linear programming under uncertainty (Näslund 1967). CCP is appropriate when the cost of risk (violating constraints) can not be a priori specified and is difficult to incorporate directly in the objective function (Kirby 1967). For instance, consider a harvest scheduling problem which incorporates non-declining even-flow (NDEF) constraints. Due to non-deterministic yield projections, this problem is under risk of violating the NDEF constraints. There is no easy means of specifying the cost associated with this constraint violation nor of incorporating it in the objective function. Moreover, when risk is due to random variations in the technical coefficients such as in this particular instance, CCP is much easier to formulate compared to stochastic programming (see Weintraub and Vera 1991).

CCP was first introduced by Charnes et al. (1958) for scheduling the production of a heating oil plant facing random future demands. This first work was followed by several papers expanding the theory of CCP (e.g., Charnes and Cooper 1959, 1963). The basic concept of CCP can be explained by beginning with the following simple optimization problem:

$$\max \sum_{j \in J} c_j \, x_j \tag{3.6}$$

$$\text{subject to} \quad \sum_{j \in J} a_{ij} x_j \le b_i . \tag{3.7}$$

This optimization can be solved as an ordinary LP if all parameters $c_j$, $a_{ij}$ and $b_i$ are deterministic quantities. When all or any of these parameters are random variables, LP is no longer feasible. Although CCP is theoretically applicable for problems in which all $c_j$, $a_{ij}$ and $b_i$ are random, it is primarily used when either or both $a_{ij}$ and $b_i$ are random. The fundamental concept of CCP is that, because of the randomness of $a_{ij}$ and $b_i$, it is admissible not to expect that the optimization holds to all possible realizations of the random variables. In other words, it is permitted to violate constraints up to a certain (small) level of probability, or conversely, constraints are required to hold with a specified level of probability but not necessarily with probability one. With this reasoning, constraint 3.7 is rewritten as:

$$\Pr\left[ \sum_{j \in J} a_{ij} x_{ij} \le b_i \right] \ge 1 - \alpha_i \tag{3.8}$$

where Pr means probability and $\alpha_i$ are specified probabilities usually to make $1- \alpha_i$ close to one. This probabilistic constraint requires the condition defined in constraint 3.7 to hold with at least $100(1-\alpha_i)$ percent of the time, or can not be violated more than $100\alpha_i$ percent of the time.

CCP is solved in its deterministic equivalent formulation. If only $a_{ij}$ are random, following the procedure defined by Rao (1984), the deterministic equivalent expression of constraint 3.8 can be derived as follow. Assume that $a_{ij}$ are normally distributed with an expected value $E(a_{ij})$. Let $Var(a_{ij})$ and $Cov(a_{ij}, a_{kl})$ be, respectively, the variance and covariances of the random variables. Define the quantity $d_i$ as

$$d_i = \sum_{j=1}^{n} a_{ij} x_{ij} \qquad i = 1,2,\ldots m. \tag{3.9}$$

Because $a_{ij}$ are normally distributed and $x_{ij}$ is constant, $d_i$ are also normally distributed with an expected value of:

$$\mathrm{E}(d_i) = \sum_{j=1}^{n} \mathrm{E}(a_{ij}) x_{ij} \qquad i = 1,2,\ldots m. \tag{3.10}$$

and a variance of

$$\mathrm{Var}(d_i) = \mathrm{X}^{\mathrm{T}} \mathrm{V}_i \mathrm{X} \tag{3.11}$$

where $V_i$ is the $i^{\text{th}}$ covariance matrix.

Hence, constraint 3.8 can be expressed as Pr $[d_i \leq b_i] \geq 1 - \alpha_i$ which leads to:

$$\Pr\left[\frac{d_i - \bar{d}_i}{\sqrt{\mathrm{Var}(d_i)}} \leq \frac{b_i - \bar{d}_i}{\sqrt{\mathrm{Var}(d_i)}}\right] \geq 1 - \alpha_i \tag{3.12}$$

The left term within the parentheses is a standard normal variate with mean of zero and variance of one. Therefore,

$$\Pr[d_i \leq b_i] = \partial\left(\frac{b_i - \bar{d}_i}{\sqrt{\mathrm{Var}(d_i)}}\right) \tag{3.13}$$

where $\delta(x)$ is the cumulative distribution function of the standard normal distribution at $x$. If $e_i$ is the value of the standard normal variable at which $\delta(e_i) = \alpha_i$, constraint 3.12 can be rewritten as:

$$\partial\left(\frac{b_i - \bar{d}_i}{\sqrt{\mathrm{Var}(d_i)}}\right) \geq \partial(e_i). \tag{3.14}$$

These inequalities will be satisfied only if

$$\left(\frac{b_i - \bar{d}_i}{\sqrt{\mathrm{Var}(d_i)}}\right) \geq (e_i) \tag{3.15}$$

or

$$\bar{d}_i + e_i\sqrt{\mathrm{Var}(d_i)} - b_i \leq 0\,. \tag{3.16}$$

Substituting expressions 3.9, 3.10 and 3.11 in 3.16 gives:

$$\sum_{j=1}^{n} \mathrm{E}(a_{ij})\, x_{ij} + e_{ij}\sqrt{\mathbf{X}^{\mathrm{T}}\mathbf{V}_i\mathbf{X}} \leq b_i \tag{2.17}$$

which is the deterministic equivalent of constraint 3.8.

Applications of CCP encompassing various areas have been reported; examples include product mix (van de Panne and Popp 1963), forage allocation (Hunter et al. 1976), water resource system (Aleksandrov et al. 1984), and finance (De et al. 1982) applications.

## 2.4. Growth and Yield Modeling

Growth and yield predictions are integral to forest management planning. With land-type classification and activity scheduling, quantitative growth and yield projections constitute essential components of forest management (Davis and Johnson 1987). More specifically, growth and yield predictions are necessary inputs in preparing any long-term forest management plans, including harvest scheduling.

Growth and yield models generally refer to various instruments for predicting growth and yield of forest stands, ranging from simple yield tables to highly sophisticated computer routines. The most conventional form of growth and yield models are tabular records containing expected volumes and other stand characteristics (e.g., number of trees, basal area, average diameter, etc.) per unit land area by combination of age and site class. These tabular records are either normal yield tables or empirical yield tables, depending on whether they were prepared from samples of selected healthy and fully stocked or "normal" stands, or samples representing the whole range of stand conditions. An obvious advantage of yield tables is that they are easy to construct. However, yield tables are usually based on a single "normal" or "average" density. Because normal stands hardly exist in reality, using a normal table usually involves some adjustments, making it less practical and potentially less accurate. Both types of yield tables are usually constructed using data from one-time measurements as opposed to data from subsequent measurements. Consequently, the patterns of stand developments implied by the tables may not reflect the actual or historical development of the individual sample stands. Therefore, yield tables must be used with caution in predicting the future condition of any given stand (Davis and Johnson 1987).

Today, most growth and yield models are in the form of mathematical equations or a set of interrelated equations. A great variety of mathematical growth and yield models have been developed, making it necessary and useful to have a classification. The most comprehensive classification is given by Davis and Johnson (1987). In this study, it is sufficient to classify mathematical growth and yield models into three main groups, namely: (1) explicit whole-stand models, (2) implicit whole-stand models, and (3) individual-tree models.

Whole-stand and individual-tree models differ in the prediction unit used and therefore, the type of predictor variables involved. Whole-stand models use stand statistics such as age, site index, number of trees per hectare, and basal area per-hectare as predictor variables, and the predictions obtained are directly in per unit area. Predictor variables used in individual-tree models are tree statistics such as tree diameter and height. Yield predictions per unit area are obtained by summation of the yield of each individual tree. Individual-tree models are potentially more accurate but tend to be data intensive and much more expensive in comparison to whole-stand models. A variant called the distance-dependent individual-tree model (Munro 1974) involves some measurement of the distance between individual trees as part of the predictor variables. This is perhaps the most complicated and expensive type of growth and yield model at the present. Due to the cost involved, the relative merit of individual-tree models versus whole-stand models has been questioned (Clutter et al. 1983). Daniels et al. (1973) evaluated the precision of whole-stand models and individual-tree models developed for loblolly pine plantations in Virginia and concluded that whole-stand models are more precise. Whole-stand models, however, are perhaps less appropriate for modeling mixed-species forests.

Whole-stand models can be broadly distinguished into explicit and implicit models. Explicit models directly give yield predictions per unit area. Implicit models, often called diameter-distribution based models, project stand structures (i.e., diameter distributions) instead of yields. Yield predictions per unit area are obtained from further computations using the predicted diameter distributions and additional treed volume equations. Because implicit models predict diameter distributions, they give more detailed information and can be used for a wider variety of purposes. For example, they can be used to simulate thinnings by removing certain portions of the diameter distributions (Knoebel et al. 1986) or to obtain yield predictions per diameter class or type of products (Bennett and Clutter 1986) which in turn enable more sophisticated economic analysis. However, using error propagation and Monte Carlo approaches, Mowrer (1987) showed that implicit growth and yield models tend to be less precise than their explicit counterparts. Lenhart (1987) compared the accuracy of explicit and implicit models in predicting yields of loblolly and slash pine plantations in East Texas and came up with a similar conclusion. Moreover, developing implicit models demands significantly more extensive data, and therefore more expense. Based on these considerations, the growth and yield models developed in this study are explicit whole-stand models.

The works by MacKinney et al. (1937) and Schumacher (1939), which introduced the methodology for developing explicit whole-stand yield prediction equations, are considered milestones in mathematical growth and yield modeling. These works presented the first variable-density yield prediction equations (i.e., equations using stand density as one of the predictor variables). The basic form of the equation, which has become well known as the Schumacher yield model is:

$$\ln(V) = \beta_0 + \beta_1 A^{-1} + \beta_2(S) + \beta_3 f(D) \tag{3.18}$$

where

| | |
|---|---|
| $V$ | = some expression of per unit-area yield |
| $A$ | = stand age |
| $S$ | = site index |
| $f(D)$ | = some function of stand density |
| $\beta_i$ | = model parameters. |

Clutter (1963) observed that, since yield is an accumulation of growth over time, growth equations and yield equations must be compatible. That is, a yield equation must be the mathematical integration of the corresponding growth equation. Based on this property, a volume growth equation can be obtained by differentiating Equation 3.18. with respect to age. This gives:

$$\frac{dV/dB}{V} = -\beta_1 A^{-2} + \beta_3\left(\frac{dD/dA}{D}\right) \tag{3.19}$$

which indicates that the relative rate of volume growth is a function of the stand age and the relative rate of growth in stand density. It also holds that the stand volume for a given future age is a function of the future age and a measure of stand density at that particular age. Since the future age is given and site index is commonly considered constant, predicting the future yield reduces into predicting the future stand density and substituting the predicted stand density into Equation 3.18. Common measures of stand density are number of trees or basal-area per unit land area. Clutter et al. (1983) suggested the following equation for predicting future stand basal-area:

$$\ln B_2 = \left(\frac{A_1}{A_2}\right)\ln B_1 + \alpha_0\left(1 - \frac{A_1}{A_2}\right) + \alpha_1 S\left(1 - \frac{A_i}{A_2}\right) \tag{3.20}$$

in which $B_1$ denotes the current stand basal-area and $B_2$ denotes stand basal-area in a given future age $A_2$. To confirm with the compatibility property, this equation is obtained by integrating a basal-area growth equation (see Clutter et al. 1983, p.121).

Given the value of $B_2$, Equation 3.18 can be rewritten to obtain an equation for predicting the stand volume in the future age $A_2$:

$$\ln(V_2) = \beta_0 + \beta_1 A_2^{-1} + \beta_2(S) + \beta_3(B_3) \tag{3.21}$$

in which $V_2$ is the stand volume at a projected future age $A_2$.

Variants of Schumacher growth and yield models have been widely used for different species in different regions. A few example are the growth and yield models for thinned and unthinned loblolly pine in the South (Clutter 1963, Sullivan and Clutter 1971, Burkhart and Sprinz 1984) and for slash pine in South Africa (Pienaar et al. 1985, Pienaar and Shiver 1986).

## CHAPTER FOUR:

## METHODS

As depicted in Figure 4.1 this study can be partitioned into two main phases. The first phase deals with developing a set of growth and yield models for teak plantations in Indonesia. The resulting models are integrated into a computer routine specifically designed for generating yield projections and computing total NPVs of various stands under different management regimes. In the second phase the computer routine is applied to a selected teak forest district. The yield projections obtained are used for developing harvest scheduling models. Subsequent sections of this chapter outline the procedures and methods applied in each phase.

### 4.1. First Phase: Growth and Yield Modeling

The product of the first phase of this study is a set of growth and yield models which can be used to predict future yields of an existing stand, based on its present condition. Since teak plantations are thinned regularly, the model set should also predict thinning yields at different ages. Specifically, the model set is to be used to obtain quantities of intermediate thinning yields and the final harvest. These quantities are, respectively, TY1, TY2, ... TYn and FH in Figure 4.2. The set of equations is comprised of :

1. a basal-area growth model,
2. a volume growth and yield model,
3. an after-thinning basal-area model,
4. an after-thinning volume model, and
5. a stand-height model.

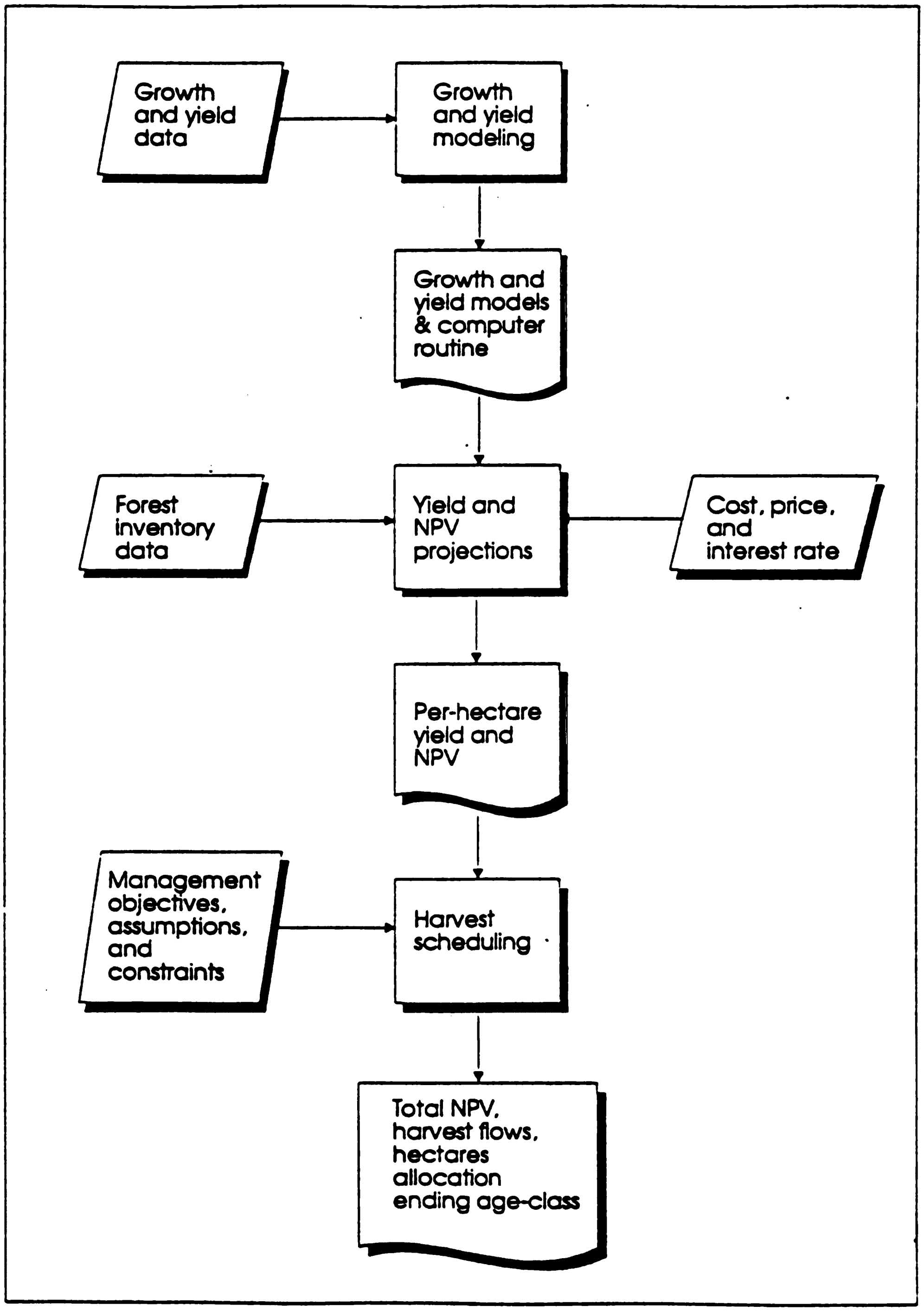



*Figure 4.1:* A general flow-chart of this study.

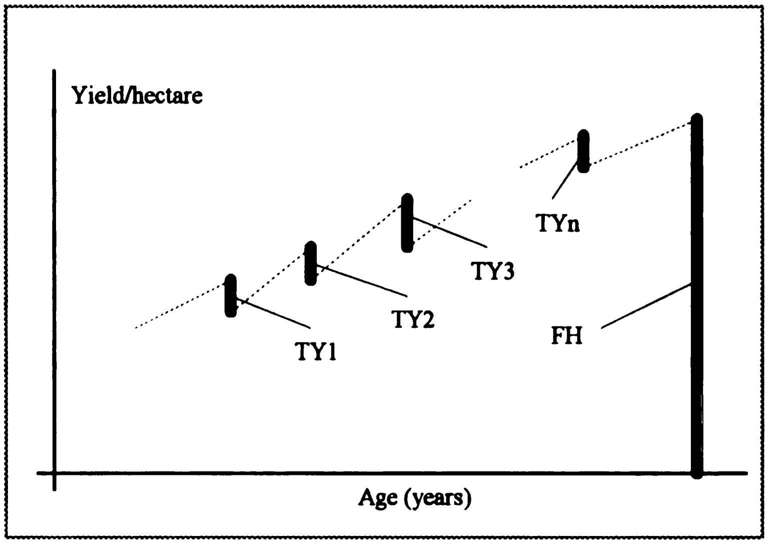



*Figure 4.2.* Intermediate thinning yields (TY1 ...TYn) and final harvest (FH) to be predicted using the growth and yield model set.

### 4.1.1. Growth and Yield Data

Growth and yield data were acquired from the Center of Forest Research and Development (CFRD) in Bogor, Indonesia. This research institution is currently under the Ministry of Forestry, and has been collecting growth and yield data of several species since it was established early in this century. The teak growth and yield data used in this study were collected from 63 permanent plots distributed in various locations in Central and East Java. This relatively small number is partly because several permanent plots were damaged during the Second World War or their remeasurement have been interrupted thereafter. Figures 4.3a and 4.3b show the distributions of permanent plots by age (at the first measurement) and site-class, respectively. The number of measurements on each plot is between two to seven times, resulting a total of 255 measurements. The time periods between two consecutive measurements range from four to ten years, but five years is common. All plots were thinned following a relative-spacing rule.

The following information can be extracted from each record (measurement): plot size; age; dominant-height; site-class; and before- and after-thinning average diameter, average height;

number of trees, basal area, and volume (all on a per-hectare basis). These data are presented in Table A.1, Appendix A.

An important issue in deriving growth data from series measurements is selecting the age interval. Three alternative age-intervals are possible for each permanent plot measured more than two times: the longest interval, all possible intervals, and non-overlapping intervals. For a permanent plot measured at $Age_1$, $Age_2$, $Age_3$ ... $Age_n$, the longest interval is the difference between $Age_1$ and $Age_n$, all possible intervals are given by the differences between all combinations of two ages (e.g., $Age_1$ and $Age_2$, $Age_1$ and $Age_3$, etc.), and non-overlapping intervals are those between $Age_1$ and $Age_2$, between $Age_2$ and $Age_3$, ..., and between $Age_{n-1}$ and $Age_n$. This study uses the last type of age-interval. Borders et al. (1987) indicated that non-overlapping intervals give the best result when two previously published basal-area models were fit using the three different types of intervals. All possible intervals are associated with the occurrence of high autocorrelation. Using the longest interval prevents dealing with autocorrelated data, but would significantly reduce the size of data set (only one data point per each plot).

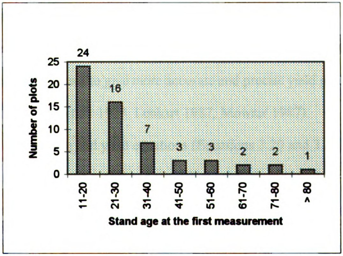



*Figure 4.3a.* Distribution of permanent plots according to stand age at the first measurement.

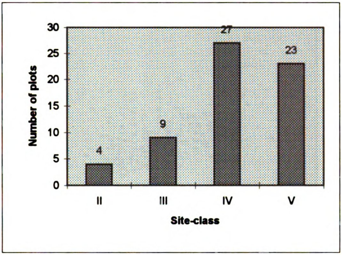



*Figure 4.3b.* Distribution of permanent plots according to site class.

## 4.1.2. Model Forms

All models used are explicit whole-stand models, as opposed to implicit whole-stand models or individual-tree models. The selection of this model type is partly because the growth and yield data available for this study are stand-average statistics. Diameter-class statistics necessary for developing implicit whole-stand models or tree-level statistics required for developing individual-tree models are not available. Moreover, as mentioned in Chapter Three, explicit whole stand models have been shown to give more accurate and precise yield predictions of some species in some locations (Daniels et al. 1973, Lenhart 1987, Mowrer 1987).

Schumacher growth and yield equations (Equations 3.20 and 3.21) are the basic functional forms of the basal-area growth model and the volume growth and yield model, respectively. Although these equations were originally developed for unthinned forests, several studies indicated that the relationships also holds for thinned plantations (e.g., Clutter 1963, Sullivan and Clutter 1972, Pienaar and Shiver 1986). In addition, data scatter-plots (Figures 4.4a - 4.4d) reveal that the dependent-independent variables relationships implied in those conceptual equations do exist.

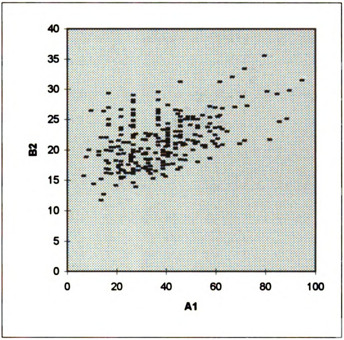



*Figure 4.4a.* Future basal area (B2) plotted against the current age (A1).

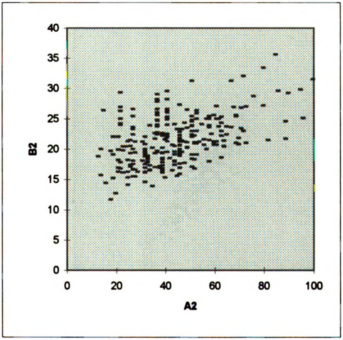



*Figure 4.4b.* Future basal area (B2) plotted against future age (A2).

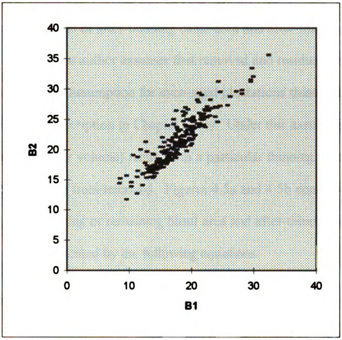



*Figure 4.4c.* Future basal area (B2) plotted against the current basal area (B1).

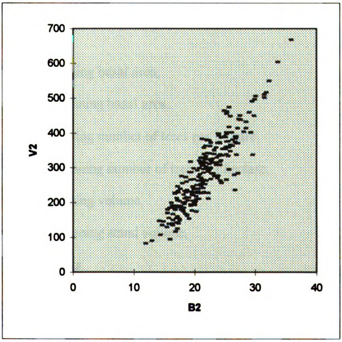



*Figure 4.4d.* Future volume (V2) plotted against future basal area (B2).

The functional forms of after-thinning basal-area and after-thinning volume models are derived as follows. First, the author assumes that removed and residual trees have the same average diameter; a tenable assumption for even-aged plantations thinned according to the relative-spacing rule (see related description in Chapter Two). Under this assumption, to some extent the proportions of basal area (or volume) removed in a particular thinning should be a function of the proportion of the number of trees removed. Figures 4.5a and 4.5b confirm that these relationships do exist. Hence, after-thinning or remaining basal area and after-thinning or remaining volume may be, respectively, represented by the following equations:

$$B_a = p\left(\frac{N_a}{N_b}\right)B_b \qquad (4.1)$$

and

$$V_a = q\left(\frac{N_a}{N_b}\right)V_b \qquad (4.2)$$

where

$B_a$ = after-thinning basal area,

$B_b$ = before-thinning basal area,

$N_a$ = after-thinning number of trees per hectare,

$N_b$ = before-thinning number of trees per hectare,

$V_a$ = after-thinning volume,

$V_b$ = before-thinning stand volume,

$p, q$ = coefficients.

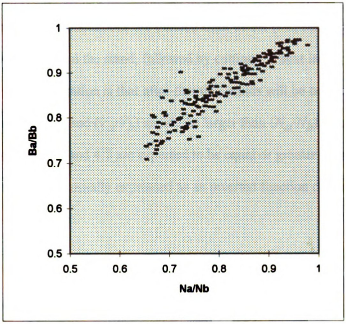



*Figure 4.5a.* Ba/Bb (the ratio between after- and before-thinning basal area) plotted against Na/Nb (the ratio between after- and before-thinning number-of-trees per hectare).

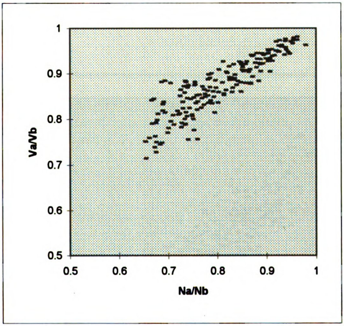



*Figure 4.5b.* Va/Vb (the ratio between after- and before-thinning volume) plotted against Na/Nb (the ratio between after- and before-thinning number-of-trees per hectare).

Operationally teak plantations are thinned from below (i.e., stands are thinned by first removing the smallest trees in the stand, followed by cutting the next larger trees until the required $N_a$ is achieved). The implication is that after-thinning stands will be comprised of larger trees, and consequently, both $(B_a/B_b)$ and $(V_a/V_b)$ should be larger than $(N_a/N_b)$. To confirm this, estimates of $p$ and $q$ in Equations 4.1 and 4.2 are expected to be equal or greater than one.

Stand-height ($H$) is usually expressed as an inverted function of stand age ($A$). One common functional form is:

$$\ln(H) = b_o + b_1\left(\frac{1}{A}\right) \tag{4.3}$$

However, an exploratory data analysis indicated that this equation is not adequate. Stand density (number of trees or basal-area) is an important determinant of height growth (Figures 4.6a and 4.6b for all ages), and therefore, should be included as one of the independent variables. Consequently, the stand-height model is empirically estimated starting from:

$$H = f(A, B, N). \tag{4.4}$$

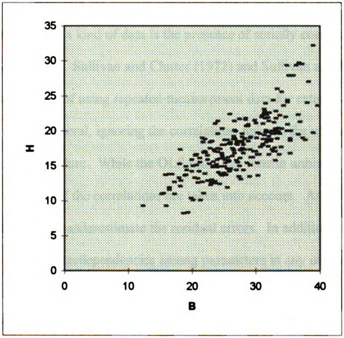



*Figure 4.6a.* Stand height (H) plotted against stand basal area (B).

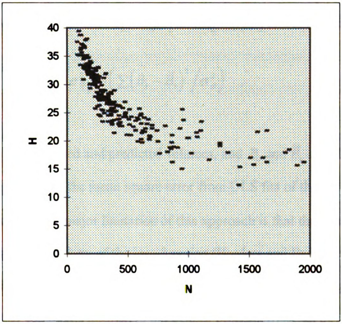



*Figure 4.6b.* Stand height (H) plotted against the number of trees per hectare (N).

### 4.1.3. Model Developments

Growth and yield data are usually repeated measurements of permanent plots. A common problem associated with this kind of data is the presence of serially correlated errors among consecutive measurements. Sullivan and Clutter (1972) and Sullivan and Reynolds (1976) discussed the implications of using repeated-measurement data for estimating a system of growth and yield equations. In general, ignoring the correlations reduces the efficiency of the ordinary least-squares (OLS) procedure. While the OLS estimates remain unbiased, their variances are larger than they would be if the correlations are taken into account. Associated with this larger variance is the tendency to underestimate the residual errors. In addition, the presence of the correlations also implies interdependencies among parameters in any one equation with those in the other equations, leading to numerically inconsistent estimates.

Burkhart and Sprinz (1984) and Knoebel et al. (1986) handled the parameter interdependency problem using a loss-function approach. Basal-area equation (3.20) and volume equation (3.21) were estimated simultaneously by iteratively adjusting the coefficients of both equations, imposing the conditions $\alpha_1 = \beta_4/\beta_3$ and $\alpha_2 = \beta_5/\beta_3$ and minimizing the loss-function

$$F = \left(\Sigma\left(V_i - \tilde{V}_i\right)^2 / \sigma_V^2\right) + \left(\Sigma\left(B_i - \tilde{B}_i\right)^2 / \sigma_B^2\right) \tag{4.5}$$

where $V_i$ and $\tilde{V}_i$ are observed and predicted volumes, and $B_i$ and $\tilde{B}_i$ are observed and predicted basal-area, $\sigma_V^2$ and $\sigma_B^2$ are the mean square error from OLS fits of the volume and basal-area equations, respectively. A major limitation of this approach is that the results are greatly affected by the arbitrarily specified form of the loss-function (Borders and Bailey 1986).

Furnival and Wilson (1971) proposed the simultaneous equation approach (e.g., multi-stage least-squares) commonly applied in the field of econometrics. In this approach, parameters of a system of related equations are estimated simultaneously rather than sequentially, thus avoiding using earlier predicted results as predictors in the other equations. Based on its conceptual superiority, many growth and yield modelers advocate this approach (e.g., Murphy 1983, Amateis et al. 1984, Borders 1989, Borders and Bailey 1986, and Gregorie 1987).

Notwithstanding, all those computationally sophisticated approaches were essentially proposed to obtain more reliable growth and yield models. In other words, it is the quality of the output that is most important. A relatively parsimonious technique would be more appealing as long as it produces a satisfactory fit to the data. Based on this practical argument, this study adopts a relatively less complicated approach used by Sullivan and Clutter (1972). They solved the interdependency problem by merging equations (3.20) and (3.21). The merged equation takes the form:

$$\ln V_2 = c_0 + c_1 S + c_2\left(\frac{1}{A_2}\right) + c_3\left(\frac{A_1}{A_2}\right)\ln B_1 + c_4\left(1 - \frac{A_1}{A_2}\right) + c_5\left(1 - \frac{A_1}{A_2}\right)S \tag{4.6}$$

This equation is simultaneously a growth and a yield equation; when $A_2 = A_1$ it gives the current volume. Together with Equations 3.20 and 3.21, this equation forms a set of equations that are logically consistent (Clutter et al. 1983). They can be used to obtain current volume and future volume, future basal area, and basal-area and volume growth rates.

Thus in summary, the set of growth and yield models in this study is comprised of Equations: 3.20; 4.1; 4.2; an empirical form of 4.4; and Equation 4.6.

### 4.1.4. The Yield-Projection Computer Routine

The resulting estimated growth and yield models will be integrated into a computer routine. The routine is designed to read tabulated forest inventory data and generate per-hectare timber yields for an individual stand under different management regimes at specified future ages, and to compute the corresponding total net present value (NPV).

To coincide with the standard 5-year thinning sequence, future yields are projected in 5-year age intervals. For example, an existing 20 years old stand is projected to ages 25, 30, 35, and so forth. Stand conditions at age $t$ are used to predict future conditions and yield at age $(t + 1)$ and, subsequently, the predicted condition at age $(t + 1)$ is the predictor of the stand condition and yield at age $(t + 2)$, and so forth.

The total NPV is the sum of discounted net revenues earned throughout the planning horizon, and computed using the common discounting procedure. Further details on the estimation of NPV are presented in Chapter Six.

## 4.2. Second Phase: Harvest Scheduling

As indicated in the beginning of this chapter, the second portion of this study deals with the development of harvest scheduling models for a selected teak forest. The computer routine discussed in Section 4.1 is utilized to produce inputs for the harvest scheduling model (i.e., per-hectare yields and NPVs for every stand under different management regimes). This section describes the selected forest district and its harvest scheduling problem, and outlines the modeling framework.

### 4.2.1. The Forest District

Perhutani's teak forest districts are similar in most aspects; they differ mainly in the extent of their forest area and timber potential. All forest districts are almost identical in terms of data availability because they follow a standard procedure for forest inventory and data management. The selection of the forest district for this study is primarily based on practical considerations, such as location and accessibility.

The selected forest district is the Cepu Forest District of Regional Unit I. Geographically it is located in the northeastern region of Central Java (Figure 4.7). Administratively, about 80% of the forest belongs to the Central Java Province and the other 20% is part of the East Java Province. The Central Java Province portion is within the area of Blora Kabupaten (kabupaten is a political unit equivalent to a county in the USA). According to the 1992/1993 forest inventory, the total forest land of the Cepu Forest District is 26,700 hectares, more than 90% of which is for teak production. The remaining hectares are in non-teak production and not for production. The Cepu Forest District covers one of the prime sites for teak in Java, and accordingly has been one of the most productive and profitable districts. It is also the site of Perhutani's main wood manufacturing plant. This particular forest district has been managed under the Burn's Method since 1974 and the most recent 10-year management plan covers the period of 1993 - 2002. The standard rotation-age is 80 years, and the targeted timber production in the first 10-year period is 40,000 cubic meters annually. The current 10-year age-class distribution (Figure 4.8) indicates that the Cepu Forest District is in a better condition compared to the entire teak forest (Figure 2.2); that is, the age-class distribution is notably more balanced.

Central Java is among the most overpopulated regions in Indonesia. The population of Kabupaten Blora in 1989 was almost 750,000; this is more than 400 inhabitants per square kilometer (Kantor Statistik Blora 1989). The Cepu Forest District is very important to the region as it employs thousands of laborers annually. In addition, as with other teak forest districts, the Cepu Forest District contributes to the growth of small-scale wood industries in the area, which create a significant number of additional job opportunities.

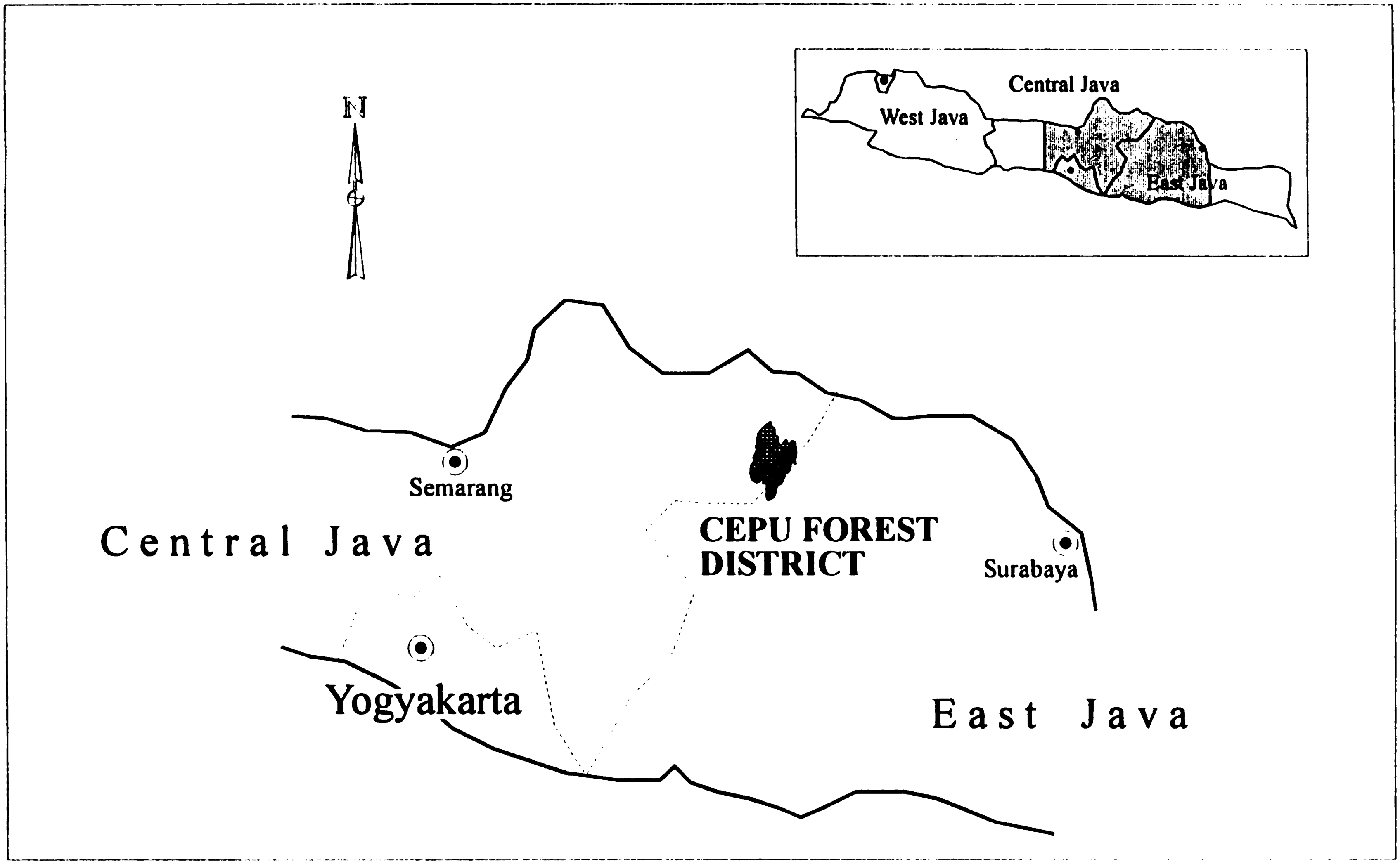
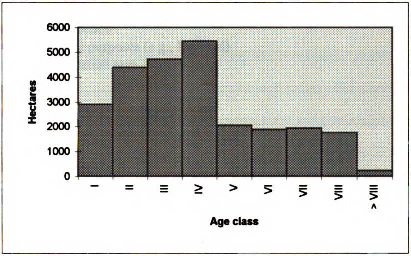



*Figure 4.7*: Location of the Cepu Forest District. (Adopted from: Perum Perhutani 1993)




*Notes:* age-classes are in a 10-year interval, e.g., age class I covers ages 1 -10 years, age class II cover ages 11 to 20 years, and so forth.

*Figure 4.8.* Age-class distribution of the Cepu Forest District.

Forest resource data used in this study were derived from Book AII, which is one of a total of six books comprising the current 10-year management plan. This book contains forest resource information collected through a periodic (10-year) forest inventory. The standard forest inventory method is systematic sampling with 2.5% sampling intensity. Data collected for every single stand include: various standing stock parameters (such as age, stand height, number of trees per hectare, stand basal area, etc.), understory condition, soil description, topographical condition, and a brief history of the stand's establishment (e.g., method of planting, source of seeds, etc.).

Based on their overall condition and predetermined purposes, stands are categorized according to the following scheme:

A. Not for production

1. Not feasible for production
2. Designated for special purposes (e.g., log yard)
3. Conservation or recreation area
4. Protected area

B. For production

1. For teak production
    - 1.1. Clearcutting feasible
        - 1.1.1. Productive
            - 1.1.1.1. Age classes I to XII (10-year interval)
            - 1.1.1.2. Overmature
            - 1.1.1.3. Low growth
        - 1.1.2. Non-productive
            - 1.1.2.1. Clearcut site not yet replanted
            - 1.1.2.2. Bare land
            - 1.1.2.3. Non-teak stand
                - 1.1.2.3.1. Plantation
                - 1.1.2.3.2. Natural forest
            - 1.1.2.4. Teak stand with small number of trees per hectare
                - 1.1.2.4.1. Plantation
                - 1.1.2.4.2. Natural forest
    - 1.2. Clearcutting not feasible
2. Not for teak production
    - 2.1. Not good for teak
        - 2.1.1. Bare land not good for teak
        - 2.1.2. Non-teak plantation not good for teak
            - 2.1.2.1. Plantation
            - 2.1.2.2. Natural forest
        - 2.1.3. Dying teak stand
            - 2.1.3.1. Plantation
            - 2.1.3.2. Natural forest
    - 2.2. Non-teak plantation
    - 2.3. Area proposed for preservation

This study deals only with productive teak stands (i.e., those belong to category 1.1.1.) which, as indicated earlier, account for nearly 90% of the total forest area. This proportion is typical of teak forest districts.

4.2.2. The Harvest Scheduling Problem

The harvest scheduling problem of the Cepu Forest District can be summarized as follows. First, the forest district is managed with the objectives: (1) to attain the highest possible profit and (2) to achieve and maintain a sustained-yield condition. The total area of the forest land is fixed, and stands comprising the forest district can be aggregated into stand-types according to age and productivity classes. Except for low productivity sites all stands are thinned every 5 years starting at age 5 until 10 years before clearcutting, and all stands are replanted following final harvest. Timber is considered the only source of revenues. Firewood is financially a minor by-product and revenues from non-traditional products such as recreation and hunting opportunities are negligible. Costs are limited to forest management operational costs such as planting, thinning, and clearcutting costs. Other costs, such as administration costs and salary of tenured employees, are centrally coordinated. These costs are assumed to be similar regardless of management activities used. Traditionally, only one rotation age has been applied to the entire forest, but in this study alternative rotation ages or clearcutting ages (i.e., 60, 70, and 80 years) are considered. In order to attain the management objectives, the Cepu Forest District needs to devise a long-term management plan (harvest schedule) determining hectares of each stand-type that should be allocated over the rotation-age alternatives.

Perhutani's operational interpretation of the second management objective (i.e., sustained-yield condition) is a relatively constant or non-declining even flow (NDEF) of timber production over time. Attaining this condition is socially and politically important. To some extent, relatively stable harvesting activities reflects an uninterrupted creation of job opportunities (i.e., employment is associated with thinning, girdling, clearcutting, and replanting), and creating employment is one of Perhutani's mandates. From Perhutani's standpoint relatively constant timber production will create a stable cash-flow.

A key aspect in attaining the management objectives is the non-deterministic nature of timber yield predictions due to spatial and temporal aggregations. Projections of per-hectare yields used in the harvest scheduling, denoted as $a_{ijt}$, are the average of per-hectare yields of many individual stands belonging to specific stand-types, under specific management regimes, and harvested in specific periods. The values $a_{ijt}$ are not free of variances. The consequence is that the actual quantities of some of the $a_{ijt}$ may differ from their corresponding average quantities used in the standard harvest scheduling. If the actual quantities of some of the $a_{ijt}$ are smaller than expected, the actual total profit earned will be less than indicated by the harvest schedule. In other words, the model solution may be optimistically biased. If the discrepancies between the actual and predicted values of $a_{ijt}$ are substantial, hectares allocated over alternative rotation ages will no longer lead to an NDEF condition.

Depending upon Perhutani's attitude toward such risk, the possibility described above may or may not be a matter of concern. If it is not a significant concern, $a_{ijt}$ may be treated as deterministic, implying that Perhutani is willing to accept the risk. However, considering the financial implications, it is more rational for Perhutani to incorporate the risk into its long-term management planning. In other words, a harvest schedule that incorporates some level of assurance for the attainment of the management objectives would be more desirable. Therefore, as noted in the opening chapter, an important specification of the harvest scheduling involves its treatment of risk of not attaining the management objectives, particularly the NDEF condition, due to the variability of timber yields.

### 4.2.3. Model Outline

Based on the harvest scheduling problem described above, the harvest scheduling model needed should maximize total profit over a specified time period (planning horizon) while simultaneously maintaining a NDEF condition. To account for the time value of money, the total profit is represented by the total NPV over the planning horizon. Alternatively it could be represented by the total timber volume, but only if the discount rate is assumed to be zero. For purposes of comparisons, the harvest scheduling model is formulated and solved in two versions: excluding risk (ordinary LP) and including risk. The nature of the problem leads to selecting chance-constrained programming (CCP) for the including-risk version. CCP is appropriate because the non-deterministic components of the problem are contained in the constraints. In addition, the cost of risk in this problem can not be easily quantified, eliminating the selection of stochastic linear programming which incorporates risk directly in the objective function. In CCP, constraints are assumed to be independent (i.e., coefficients in one constraint are not correlated to those in other constraints). In this study, yields of a given stand in different periods may not be perfectly independent, and therefore, the assumption is likely not fully satisfied. The effect of this violation is unknown (Hof et al. 1992). In this study, a zero correlation is assumed.

A rule-of-thumb in forest management planning is to set a planning horizon between 1.5 to 2 times the rotation length (Clutter et al. 1983). Leefers (1991) examined the effect of using different lengths of planning horizon in harvest scheduling and reported that shorter planning horizons tend to allocate a larger portion of the forest for harvest in the early years or periods. In other words, using longer planning horizons helps ensure the long-run sustainability of the forest. A 120-year planning horizon is used for the harvest scheduling in this study. For rotations considered (i.e., 60, 70, and 80 years) this planning horizon is 1.5 to 2 times of the rotation length. This planning horizon is divided into 12 equal planning periods to reduce model size.

The harvest scheduling model will be structured with a Model I formulation (Johnson and Scheurman 1977). For the harvest scheduling under study, Model I is easier to formulate and requires fewer constraints. The first management objective, to maximize the total NPV, is treated as the objective function; the second management objective, to achieve and maintain a sustained-yield condition, is represented by a set of NDEF constraints. The Model I formulation requires explicit definitions of stand-types and management regimes. A stand-type is defined as an aggregate of individual stands belonging to the same age class with similar productivity. For this study, age-classes are arranged in 10-year increments, and the productivity of a given stand is measured by the stand's total yield with a maximum 80-year rotation. By definition a management regime is a sequence of management activities applied to any stand-type throughout the planning horizon. Since all stands (except some low productivity sites) are mandatorily thinned every 5 years and must be replanted following clearcutting, management regimes are solely characterized by the rotation length. A management regime, therefore, is simply formed by any combination of a rotation-age and a stand-type. It is assumed that an identical rotation age is applied to both the current and regenerated stands. For example, assigning a 60-year rotation to a 40-year old stand implies that both the existing and regenerated stands will be harvested at age 60, or in periods 3 and 9 respectively. A more elaborate model could include multiple regenerated stand rotations for any given current stand rotation.

### 4.2.4. Model Formulation

For convenience, the problem is formulated starting from the LP version. The CCP version is obtained by slightly modifying the LP formulation. The basic LP formulation follows.

$$\max Z = \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij} x_{ij} \tag{4.7}$$

subject to:

$$\sum_{j=1}^{n} x_{ij} \le L_i \tag{4.8}$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijt} x_{ij} \ge LV_t \qquad (t = 1) \tag{4.9}$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijt} x_{ij} \le UV_t \qquad (t = 1) \tag{4.10}$$

$$(1+u)\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijt} x_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij(t+1)} x_{ij} \ge 0 \qquad (t = 1...11) \tag{4.11}$$

$$(1-l)\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijt} x_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij(t+1)} x_{ij} \le 0 \qquad (t = 1...11) \tag{4.12}$$

$$x_{ij} \geq 0 \tag{4.13}$$

where

| | |
|---|---|
| $c$ | = net present value (Rupiah/ha, 1993 constant rupiahs) |
| $x$ | = hectares allocated (ha) |
| $L$ | = total forest area (ha) |
| $a$ | = per-hectare yield ($m^3$/ha) |
| $LV$ and $UV$ | = respectively, minimum and maximum harvest volumes |
| $u$ and $l$ | = respectively, maximum allowed increase and decrease in periodic harvest volumes (percent) |
| $i, j, t$ | = respectively, stand-type $i$, management regime $j$, period $t$. |

The objective function 4.7 maximizes the total *NPV* of the entire forest. Constraint 4.8 is the land-area constraint, which ensures that the total hectares of stand type $i$ allocated over the management regime alternatives not exceed the corresponding total hectares available. Constraints 4.9 and 4.10 restrict the total harvest volume in period one to be within the specified upper ($UV$) and lower ($LV$) bounds. Constraints 4.11 and 4.12 control the fluctuation of harvest volumes over time. The upper and lower bounds $u$ and $l$ are in terms of percentage of the harvest volume in period $t$. Thus, for any positive $u$ and $l$ the harvest volume in period $(t+1)$ is restricted within $(100 - l)$% and $(100+u)$% of the harvest volume in period $t$. Constraint 4.13 is the common non-negative constraint.

Transforming the LP formulation into a CCP requires reformulating constraints 4.9 - 4.12 into chance-constraints. First, these constraints are expressed in the following probabilistic terms:

$$\Pr[Y_t \geq LV_t] \geq 1 - \alpha \qquad (t = 1) \tag{4.14}$$

$$\Pr[Y_t \leq LV_t] \geq 1 - \alpha \qquad (t = 1) \tag{4.15}$$

$$\Pr\left[(1+u)Y_t - Y_{t+1} \geq 0\right] \geq 1-\alpha \qquad (t = 1...11) \tag{4.16}$$

$$\Pr\left[(1-l)Y_t - Y_{t+1} \geq 0\right] \geq 1-\alpha \qquad (t = 1...11) \tag{4.17}$$

where

$$Y_t = \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijt}x_{ij} \quad \text{and} \quad Y_{t+1} = \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij(t+1)}x_{ij}$$

and Pr = probability, and $\alpha$ = the probability level, which is usually selected to set (1-$\alpha$) close to one. For purpose of this study, $\alpha = 0.05$ is arbitrarily selected as the starting probability level. In practice, this level should be determined by the decision makers. Constraints 4.14 and 4.15 impose that (1-$\alpha$) per cent out of 100 chances the total harvest volume in period 1 should be within the specified lower- and upper bounds ($LV_t$ and $UV_t$). Similarly, constraints 4.16 and 4.17 require that (1-$\alpha$) per cent out of 100 chances the harvest flow should be within the allowed maximum increase ($u$) and maximum decrease ($l$).

Through the procedure described in Chapter Four, 4.14 - 4.17 are transformed into:

$$E(Y_t) - \beta\left[\text{Var}(Y_t)\right]^{.5} \geq LV_t \qquad (t = 1) \tag{4.18}$$

$$E(Y_t) + \beta\left[\text{Var}(Y_t)\right]^{.5} \leq UV_t \qquad (t = 1) \tag{4.19}$$

$$E\left((1+u)Y_t - Y_{t+1}\right) - \beta\left[\text{Var}\left((1-l)Y_t - Y_{t+1}\right)\right]^{.5} \geq 0 \qquad (t = 1...11) \tag{4.20}$$

$$E\left((1-l)Y_t - Y_{t+1}\right) - \beta\left[\text{Var}\left((1-l)Y_t - Y_{t+1}\right)\right]^{.5} \geq 0 \qquad (t = 1...11) \tag{4.21}$$

in which E = expected value, Var = variance, $\beta$ = the value of the normal density function associated with the probability level $\alpha$, and

$$\text{Var}(Y_t) = \sum_{i=1}^{m}\sum_{j=1}^{n} \text{Var}(a_{ijt})\, x_{ij}^2$$

$$\mathrm{Var}\left((1+u)Y_t - Y_{t+1}\right) = \sum_{i=1}^{m}\sum_{j=1}^{n} \mathrm{Var}\left((1+u)a_{ijt} - a_{ijt+1}\right) x_{ij}^2$$

$$\mathrm{Var}\left((1-l)Y_t - Y_{t+1}\right) = \sum_{i=1}^{m}\sum_{j=1}^{n} \mathrm{Var}\left((1-l)a_{ijt} - a_{ijt+1}\right) x_{ij}^2$$

Thus, the CCP formulation is comprised of the objective function 4.7, set of land-area constraints 4.8, set of non-negative constraints 4.13, and sets of deterministic equivalent chance constraints of the first-period yield (4.18 and 4.19) and NDEF condition (4.20 and 4.21).

### 4.2.4. Model Solution

Because chance constraints 4.18 - 4.21 are non-linear, the CCP model can not be solved using an ordinary LP algorithm directly. It may be solved using the simplex method, but only after linearizing the non-linear constraints. Linearization can be done by applying the MOTAD technique (Hazell and Norton 1986) or the linear-approximation technique proposed by Olson and Swenseth (1987). Linearization, however, may inflate the model size.

Weintraub and Vera (1991) proposed a cutting-plane approach for solving a CCP in its non-linear form. However, they only provide the theoretical explanation of the approach and leave interested adopters to develop their own computer codes. Seppälä (1972) developed CHAPS (Chance-Constrained Programming System), a specifically designed algorithm for solving CCP. CHAPS has been demonstrated to be efficient and accurate (Seppälä and Orpana 1984), but has not been made available to public users. Thus, the best option at this point is to solve the CCP model using any general non-linear programming software readily available commercially. This study uses SOLVER, an add-in to Microsoft EXCEL®. A more detailed description of this particular software is given in Chapter Six.

## CHAPTER FIVE:

## THE GROWTH AND YIELD MODELS AND THE YIELD PROJECTION COMPUTER ROUTINE

The results of the first half of this study are presented in this chapter. The resultant growth and yield models along with model testing procedures and results are described. The computer routine for integrating the models is also discussed. All models were estimated using SYSTAT®.

### 5.1. Model Estimates

#### 5.1.1. Basal-Area Growth Model

The base form of the basal-area growth model is Equation 3.20. This particular equation has no intercept and the coefficient of the predictor variable $(A_1/A_2)\ln B_1$ is required to be one. Imposing the latter condition is easier through a non-linear procedure. Therefore, although this equation is linear, it was estimated using a non-linear estimation procedure available in SYSTAT®. The loss-function minimized remains least squares, and the default quasi-Newton search method was used.

The equation was first estimated in its original form, in which the independent variable $S$ (site-index) was obtained from:

$$\ln S = 6.0375 + (\ln H - 6.0375)\left(\frac{A}{80}\right)^{.1435} \tag{5.1}$$

after Budiantho (1985). However, the resulting model has a very low coefficient of determination ($R^2$), leading to replacing $S$ with dominant-height $H$. Using $H$ instead of $S$ eliminates any error inherent in the site-index equation (5.1), and therefore, should result in a better estimate. The estimation result is presented in Table 5.1.

*Table 5.1*. Estimation of the basal-area growth model.

| Variable | Coefficient | Asymptotic SE | CI (95%) |
|---|---|---|---|
| $(1-A_1/A_2)$ | 2.927 | .097 | 2.737 - 3.117 |
| $(A_1/A_2)H_1$ | .044 | .004 | .036 - .052 |

*Note:* Adjusted coefficient of determination ($\overline{R}^2$) = .90; SE = standard error; CI = confidence interval.

Explicitly, the final estimated basal-area growth model is:

$$\ln B_2 = \left(\frac{A_1}{A_2}\right)\ln B + 2.927\left(1-\frac{A_1}{A_2}\right) + .044\left(1-\frac{A_1}{A_2}\right)H_1 . \tag{5.2}$$

5.1.2. Simultaneous Volume Growth and Yield Model

Equation 4.5 is the base form for this model. This simultaneous volume growth and yield model was estimated using an OLS procedure. As in model 5.2, *H* was used in the place of *S*. The predictor variable $1/A_2$ was excluded because it was not significant in the model. The final estimation result is shown in Table 5.2.

*Table 5.2*. Estimation of the volume growth and yield model.

| Variable | Coefficient | Coefficient SE | t (.05) |
|---|---|---|---|
| Intercept | 1.739 | .315 | 17.560* |
| $\ln H_1$ | .034 | .045 | 15.580* |
| $(A_1/A_2)\ln B_1$ | .952 | .200 | 23.975* |
| $(1-A_1/A_2)$ | 1.796 | .517 | 6.711* |
| $(1-A_1/A_2)\ln H_1$ | .092 | .100 | 8.829* |

*Note*: $\overline{R}^2$ = .95; Standard error of estimate (SEE) = .077; * = significant at $\alpha$ = .005.

The explicit form of the simultaneous volume growth and yield model is:

$$\ln V_2 = 1.739 + .034 \ln H_1 + .952\left(\frac{A_1}{A_2}\right) \ln B_1 + 1.796\left(1 - \frac{A_1}{A_2}\right) + .092\left(1 - \frac{A_1}{A_2}\right) H_1 . \qquad (5.3)$$

5.1.3. After-Thinning Basal-Area and Volume Models

The base forms of these models are Equations 4.1 and 4.2 respectively. Both models were estimated using OLS procedures. The estimated statistics are shown in Table 5.3.

*Table 5.3.* Estimations of the after-thinning basal-area and volume models.

| Eqn. | Variable | Coefficient | Coeff. SE | t(.05) | $\bar{R}^2$ | SEE |
|---|---|---|---|---|---|---|
| 4.1 | $(N_b/N_a)B_b$ | 1.074 | .005 | 236.545* | .99 | 1.185 |
| 4.2 | $(N_b/N_a)V_b$ | 1.048 | .008 | 127.017* | .98 | 11.429 |

* = significant at α = .005.

Explicitly, the two models are:

$$B_a = 1.074\left(\frac{N_a}{N_b}\right) B_b \qquad (5.4)$$

and

$$V_a = 1.048\left(\frac{N_a}{N_b}\right) V_b \qquad (5.5)$$

As expected, the regression coefficients of these equations are greater than unity. This confirms the assumption that the proportion of both basal-area removed is greater than the proportion of the number of trees removed because thinning from below normally leave larger trees.

### 5.1.4. Stand Height Model

The original form of the stand height model is Equation 4.3. However, as indicated earlier, this conceptual form fits the data poorly; the resulting model has a very low coefficient of determination. Examinations of data scatter plots (Figures 4.5a and 4.5b) led to including stand density (number of trees and/or basal-area per hectare) as a predictor variable. Several explicit formulations of $H = f(A, N, B)$, using various transformations of $A$, $N$ and $B$, were examined. The final estimated height model was:

$$\ln H_1 = 2.575 - .143 \ln\left(\frac{N_1}{A_1}\right) + .341 \ln B_1 . \qquad (5.6)$$

Table 5.4 presents a more complete estimation result.

*Table 5.4.* Estimation of the stand height model.

| Variable | Coefficient | Coefficient SE | t (.05) |
|---|---|---|---|
| Intercept | 2.575 | .077 | 33.637* |
| $\ln(N_1/A_1)$ | -.143 | .004 | -36.241* |
| $\ln B_1$ | .341 | .024 | 14.361* |

*Note*: $\overline{R}^2$ = .91; SEE = .066; * = significant at $\alpha$ = .005.

Residuals of all model estimates (Figures 5.1a - 5.1e) were examined to detect possible departures from assumptions. In general, there is no apparent pattern indicating a serious departure. In addition, the scatter plots showed an absence of outliers.

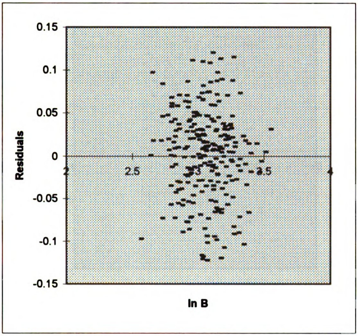



*Figure 5.1a.* Residual analysis of Model 5.2; scatter plots of ln*B* estimates (*B*: basal area) against residuals.

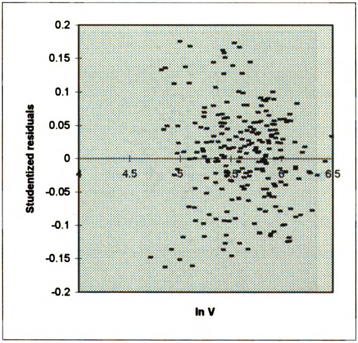



*Figure 5.1b.* Residual analysis of Equation 5.3; scatter plots of ln*V* estimates (*V* : volume) against studentized residuals.

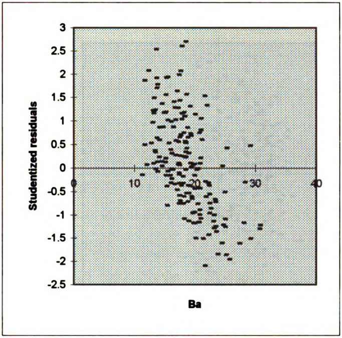



*Figure 5.1c.* Residual analysis of Equation 5.4; scatter plots of *Ba* estimates ($B_a$: after-thinning basal area) against studentized residuals.

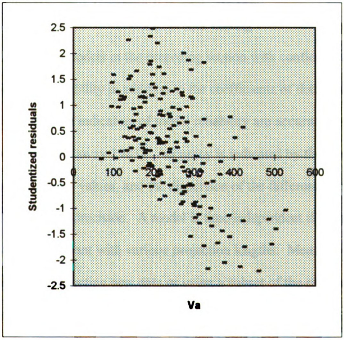



*Figure 5.1d.* Residual analysis of Equation 5.5; scatter plots of *Va* estimates ($V_a$: after-thinning volume) against studentized residuals.

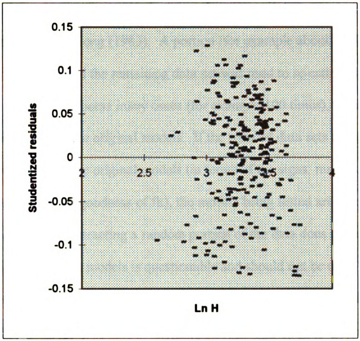



*Figure 5.1e.* Residual analysis of Equation 5.6; scatter plots of ln*H* estimates (*H*: stand height) against studentized residuals

**5.2. Model Testing**

In order to use the models in the preceding section with confidence, it is necessary to have some indicators of their reliability in addition to the coefficients of determination and standard error of estimates. Common indicators of model reliability are accuracy, precision, and time dependence (Brand and Holdaway 1983). Accuracy is indicated by the mean difference between model predictions and actual values, and the dispersion of the difference between predicted and actual values reflects model precision. A model is time-independent if both its accuracy and precision are relatively constant with various projection lengths. Measuring these three indicators, however, requires either collecting new data or using a subset of the currently available data not used in model estimation. Collecting new data was not feasible due to cost and time constraints. Setting aside a subset of the data was also not feasible because the data set presently available is not very large. Thus, an alternative approach, using the original data set, was used to test the numerical stability of the models.

The validation approach used is similar to the cross-validation technique described by Efron (1982) and Efron and Gong (1983). A portion (for example about 25%) of the original data set was removed randomly and the remaining data set was used to re-estimate the models being tested. After repeating this process many times (for example 100 times), the resulting new estimates were compared to the original models. If the reduced data sets consistently produce estimates that are similar to the original models (in terms of the signs, magnitudes, and significance of the coefficients, as well as goodness of fit), the models being tested are considered numerically consistent. Conversely, if subtracting a random portion of the data does greatly affect the resulting estimates, the reliability of the models is questionable and should not be used for yield prediction. Host et al. (1993) applied this approach for assessing the reliability of an ecological-land-classification model developed for the Manistee National Forest in Michigan.

Subsets of re-estimation results of Models 5.2 - 5.6 are presented in Tables 5.5a -5.5d, respectively. After reviewing the results, it was concluded that all models are numerically consistent as reflected by the consistency of their coefficients as well as their $\overline{R}^2$ and SEE values.

*Table 5.5a.* A sample of results from re-estimating the basal-area growth model (Model 5.2) using random subsets of the data.

| Sample # | n | $b_1$ | $b_2$ | $b_3$ | $\overline{R}^2$ |
|---|---|---|---|---|---|
| 1 | 212 | 1 | 2.865 | .047 | .90 |
| 2 | 192 | 1 | 2.966 | .044 | .90 |
| 3 | 203 | 1 | 2.967 | .042 | .89 |
| 4 | 210 | 1 | 2.994 | .042 | .90 |
| 5 | 199 | 1 | 2.968 | .043 | .90 |
| 6 | 198 | 1 | 2.882 | .045 | .91 |
| 7 | 212 | 1 | 2.875 | .046 | .90 |
| 8 | 191 | 1 | 3.068 | .039 | .89 |
| 9 | 202 | 1 | 2.907 | .045 | .90 |
| 10 | 209 | 1 | 2.828 | .047 | .90 |
| 11 | 200 | 1 | 2.927 | .044 | .89 |
| 12 | 196 | 1 | 3.026 | .044 | .90 |
| 13 | 204 | 1 | 2.934 | .044 | .88 |
| 14 | 213 | 1 | 2.959 | .043 | .89 |
| 15 | 196 | 1 | 2.969 | .042 | .89 |
| Original Eqn. | 255 | 1 | 2.927 | .044 | .90 |

*Table 5.5b.* A sample of results from re-estimating the volume growth and yield model (Model 5.3) using random subsets of the data.

| Sample # | n | $b_0$ | $b_1$ | $b_2$ | $b_3$ | $b_4$ | $\overline{R}^2$ | SEE |
|---|---|---|---|---|---|---|---|---|
| 1 | 212 | 1.718 | .031 | .99 | 1.436 | .109 | .96 | .077 |
| 2 | 192 | 1.555 | .036 | .996 | 2.338 | .078 | .96 | .073 |
| 3 | 203 | 1.787 | .032 | .961 | 1.612 | .097 | .95 | .076 |
| 4 | 210 | 1.694 | .036 | .948 | 2.087 | .081 | .96 | .075 |
| 5 | 199 | 1.653 | .036 | .965 | 2.140 | .079 | .96 | .074 |
| 6 | 198 | 1.802 | .032 | .942 | 1.442 | .103 | .96 | .077 |
| 7 | 212 | 1.726 | .031 | .986 | 1.436 | .109 | .96 | .077 |
| 8 | 191 | 1.719 | .037 | .930 | 2.215 | .075 | .95 | .079 |
| 9 | 202 | 1.734 | .033 | .967 | 1.768 | .092 | .95 | .078 |
| 10 | 209 | 1.727 | .036 | .927 | 1.780 | .092 | .96 | .075 |
| 11 | 200 | 1.807 | .033 | .938 | 1.737 | .091 | .95 | .076 |
| 12 | 196 | 1.682 | .036 | .952 | 2.127 | .078 | .95 | .080 |
| 13 | 204 | 1.844 | .033 | .926 | 1.694 | .089 | .95 | .075 |
| 14 | 213 | 1.803 | .033 | .943 | 1.637 | .095 | .95 | .077 |
| 15 | 196 | 1.681 | .035 | .954 | 2.092 | .081 | .95 | .077 |
| Original Eqn. | 255 | 1.739 | .034 | .952 | 1.796 | .092 | .95 | .077 |

*Table 5.5c.* A sample of results from re-estimating after-thinning basal-area and after-thinning volume models (Models 5.4 and 5.5) using random subsets of the data.

| | | Model 5.4 | | | Model 5.5 | | |
|---|---|---|---|---|---|---|---|
| Sample # | n | p | $\overline{R}^2$ | SEE | q | $\overline{R}^2$ | SEE |
| 1 | 147 | 1.060 | .99 | .758 | 1.063 | .99 | 10.244 |
| 2 | 138 | 1.063 | .98 | .740 | 1.065 | .98 | 11.934 |
| 3 | 151 | 1.063 | .98 | .745 | 1.068 | .97 | 11.781 |
| 4 | 149 | 1.064 | .99 | .760 | 1.065 | .98 | 11.882 |
| 5 | 154 | 1.064 | .99 | .761 | 1.064 | .99 | 11.027 |
| 6 | 139 | 1.065 | .99 | .756 | 1.066 | .98 | 12.290 |
| 7 | 145 | 1.064 | .99 | .763 | 1.065 | .98 | 11.402 |
| 8 | 147 | 1.063 | .98 | .738 | 1.065 | .97 | 12.353 |
| 9 | 145 | 1.063 | .99 | .747 | 1.065 | .99 | 11.465 |
| 10 | 152 | 1.062 | .99 | .768 | 1.067 | .99 | 11.389 |
| 11 | 144 | 1.058 | .99 | .753 | 1.064 | .99 | 11.320 |
| 12 | 150 | 1.061 | .99 | .760 | 1.063 | .97 | 11.871 |
| 13 | 149 | 1.056 | .99 | .767 | 1.065 | .98 | 11.648 |
| 14 | 153 | 1.060 | .99 | .758 | 1.066 | .97 | 11.855 |
| 15 | 139 | 1.065 | .98 | .743 | 1.065 | .98 | 11.547 |
| Original Eqn. | 181 | 1.064 | .99 | .764 | 1.065 | .99 | 11.429 |

*Table 5.5d.* A sample of results from re-estimating the stand height model (Model 5.6) using random subsets of the data.

| Sample # | n | $b_0$ | $b_1$ | $b_2$ | $\overline{R}^2$ | SEE |
|---|---|---|---|---|---|---|
| 1 | 212 | 2.577 | -.144 | .339 | .90 | .068 |
| 2 | 192 | 2.535 | -.140 | .352 | .90 | .066 |
| 3 | 203 | 2.518 | -.144 | .36 | .90 | .065 |
| 4 | 210 | 2.617 | -.144 | .327 | .91 | .065 |
| 5 | 199 | 2.931 | -.137 | .232 | .90 | .079 |
| 6 | 198 | 2.584 | -.144 | .338 | .90 | .070 |
| 7 | 212 | 2.574 | -.144 | .340 | .90 | .068 |
| 8 | 191 | 2.589 | -.142 | .336 | .91 | .066 |
| 9 | 202 | 2.581 | -.145 | .340 | .90 | .067 |
| 10 | 209 | 2.621 | -.145 | .327 | .91 | .067 |
| 11 | 200 | 2.533 | -.146 | .358 | .90 | .064 |
| 12 | 196 | 2.558 | -.145 | .347 | .90 | .069 |
| 13 | 204 | 2.609 | -.141 | .329 | .90 | .066 |
| 14 | 213 | 2.587 | -.144 | .338 | .90 | .066 |
| 15 | 196 | 2.628 | -.143 | .324 | .90 | .064 |
| Original eqn. | 255 | 2.575 | -.143 | .341 | .91 | .066 |

An additional compatibility test was used to examine Models 5.2 and 5.3. Compatibility is easily described by an example. Suppose Model 5.2 is used to predict the basal area of a given stand 10 years in the future. If Model 5.2 is compatible, it should give similar predictions regardless whether the basal area is predicted in two steps of 5-year intervals (incremental) or directly using a 10-year interval. A portion of the results given in Table 5.6 indicates that Models 5.2 and 5.3 are quite compatible, that is, the differences between 5-year incremental and 10-year direct projections are relatively small. For basal area, the differences are generally between -0.6 to 0.3 per cent relative to the 5-year incremental projection. For stand volume, this range is between -2.0 to 2.5 per cent.

As noted by Buchman and Shifley (1983), there is no projection system that can portray the real world perfectly. The idea of evaluating (growth and yield ) models, therefore, is not to prove that the models do not represent the nature exactly. Rather, it is to examine the models' performances relative to available alternatives, when there are such alternatives. This principle is adopted in evaluating the models developed in this study.

*Table 5.6.* A sample of results from testing the compatibility of Models 5.3 and 5.4.

| Age | | | Initial | Initial | Basal area at age 3 | | Volume at age 3 | |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | height | basal area | Incremental | Direct | Incremental | Direct |
| 21 | 26 | 31 | 24.3 | 14.9 | 22.7 | 22.6 | 129.4 | 133.0 |
| 26 | 31 | 38 | 24.9 | 15.9 | 24.0 | 23.6 | 140.3 | 139.9 |
| 31 | 38 | 43 | 26.9 | 15.5 | 23.0 | 22.7 | 133.0 | 137.5 |
| 40 | 45 | 50 | 25.3 | 18.7 | 23.4 | 23.4 | 131.8 | 134.8 |
| 45 | 50 | 57 | 25.8 | 18.4 | 23.6 | 23.4 | 135.3 | 136.5 |
| 30 | 35 | 40 | 26.9 | 18 | 24.4 | 24.4 | 139.4 | 145.8 |
| 35 | 40 | 47 | 26.9 | 18.4 | 25.3 | 25.0 | 147.4 | 149.3 |
| 38 | 43 | 48 | 15.7 | 19.6 | 22.5 | 22.4 | 119.6 | 115.6 |
| 43 | 48 | 55 | 16.8 | 20.3 | 23.6 | 23.4 | 126.7 | 122.1 |
| 48 | 55 | 60 | 18.5 | 21.6 | 24.7 | 24.7 | 132.2 | 131.4 |
| 52 | 57 | 62 | 28.2 | 21.6 | 26.0 | 25.8 | 148.7 | 150.5 |
| 57 | 62 | 70 | 30.8 | 22.2 | 27.7 | 27.7 | 161.2 | 167.1 |
| 61 | 66 | 71 | 34.6 | 29.3 | 34.3 | 34.1 | 197.4 | 205.1 |
| 15 | 20 | 25 | 21.8 | 17.1 | 26.2 | 26.0 | 146.6 | 146.4 |
| 84 | 89 | 94 | 34.9 | 27.9 | 31.5 | 31.5 | 179.1 | 185.7 |
| 49 | 54 | 59 | 28.2 | 21.8 | 26.5 | 26.2 | 152.1 | 153.4 |
| 54 | 59 | 67 | 31.2 | 22.7 | 28.5 | 28.5 | 166.6 | 173.7 |
| 59 | 67 | 72 | 31.3 | 23.9 | 29.6 | 29.3 | 169.5 | 177.0 |
| 54 | 59 | 64 | 32.1 | 20.4 | 25.2 | 25.1 | 145.8 | 151.6 |
| 59 | 64 | 71 | 33.2 | 17.7 | 22.9 | 22.9 | 135.5 | 141.3 |

*Note*: Ages are in years, heights are in meters (m), basal areas are in $m^2$, and volumes are in $m^3$. Basal areas were predicted using Model 5.3, volumes were predicted using Model 5.4.

### 5.3. The Yield-Projection Computer Routine

The computer routine was written in QuickBASIC®. It was noted in Chapter Four that the stand condition and yield in period $t+1$ are projected on the basis of the stand condition and yield in period $t$, and subsequently, the projected stand condition in period $t+1$ is used to project stand condition in period $t+2$, and so forth.

In its present state, the routine reads input files and likewise stores all outputs in files. Users, therefore, need to type stand data and other inputs only once for an indefinite number of runs. The routine may be modified into an interactive mode quite easily if desired. In fact, developing an interactive version may be much simpler than developing the original program. Due to time constraints, the main focus at this point is to the develop a computer routine that meets the needs in this study. Therefore, the routine is not yet very efficient. For example, the routine has not yet incorporated rotation-age options and a separate run is needed for each rotation age.

Stand data and other inputs must be prepared as ASCII files. The routine starts by reading all input (except stand data) files and storing them in arrays or matrices. The next step is to read the stand data file one line at a time (the routine projects one individual stand at a time). In general, at every line (stand), the following steps are executed:

1. Given the stand's current age and the rotation-age assigned, the routine defines the activity that must be implemented in each sub-period throughout the planning horizon[1]. For example, for a 30-year old stand in the 60-year rotation age, the activity in each sub-period is defined as follow:

| Sub-period | Stand age | Activity |
|---|---|---|
| 1 - 5 | 30 - 50 | Thinning |
| 6 | 55 | None |
| 7 | 60 | Clearcutting |
| 8 | - | Planting |
| 8 - 17 | 5 - 50 | Thinning |
| 18 | 55 | None |
| 19 | 60 | Clearcutting |
| 20 | - | Planting |
| 20 - 24 | 5 - 25 | Thinning |

2. Current stand volume is predicted using Model 5.3. If the stand is clearcut in this first sub-period, the volume predicted is the first final-harvest yield. If the stand is thinned, the

[1]Recall that the harvest scheduling models cover a 120-year planning horizon, which is divided into 12 10-year cutting periods. To accommodate the 5-year thinnings, each cutting period is divided into 2 sub-periods.

routine refers to the thinning instruction file (which is stored in a matrix), checking the appropriate after-thinning number of trees per hectare, then predicting after-thinning basal-area and volume using Models 5.4 and 5.5, respectively. The thinning yield is the difference between the stand's current volume (before thinning) and the stand's after-thinning volume.

3. Average tree diameter of the current stand is computed from stand basal area and number of trees per hectare. This average diameter is used to approximate the price bracket of the timber yield.

4. If the stand is clearcut, the routine will estimate the regenerated stand's basal area and its dominant height at age 5-years using appropriate equations in Table 5.7. These estimates are used as the starting points for growing the stand to the next sub-period. If the stand is thinned, the routine defines the current after-thinning basal area and number of trees per hectare, and the current stand's dominant height as the starting points.

5. The stand is grown by 5 years to the next sub-period by projecting the stand's basal area and volume in the next 5 years using Models 5.2 and 5.3, respectively, and estimating the stand's dominant height using Model 5.6. If the stand is clearcut in this sub-period, the stand volume is the final harvest yield. Otherwise, the routine refers to the thinning instruction file to check the appropriate after-thinning number of trees per hectare, and predicts after-thinning basal area, volume and thinning yield.

6. Then, NPV is computed. Given the average diameter in step 3, the routine selects an appropriate timber price and computes the revenue obtained in the given sub-period. The total cost depends on the activities taking place in the given sub-period. For example, if the stand is regenerated in this particular sub-period, the cost incurred includes planting cost and may also include thinning cost depending on whether the stand is thinned or not. If the activity is clearcutting, the total cost includes girdling and clearcutting costs. Clearcutting cost is per cubic meter, thus it is derived from the per-hectare timber yield produced in the sub-period.

7. Steps 3 - 6 are repeated through sub-period 24.
8. Program output is stored in ASCII files with user-specified names.

A general flow chart of the routine is provided in Figure 5.2 and the computer code is presented in Appendix B.

### 5.4. Additional Models

Additional models have been developed to complement Models 5.2 - 5.6. Models 5.2 - 5.6 which require inputs of initial age ($A$), initial basal-area ($B$), initial dominant height ($H$) and initial number of trees per hectare ($N$). These values are not available for regenerated stands. At the present, this problem is addressed as follows:

1. Age 5 years is used as the starting point.
2. Develop $B = f(A)$ and $H = f(A)$ models using forest inventory data to predict the initial $B$ and $H$ of regenerated stands. Ideally, these equations should be developed exclusively using 5-year old stands. However, it was observed that $B = f(A)$ and $H = f(A)$ relationships are more apparent if stands are grouped according to site class. If this grouping is used to impose model performance, the number of 5-year old stands in each group is not very large. Therefore, the models were developed using 5 - 25 year old stands with separate equations for each site class. Here, site class is the original site classification according to the forest inventory data, not the site index as given by Model 5.1. The initial-$B$ and initial-$H$ equations and their measures of goodness of fits are presented in Table 5.7. These equations are used in step 4 of the yield projection process.
3. Teak is planted with a 1 x 3 meter spacing. This means that a 5-year old plantation with 100% survival should have 3300 trees per hectare. However, the forest inventory data suggest that most stands between 5 - 10 years have a smaller $N$. For this reason, the initial $N$s of regenerated stands are represented by the average $N$ of the current 5 -10 year old stands within the corresponding site class.

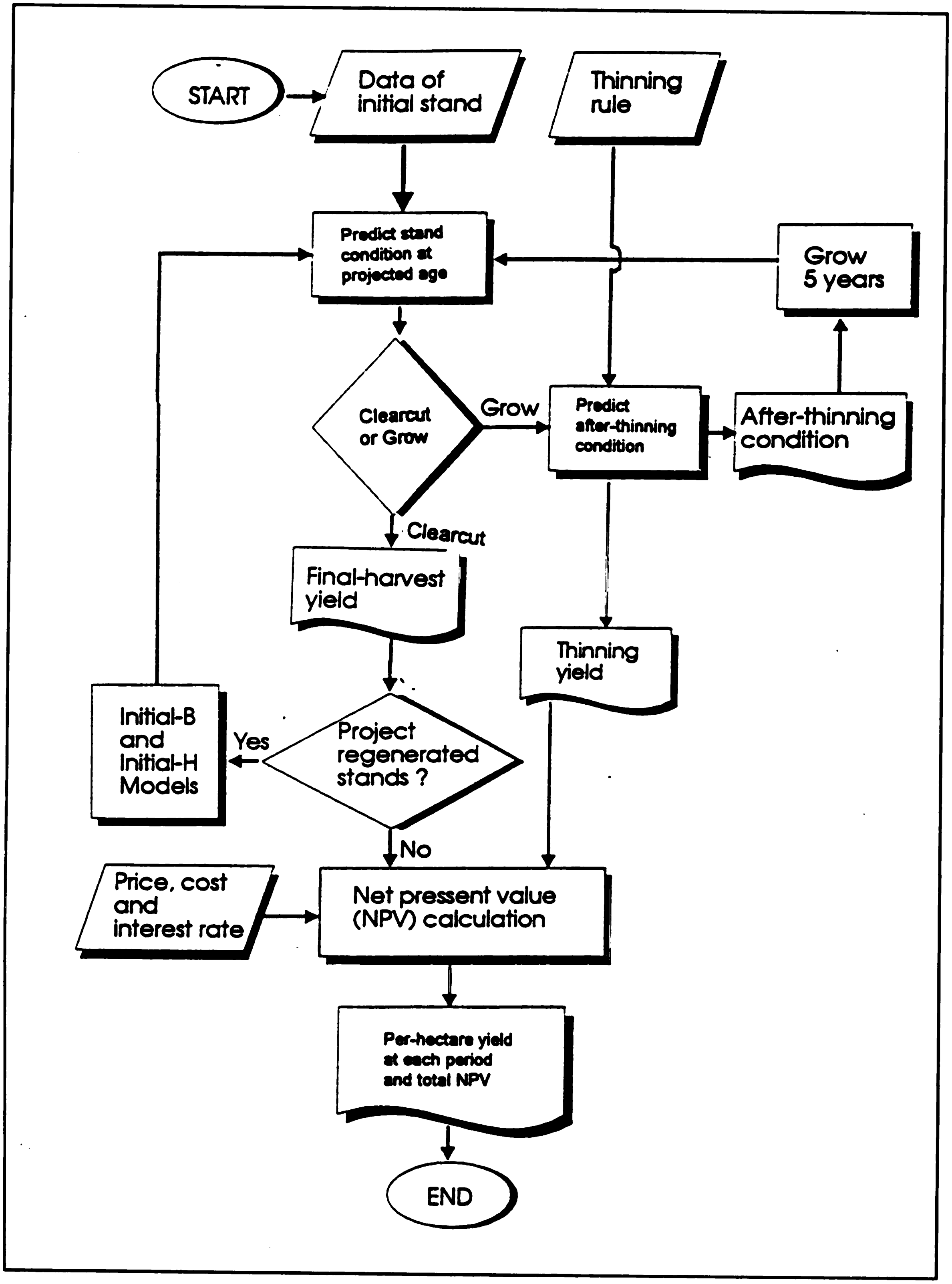



*Figure 5.2*. Flow chart of the yield-projection computer routine

*Table 5.7.* Estimations of the Initial-*B* and Initial-*H* models.

| Equation | Site class | Intercept | Slope | $\overline{R}^2$ | SEE |
|---|---|---|---|---|---|
| $\ln H = b_0 + b_1 \ln A$ | low | 1.385 | .399 | .81 | .102 |
| | medium | 1.675 | .394 | .82 | .069 |
| | high | 2.003 | .344 | .85 | .039 |
| $\ln B = c_0 + c_1 \ln A$ | low | -3.362 | 5.126 | .87 | .614 |
| | medium | -3.527 | 5.398 | .88 | .639 |
| | high | -3.989 | 5.642 | .88 | .668 |

*Note*: $H$ = stand height, $A$ = stand age, and $B$ = stand basal area.

An additional model depicts the basal-area growth over finite time periods, or $\Delta B = f(A_1, A_2)$. The explicit form successfully fitted is:

$$\ln(B_2 - B_1) = .303\left(1 - \frac{A_1}{A_2}\right)H_1 \tag{5.7}$$

with a standard error of the coefficient = .005, $R^2$ = .96 and SEE = .34. This model was estimated using the growth and yield data (permanent plot data). It gives the basal-area growth for the period of $(A_1\text{-}A_2)$ of a given stand with current dominant height $H_1$.

Model 5.7 is used as the upper bound of projected stand basal-area (Model 5.2) . It is used to prevent overestimation of stands' basal area growth (and hence volume growth) relative to empirical data. For example, consider a particular stand with a current age $A_1$, current basal area $B_1$, and current dominant height $H_1$. Suppose that, given these initial conditions, Model 5.2 predicts $B_2 = D$. Meanwhile, using the same inputs, Model 5.7 gives $(B_2 - B_1) = E$. If $(D - B_1)$ is larger than $E$, the projected basal-area $B_2$ is set equal to $(B + E)$.

# CHAPTER SIX:

# THE HARVEST SCHEDULING MODELS

The purpose of this chapter is to describe the process of constructing and solving the harvest scheduling models for the Cepu Forest District and to discuss model solutions. The first section describes model components and inputs. LP versions of the harvest scheduling models are presented in the second section, followed by the CCP version in the third section. A discussion on the model solutions is given in the last section.

## 6.1. Model Components and Inputs

### 6.1.1. Decision Variables $x_{ij}$

According to the 1991/1992 forest inventory data, Cepu Forest District has 1,742 individual stands with existing teak plantations. A common practice in harvest scheduling is to aggregate stands, usually according to age classes, in order to reduce model size. For teak forests in Java, age classes are defined in 10-year increments. Accordingly, for purposes of this study, the 1,742 individual stands are aggregated into nine 10-year age classes. Each of these age classes is further divided into 3 to 6 productivity classes, resulting in a total of 35 stand-types as shown in Table 6.1.

Due to the mandatory 5-year thinnings (described in Chapter Four), management regimes are solely determined by the rotation ages. A management regime is a combination of any one of the rotation-age alternatives (i.e., 60, 70, and 80 years) with each one of the 35 stand-types. For example, a combination of the 60-year rotation and stand-type 3C results in a management regime, here labeled as 3C60. Clearly, in this problem a management regime is identical with a decision variable; that is, a decision must either include or exclude a specific management regime for each stand-type. With 35 stand-types and 3 rotation-ages, there are a total of 105 management regimes or decision variables, as presented in Table 6.2. Another management option for each stand type is no management.

*Table 6.1.* Stand-type labels based on age and productivity classes and on existing stands.

| Age class | Productivity class | | | | | |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | F |
| 1 - 10 | 1A (327) | 1B (527) | 1C (263) | 1D (1631) | 1E (1567) | |
| 11-20 | 2A (496) | 2B (384) | 2C (122) | 2D (588) | 2E (1717) | 2F (1085) |
| 21 - 30 | 3A (208) | 3B (1473) | 3C (1456) | 3D (950) | 3E (633) | |
| 31 - 40 | 4A (2278) | 4B (2124) | 4C (684) | 4D (362) | | |
| 41 - 50 | 5A (628) | 5B (950) | 5C (476) | | | |
| 51 - 60 | 6A (455) | 6B (713) | 6C (714) | | | |
| 61 - 70 | 7A (274) | 7B (894) | 7C (200) | 7D (233) | 7E (337) | |
| 71 - 80 | 8A (380) | 8B (600) | 8C (781) | | | |
| > 80 | 9A (229) | | | | | |

*Notes:* Figures in parentheses are the corresponding total land-area (in hectares). Shaded cells indicate that there are no stands with the corresponding combination of age class and productivity class.

A management regime implies the sequence of thinnings and clearcuttings applied to the particular stand-type over the planning horizon. It has been stated that the 120-year planning horizon is divided into 12 10-year cutting periods. Therefore, a stand-type 3C for example, will reach age-class 6 (51-60 years) in period 4, age-class 7 (61-70 years) in period 5, or age-class 8 (71-80 years) in period 6. Hence, management regime 3C70 for instance, implies that stands belonging to stand-type 3C will be clearcut in period 5, regenerated into the 1-10 age-class in period 6, and clearcut again in period 12. It also implies that this regime includes thinnings every 5 years during periods 1 - 4 and 6 - 11 (the last thinning takes place 10 years before clearcut). The sequence of thinnings and clearcuttings associated with each management regime is presented in Table 6.3.

*Table 6.2*. Management regimes (105) resulting from the combination of 35 stand-types and 3 rotation ages.

| Stand-type | Rotation age | | |
|---|---|---|---|
| | 60 | 70 | 80 |
| 1A | 1A60 | 1A70 | 1A80 |
| 1B | 1B60 | 1B70 | 1B80 |
| 1C | 1C60 | 1C70 | 1C80 |
| 1D | 1D60 | 1D70 | 1D80 |
| 1E | 1E60 | 1E70 | 1E80 |
| 2A | 2A60 | 2A70 | 2A80 |
| 2B | 2B60 | 2B70 | 2B80 |
| 2C | 2C60 | 2C70 | 2C80 |
| 2D | 2D60 | 2D70 | 2D80 |
| 2E | 2E60 | 2E70 | 2E80 |
| 2F | 2F60 | 2F70 | 2F80 |
| 3A | 3A60 | 3A70 | 3A80 |
| 3B | 3B60 | 3B70 | 3B80 |
| 3C | 3C60 | 3C70 | 3C80 |
| 3D | 3D60 | 3D70 | 3D80 |
| 3E | 3E60 | 3E70 | 3E80 |
| 4A | 4A60 | 4A70 | 4A80 |
| 4B | 4B60 | 4B70 | 4B80 |
| 4C | 4C60 | 4C70 | 4C80 |
| 4D | 4D60 | 4D70 | 4D80 |
| 5A | 5A60 | 5A70 | 5A80 |
| 5B | 5B60 | 5B70 | 5B80 |
| 5C | 5C60 | 5C70 | 5C80 |
| 6A | 6A60 | 6A70 | 6A80 |
| 6B | 6B60 | 6B70 | 6B80 |
| 6C | 6C60 | 6C70 | 6C80 |
| 7A | 7A60 | 7A70 | 7A80 |
| 7B | 7B60 | 7B70 | 7B80 |
| 7C | 7C60 | 7C70 | 7C80 |
| 7D | 7D60 | 7D70 | 7D80 |
| 7E | 7E60 | 7E70 | 7E80 |
| 8A | 8A60 | 8A70 | 8A80 |
| 8B | 8B60 | 8B70 | 8B80 |
| 8C | 8C60 | 8C70 | 8C80 |
| 9A | 9A60 | 9A70 | 9A80 |

*Note*: Stand types (e.g., 1A) are identified by age class (e.g., 1 = age 1 - 10) and productivity class (e.g., A = the lowest productivity).

*Table 6.3*. Thinning and clearcutting sequences over the planning horizon under different management regimes.

| **Management regimes** | **P e r i o d** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| 1A60,1B60,1C60,1D60,1E60 | t | t | t | t | t | C | t | t | t | t | t | C |
| 2A60,2B60,2C60,2D60,2E60,2F6 | t | t | t | t | C | t | t | t | t | t | C | t |
| 3A60,3B60,3C60,3D60,3E60 | t | t | t | C | t | t | t | t | t | C | t | t |
| 4A60,4B60,4C60,4D60 | t | t | C | t | t | t | t | t | C | t | t | t |
| 5A60,5B60,5C60 | t | C | t | t | t | t | t | C | t | t | t | t |
| 6A60,6B60,6C60 | C | t | t | t | t | t | C | t | t | t | t | t |
| 7A60,7B60,7C60,7D60,7E60 | C | t | t | t | t | t | C | t | t | t | t | t |
| 8A60,8B60,8C60 | C | t | t | t | t | t | C | t | t | t | t | t |
| 9A60 | C | t | t | t | t | t | C | t | t | t | t | t |
| | | | | | | | | | | | | |
| 1A70,1B70,1C70,1D70,1E70 | t | t | t | t | t | t | C | t | t | t | t | t |
| 2A70,2B70,2C70,2D70,2E70,2F7 | t | t | t | t | t | C | t | t | t | t | t | t |
| 3A70.3B70,4C70,3D70,3E70 | t | t | t | t | C | t | t | t | t | t | t | C |
| 4A70,4B70,4C70,4D70 | t | t | t | C | t | t | t | t | t | t | C | t |
| 5A70,5B70,5C70 | t | t | C | t | t | t | t | t | t | C | t | t |
| 6A70,6B70,6C70 | t | C | t | t | t | t | t | t | C | t | t | t |
| 7A70,7B70,7C70,7D70,7E70 | C | t | t | t | t | t | t | C | t | t | t | t |
| 8A70,8B70,8C70 | C | t | t | t | t | t | t | C | t | t | t | t |
| 9A70 | t | t | t | t | t | t | t | C | t | t | t | t |
| | | | | | | | | | | | | |
| 1A80,1B80,1C80,1D80,1E80 | t | t | t | t | t | t | t | C | t | t | t | t |
| 2A80,2B80,2C80,2D80,2E80,2F8 | t | t | t | t | t | t | C | t | t | t | t | t |
| 3A80,3B80,3C80,3D80,3E80 | t | t | t | t | t | C | t | t | t | t | t | t |
| 4A80,4B80,4C80,4D80 | t | t | t | t | C | t | t | t | t | t | t | t |
| 5A80,5B80,5C80 | t | t | t | C | t | t | t | t | t | t | t | C |
| 6A80,6B80,6C80 | t | t | C | t | t | t | t | t | t | t | C | t |
| 7A80,7B80,7C80,7D80,7E80 | t | C | t | t | t | t | t | t | t | C | t | t |
| 8A80,8B80,8C80 | C | t | t | t | t | t | t | t | C | t | t | t |
| 9A80 | C | t | t | t | t | t | t | t | C | t | t | t |

*Note*: Management regimes are described in Table 6.2, t = thinning, C = clearcutting.

6.1.2. Decision-Variable Coefficients $c_{ij}$

The values of decision-variable coefficients $c_{ij}$ are tabulated in Table 6.4. These coefficients are per-hectare total NPVs associated with management regime $j$ (recall that a decision variable is identical with a management regime). These quantities equal the average values of the total NPVs of all individual stands aggregated into stand type $i$, or

$$c_{ij} = \tfrac{1}{k}\sum_{h=1}^{k} NPV_{hij} \tag{6.1}$$

where

| | | |
|---|---|---|
| $k$ | = | the number of individual stands in stand type $i$ |
| $NPV_{hij}$ | = | per-hectare NPV of stand $h$ of stand type $i$ under management regime $j$. |

In these NPV calculations, the stand-type mean is used. Another approach would be to have an area-weighted mean. In this study, the stand-type means were fairly similar. The total NPV of each individual stand is the total discounted net revenues produced in cutting periods throughout the planning horizon. To accommodate the 5-year thinnings, each cutting period is divided into 2 sub-periods, and for discounting purposes it is assumed that costs and revenues take place in the third year of these 5-year sub-periods. Thinning, clearcutting and girdling occur in the same sub-period as timber yields. Planting costs are incurred in the next sub-period. The formula for computing the total NPV of each individual stand is:

$$NPV = \sum_{t=1}^{24}\left(\frac{Pa_t - C_t}{(1+r)^{5t-2}}\right) \tag{6.2}$$

where

| | | |
|---|---|---|
| $P$ | = | per-cubic-meter timber price |
| $a$ | = | per-hectare timber yield in period $t$ |
| $C$ | = | per-hectare cost incurred in period $t$ |
| $r$ | = | discount rate |

*Table 6.4*. Per-hectare total NPV produced with each management regime.

| Management regime | NPV (million Rp) | Management regime | NPV (million Rp) | Management regime | NPV (million Rp) |
|---|---|---|---|---|---|
| 1A60 | 0.53 | 1A70 | 0.255 | 1A80 | 0.117 |
| 1B60 | 1.128 | 1B70 | 0.524 | 1B80 | 0.25 |
| 1C60 | 1.217 | 1C70 | 0.856 | 1C80 | 0.712 |
| 1D60 | 2.064 | 1D70 | 1.892 | 1D80 | 1.798 |
| 1E60 | 4.443 | 1E70 | 4.215 | 1E80 | 4.113 |
| 2A60 | 1.144 | 2A70 | 0.582 | 2A80 | 0.282 |
| 2B60 | 1.636 | 2B70 | 0.8 | 2B80 | 0.381 |
| 2C60 | 1.707 | 2C70 | 0.78 | 2C80 | 0.442 |
| 2D60 | 1.772 | 2D70 | 1.082 | 2D80 | 0.801 |
| 2E60 | 3.42 | 2E70 | 2.774 | 2E80 | 2.499 |
| 2F60 | 6.946 | 2F70 | 6.304 | 2F80 | 5.985 |
| 3A60 | 2.423 | 3A70 | 1.248 | 3A80 | 0.62 |
| 3B60 | 2.959 | 3B70 | 1.49 | 3B80 | 0.725 |
| 3C60 | 3.544 | 3C70 | 1.774 | 3C80 | 1.088 |
| 3D60 | 5.091 | 3D70 | 3.439 | 3D80 | 2.747 |
| 3E60 | 8.304 | 3E70 | 6.699 | 3E80 | 5.986 |
| 4A60 | 6.059 | 4A70 | 3.078 | 4A80 | 1.507 |
| 4B60 | 8.053 | 4B70 | 3.884 | 4B80 | 2.216 |
| 4C60 | 10.754 | 4C70 | 7.012 | 4C80 | 5.327 |
| 4D60 | 13.505 | 4D70 | 10.234 | 4D80 | 8.709 |
| 5A60 | 9.805 | 5A70 | 5.2285 | 5A80 | 2.682 |
| 5B60 | 15.479 | 5B70 | 7.745 | 5B80 | 3.755 |
| 5C60 | 14.532 | 5C70 | 7.333 | 5C80 | 4.244 |
| 6A60 | 18.236 | 6A70 | 10.164 | 6A80 | 5.294 |
| 6B60 | 29.457 | 6B70 | 14.472 | 6B80 | 7.271 |
| 6C60 | 37.994 | 6C70 | 20.141 | 6C80 | 9.938 |
| 7A60 | 20.446 | 7A70 | 16.144 | 7A80 | 8.47 |
| 7B60 | 35.23 | 7B70 | 27.569 | 7B80 | 13.884 |
| 7C60 | 20.856 | 7C70 | 22.116 | 7C80 | 12.083 |
| 7D60 | 31.612 | 7D70 | 33.444 | 7D80 | 17.521 |
| 7E60 | 40.02 | 7E70 | 42.429 | 7E80 | 21.764 |
| 8A60 | 24.076 | 8A70 | 23.957 | 8A80 | 21.914 |
| 8B60 | 35.399 | 8B70 | 35.275 | 8B80 | 30.769 |
| 8C60 | 46.949 | 8C70 | 46.829 | 8C80 | 39.989 |
| 9A60 | 33.138 | 9A70 | 33.776 | 9A80 | 33.712 |

The current bank interest rates for investment credits in Indonesia vary between 13% to 17%, or 15% on average, and the inflation rate is roughly 6%. (Bank of Indonesia 1994). Therefore, 9% is a reasonable approximation of the real discount rate, which is used in this study. Perhutani's opportunity cost of capital is not known.

As indicated in the formula, per-hectare revenue is the product of per-hectare timber yield (either thinning or final-harvest yield) and the associated timber price. Timber yield is differentiated into 3 diameter classes, and the corresponding per-cubic-meter prices are derived from the actual selling prices in 1992-1993. The yield is for the bole only, and the entire bole is treated within one diameter class. Though excluded from the analysis, tops of mature trees have high value, too. Costs are also derived from the actual expenses during the last 1992-1993 management year. Clearcutting cost includes any expenses from felling trees to piling logs at the log yards. Because clearcutting costs are on per cubic meter basis, per-hectare total cost varies across stand-types. Price and cost data are presented in Table 6.5.

*Table 6.5.* Timber prices and management costs at Cepu Forest District for the management year 1992/1993.

| **Diameter class (cm)** | **Timber price (Rp/m³)** |
|---|---|
| diameter ≥ 30 | 530,000 |
| 20 ≤ diameter < 30 | 275,000 |
| 4 ≤ diameter < 19.9 | 155,000 |

| **Activity** | **Cost (Rp)** |
|---|---|
| Planting | 188,700/hectare |
| Thinning | 64,085/hectare |
| Girdling | 54,575/hectare |
| Clearcutting | 21,700/cubic meter |

In this study, real timber prices and all costs are assumed to be constant over time. Historically, increases in timber prices are consistent across timber sizes, and similarly, any change in costs apply to all stand-types.

### 6.1.3. Yield Coefficients $a_{ijt}$

Yield coefficients $a_{ijt}$ are the expected values of per-hectare yields of stand type $i$ under management regime $j$ harvested in period $t$, or $E(a_{ijt})$. These quantities are obtained using:

$$a_{ijt} = E\left(a_{ijt}\right) = \frac{i}{k}\sum_{h=1}^{k} Y_{hijt} \tag{6.3}$$

where

| | | |
|---|---|---|
| $k$ | = | the number of individual stands in stand type $i$ |
| $Y_{hijt}$ | = | per-hectare yield of stand $h$ of stand type $i$, under management regime $j$, harvested in period $t$. |

The quantities $a_{ijt}$ is zero when neither thinning nor clearcutting takes place in the period $t$. Otherwise, the quantity is either a thinning or a final harvest yield.

The formulation of the CCP version of the harvest scheduling model requires the variances of $a_{ijt}$, or Var($a_{ijt}$). These variances are computed by:

$$\text{Var}\left(a_{ijt}\right) = \frac{1}{k}\sum_{h=1}^{k}\left(a_{ijt} - \bar{a}_{ijt}\right)^2 \tag{6.4}$$

The values of $a_{ijt}$ and Var ($a_{ijt}$) are tabulated in Table A.2, Appendix A.

### 6.1.4. Right Hand Sides (RHS)

The total land areas of each stand-type shown in Table 6.1 are the RHS values for area constraints. Other RHS values are the lower and upper bounds of the total harvest volume in the first period, which are 400,000 and 440,000 cubic meters respectively. These figures are inferred from Cepu Forest District current 10-year management plan.

### 6.2. Linear Programming Harvest Scheduling Models

Several LP versions of the harvest scheduling problem were solved and reported by Parthama et al. (1994). These LPs are reviewed in this section to provide some insights facilitating the formulation of the CCP in the next section. In total, these models represent a range of possible management alternatives for the Cepu Forest District. The following are the descriptions of the models solved:

*LP 1*: This model approximates the current management practice, that is a single rotation-age (80 years) is used and all stands must be managed. The model does not include any constraints to control the harvest flow over time. Obviously, this is a completely constrained optimization model, (i.e., no management choices are available). The purpose of formulating this model is to approximate the NPV and timber flow from the entire forest if treated under the current management approach; it provides a base for comparisons.

*LP 2*: LP 2 is a harvest scheduling model in its simplest form. It optimizes the allocation of hectares of each stand-type over the 3 rotation-age alternatives without harvest-flow constraints being imposed. Unmanaged stands are allowed.

*LP 3*: This model incorporates some harvest-flow constraints. The total harvest in the first decade is constrained within the pre-specified lower and upper bounds. The harvest volume in any subsequent decade is restricted to be at least equal to the volume in the previous decade but allowed to increase up to 20%.

*LP 4*: LP 4 is like LP 3, but the non-declining restriction is relaxed by allowing the harvest volume in subsequent decade to decline up to 5% relative to the volume in the previous decade.

*LP 5*: LP 5 also resembles LP 3, but is liberalized by allowing the harvest volume to increase with no explicit upper bound.

The optimal solutions of these LP models are summarized in Table 6.6 and the corresponding timber-flows over time are depicted in Figures 6.1a and 6.1b. An extended discussion on these solutions is postponed until Section 6.4 of this chapter. The focus at this point is to select a model that will be used as a base model for the CCP in the next section. Based on LP solutions, LP 5 is used to provide a comparative solution for the CCP formulation. In practice, any model could be used as the comparative basis. Several aspects of the LP 5 solution make it unique. Among all models incorporating timber-flow constraints, LP 5 gives the highest NPV. LP 5 also maintains a steady increase in harvest volume from period 1 to period 5 with a constant level thereafter. In addition, with LP 5 the entire forest is managed (no stand is left idle) which is very important with respect to the goal of generating employment.

Both LP 3 and LP 4 leave about 20% of the total forest area unmanaged. LP 3 which restricts the increase in harvest volume to an upper-bound also leads to a lower harvest volume throughout the planning horizon and hence a lower total NPV. LP 4 which allows the harvest volume to decline results in a less desirable harvest flow relative to those of LP 3 and LP 5. Thus, LP 5 is selected as the base model for the CCP.

*Table 6.6.* Summarized optimal solutions of LP harvest scheduling models.

| Model | Total NPV (million Rp) | Total Volume (1000 cu m) | Hectare unmanaged (%) |
|---|---|---|---|
| LP 1 | 155,974 | 9159 | 0 |
| LP 2 | 306,746 | 10980 | 0 |
| LP 3 | 239,788 | 8351 | 21 |
| LP 4 | 245,511 | 8445 | 19 |
| LP 5 | 262,137 | 10725 | 0 |

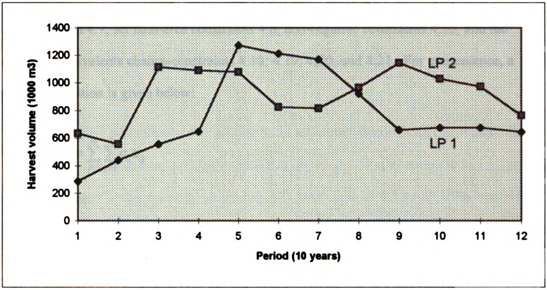



*Figure 6.1a*. Harvest flows with the absence of NDEF constraints (LP 1 and LP 2).

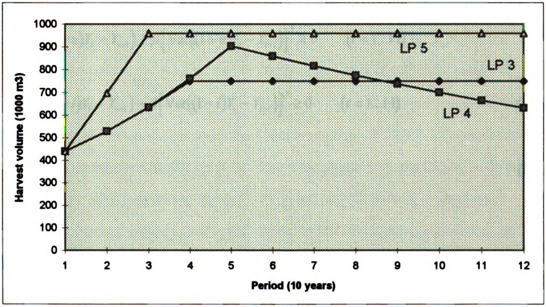



*Figure 6.1b*. Harvest flows when NDEF constraints are included (LP 3, LP 4, and LP 5).

### 6.3. Chance-Constrained Programming Harvest Scheduling Models

The chance-constrained programming (CCP) formulation of LP 5 is comprised of the objective function 4.7, set land-area constraints 4.8, non-negative constraints 4.13, and the deterministic equivalents chance-constraints 4.18; 4.19; 4;20; and 4.21. For convenience, a complete formulation is given below:

$$\max Z = \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} \tag{6.5}$$

subject to:

$$\sum_{i=1}^{m} x_{ij} \le L_i \tag{6.6}$$

$$\mathrm{E}(Y_t) - \beta\left[\mathrm{Var}(Y_t)\right]^{.5} \ge LV_t \qquad (t = 1) \tag{6.7}$$

$$\mathrm{E}(Y_t) + \beta\left[\mathrm{Var}(Y_t)\right]^{.5} \le UV_t \qquad (t = 1) \tag{6.8}$$

$$\mathrm{E}\left((1+u)Y_t - Y_{t+1}\right) - \beta\left[\mathrm{Var}\left((1+u)Y_t - Y_{t+1}\right)\right]^{.5} \ge 0 \qquad (t = 1\ldots11) \tag{6.9}$$

$$\mathrm{E}\left((1-l)Y_t - Y_{t+1}\right) - \beta\left[\mathrm{Var}\left((1-l)Y_t - Y_{t+1}\right)\right]^{.5} \ge 0 \qquad (t = 1\ldots11) \tag{6.10}$$

$$x_{ij} \ge 0 \tag{6.11}$$

where

$$Y_t = \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ijt}x_{ij} \quad \text{and} \quad Y_{t+1} = \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij(t+1)}x_{ij}$$

$$\mathrm{Var}(Y_t) = \sum_{i=1}^{m}\sum_{j=1}^{n} \mathrm{Var}(a_{ijt})x_{ij}^2$$

$$\mathrm{Var}\left((1+u)Y_t - Y_{t+1}\right) = \sum_{i=1}^{m}\sum_{j=1}^{n}\left((1+u)^2 \mathrm{Var}\left(a_{ijt}\right) + \mathrm{Var}\left(a_{ijt+1}\right)\right)x_{ij}^2$$

$$\mathrm{Var}\left((1-l)Y_t - Y_{t+1}\right) = \sum_{i=1}^{m}\sum_{j=1}^{n}\left((1-l)^2 \mathrm{Var}\left(a_{ijt}\right) + \mathrm{Var}\left(a_{ijt+1}\right)\right)x_{ij}^2$$

This problem was solved using SOLVER, an add-in to Microsoft EXCEL® capable of solving non-linear programming problems. In SOLVER, the problem is presented in a spreadsheet. After the spreadsheet is appropriately structured, SOLVER must be informed of: the cell to be optimized (the objective function), the cells that should be adjusted (the cells of decision variables), the constraint vectors, and the type of optimization (maximization, minimization, or equal to a specific value). Users must also define the maximum time, number of iterations, levels of precision (and tolerance when it is an integer programming problem). Optionally, users can also activate or deactivate the auto-scaling feature, select the estimation methods (tangential or quadratic), the derivation methods (forward or central), and the search method (quasi-Newton or conjugate gradient).

For the problem in this study, the spreadsheet is structured as shown in Figure 6.2. The objective-function cell AC106 is maximized by changing the values in cells AB1 to AB105 (decision variables) subject to the conditions: AB1 to AB105 ≥ 0 (non-negative constraints), AD1 to AD35 ≤ B1 to B35 (management regime/land-area constraints), AQ108 ≥ $LV_I$ (constraint 6.7), AQ109 ≤ $UV_I$ (constraint 6.8), BN108 to BX108 ≥ 0 (constraint 6.9), and CK108 to CV108 ≤ 0 (constraint 6.10). Main outputs are: the total NPV in cell AC106, hectares of stand-type $i$ allocated to management regime $j$ in cells AB1 to AB105, the total hectares managed in cell AB106, and periodic harvest volumes in cells AE106 to AP106. Values in cells AQ107 to BB107 are added or subtracted from their corresponding periodic volumes (cells AE106 to AP106) to provide the 95% confidence interval. The spreadsheet is explained in detail in Appendix C.

| | A | B | C | D | ... | O | P | ... | AA | AB | AC | AD | AE | ... | AP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $c_{ij}$ | $L_i$ | | $a_{ijt}$ (t=1) | ... | $a_{ijt}$ (t=12) | Var($a_{ijt}$) (t=1) | ... | Var($a_{ijt}$) (t=12) | $x_{ij}$ | $c_{ij}x_{ij}$ | S$x_{ij}$ (j=1,2,3) | $a_{ijt}x_{ij}$ (t=1) | ... | $a_{ijt}x_{ij}$ (t=12) |
| 1 | $c_{11}$ | L 1 | βvalue | $a_{111}$ | ... | $a_{1112}$ | Var($a_{111}$) | ... | Var($a_{1112}$) | $x_{11}$ | $c_{11}x_{11}$ (C1 * B1) | AB1+ AB36+ AB71 | $a_{111}x_{111}$ (C1*F1) | .... | $a_{1112}x_{1112}$ C1*Q1 |
| 2 | $c_{21}$ | . | $u$ value | $a_{211}$ | ... | $a_{2112}$ | Var($a_{211}$) | ... | Var($a_{2112}$) | $x_{21}$ | $c_{21}x_{21}$ (C2 * B2) | . | . | .... | . |
| 3 | . | . | $l$ value | . | ... | . | . | ... | . | . | . | . | . | ... | . |
| . | . | . | | . | ... | . | . | ... | . | . | . | . | . | ... | . |
| . | . | | | . | ... | . | . | ... | . | . | . | . | . | ... | . |
| . | . | . | . | . | ... | . | . | ... | . | . | . | . | . | | . |
| 105 | | | | | | | | | | | . | | . | | . |
| 106 | | | | | | | | | | Σ (AB1... ..AB105) | Σ (AC1... ..AC105) | | Σ(AE1... ..AE105) | | Σ (AP2.. ..AP107) |

| | AQ | ... | BB | BC | ... | BM | BN | ... | BX |
|---|---|---|---|---|---|---|---|---|---|
| | Var($a_{ijt}$)($x_{ij}$)$^2$ (t=1) | ... | Var($a_{ijt}$)($x_{ij}$)$^2$ (t=12) | ((1+$u$)$a_{ijt}x_{ij}$-$a_{ijt+1}x_{ij}$) (t=1) | ... | ((1+$u$)$a_{ijt}x_{ij}$-$a_{ijt+1}x_{ij}$) (t=11) | (1+$u$)$^2$Var($a_{ijt}$) ($x_{ij}$)$^2$ + Var($a_{ijt+1}$)($x_{ij}$)$^2$ (t=1) | ... | (1+$u$)$^2$Var($a_{ijt}$) ($x_{ij}$)$^2$ + Var($a_{ijt+1}$)($x_{ij}$)$^2$ (t=11) |
| 1 | P1*AB1$^2$ | ... | AA1*AB1$^2$ | (1+C2)*D1*AB1-E1*AB1 | ... | (1+C2)*M1*AB1 O1*AB1 | (1+C2)$^2$ *P1*AB1$^2$ + Q1*AB1$^2$ | ... | (1+C2)$^2$ *Z1*AB1$^2$ + AA1*AB1$^2$ |
| 2 | P2*AB2$^2$ | ... | AA2*AB2$^2$ | . | | . | . | | . |
| 3 | | | | . | | . | . | | . |
| . | | | | . | | . | . | | . |
| 105 | P105*AB105$^2$ | ... | AA105*AB105$^2$ | (1+C2)*D105*AB105-E105*AB105 | ... | (1+C2)*M105*AB105 O105*AB105 | (1+C2)$^2$ *P105*AB105$^2$ + Q1*AB105$^2$ | | (1+C2)$^2$ *Z105*AB105$^2$ + AA105*AB105$^2$ |
| 106 | Σ (AQ2...AQ105) | | Σ(BB1...BB105) | Σ(BC1...BC105)) | | Σ (BM1...BM105)) | Σ(BN1...BO105) | | Σ(BX1...BX105) |
| 107 | C1*(AQ106)$^{.5}$ | | C1*(BB106)$^{.5}$ | | | | C1*BN106$^{.5}$ | | C1*BX106$^{.5}$ |
| 108 | AE106-AQ106 | | AP106-BB106 | | | | BC106-BN106 | | BM106-BX106 |
| 109 | AE106+AQ106 | | AP108+BB106 | | | | | | |

*Figure 6.2.* **The CCP SOLVER spreadsheet.**

| | BY | ... | CJ | CK | ... | CV |
|---|---|---|---|---|---|---|
| | $((1-l)a_{ijt}x_{ij}-a_{ijt+1}x_{ij})$ (t=1) | ... | $((1-l)a_{ijt}x_{ij}-a_{ijt+1}x_{ij})$ (t=11) | $(1-l)^2Var(a_{ijt})(x_{ij})^2 + Var(a_{ijt+1})(x_{ij})^2$ (t=1) | ... | $(1-l)^2Var(a_{ijt})(x_{ij})^2 + Var(a_{ijt+1})(x_{ij})^2$ (t=11) |
| 1 | (1-C3)*D1*AB1-E1*AB1 | ... | (1-C3)*N1*AB1-O1*AB1 | (1-C3)$^2$ *D1*AB1$^2$ + E1*AB1$^2$ | ... | (1-C3)$^2$ *N1*AB1$^2$ + O1*AB1$^2$ |
| 2 | . | ... | . | . | ... | . |
| 3 | . | ... | . | . | ... | . |
| | . | ... | . | . | ... | . |
| | . | ... | . | . | ... | . |
| 105 | (1-C3)*D105*AB105 - E105*AB105 | ... | (1-C3)*N105*B105 - O105*AB105 | (1-C3)$^2$ *D105*AB105$^2$ + E105*AB105$^2$ | ... | (1-C3)$^2$ *N105*AB105$^2$ + O105*AB105$^2$ |
| 106 | Σ(BY1...BY105) | ... | Σ(CJ1...CJ105) | Σ (CK1...CK105). | ... | Σ(CV1...CV105). |
| 107 | | | | C1*CK106$^{.5}$ | ... | C1*CV106$^{.5}$ |
| 108 | | | | BY106-CK106 | ... | CJ106-CV106 |

*Figure 6.2.* **(cont'd).**

As mentioned earlier, SOLVER provides two options of search methods: the quasi-Newton method and the conjugate gradient method. Theoretical descriptions of these search methods can be found in many theoretical mathematical programming or non-linear programming texts, such as Gottfried and Weisman (1973) and Avriel (1976). These two methods differ primarily in terms of their speed to convergence and space (memory) requirement. Neither one of these method is clearly superior to the other. In general, the conjugate gradient method requires less memory but more iterations (time), and conversely the quasi-Newton approach requires less time but more memory. Given today's computer speed and wealth of memory, to some extent the trade-off is insignificant. However, Broyden (1972) noted that the quasi-Newton method often fails to converge if it starts from a poor initial estimate. The CCP above was solved using the conjugate gradient method.

The CCP harvest scheduling model can be solved in various versions by using different values of the right-hand-sides $LV_t$ and $UV_t$ of constraints 6.7 and 6.8, and assigning different values for the upper- and lower-bound percentages $u$ and $l$ in constraint 6.9 and 6.10. In addition, it may also be modified by assigning different probability levels $\alpha$ which results in different values of $\beta$. A smaller $\alpha$-value is associated with a larger $\beta$-value. Intuitively, using a smaller $\alpha$-value reflects a more conservative attitude toward risk in the sense that yield estimates are represented by wider ranges, hence giving more allowance to the possibility that the actual and projected yields may be different. Increasing the $\alpha$-value, therefore, is moving toward less conservative attitude. In this case, yield estimates are represented by narrower ranges reflecting the decision makers' higher confidence that actual yields will not greatly deviate from their projected quantities. At one extreme, assigning $\alpha = 0.5$, in which $\beta = 0$, returns the CCP into an LP which treats yield as deterministic (as point estimates instead of range estimates). As indicated in Chapter Four, in this study $\alpha = 0.05$ was arbitrarily chosen as the starting point. To examine the effect on model outputs, some other $\alpha$-values were also tested but not reported.

The CCP was first solved by setting $LV_1 = 350{,}000$, $UV_1 = 500{,}000$, $u = 1$ and $l = 0$. Except for the values of $LV_1$ and $UV_1$, these are the same parameters used in LP 5 (in LP 5: $LV_1$ = 400,000 and $UV_1$ = 440,000). The values of $LV_1$ and $UV_1$ were modified because the LP solutions indicate that the original values were not binding. With these values the harvest volume in the first period is restricted within the given lower- and upper-bounds, and harvest volumes in subsequent periods are allowed to double the volume in the preceding period (increase by 100%) but not allowed to decline (i.e., $l = 0$). However, the CCP did not converge in this setting. It seemed that, when variances of yield estimates are included in the model, a strict NDEF constraint is no longer feasible. Therefore, the CCP was solved by incrementally relaxing the NDEF requirement (i.e., incrementally increasing the value of $l$ ), keeping other constraints the same. The model converged with $l = .1$, which means that periodic yields are allowed to decrease up to a lower bound equal to 90% of the volume in the previous period. This model, which is labeled as CCP 1, resulted in optimal solutions summarized in Table 6.7.

Figure 6.3a depicts the resulting harvest-flow pattern if solutions of CCP 1 are implemented. The optimist (plus deviation) and pessimist (minus deviation) lines indicate that, given the yield variability, periodic harvest volumes will be within these bounds, with a 95% confidence level. The fact that the lower-bound parameter (maximum allowed decrease) is binding is reflected in this figure. This harvest-flow obviously does not follow an ideal trajectory such as that of LP 5. However, there is a 95% confidence level that a trajectory within the optimist and pessimist lines will materialize if the optimal solutions are completely implemented. No such assurance is associated with deterministic LP solutions.

Some modifications were examined to obtain a less fluctuating harvest flow. One modification involved using a larger value of $\alpha$, which means reducing the confidence level to less than 95%. Theoretically, increasing the value of $\alpha$ will level off the harvest flow, since $\alpha = 0.5$ will lead to a harvest flow exactly like that of LP 5. However, increasing the value of $\alpha$ up to 0.10 did not notably improve the harvest flow. Using value of larger than 0.10 was not considered because the outputs would have less practical value; a decision maker may opt for a deterministic model rather than a stochastic model which only provides for instance, a 75% confidence level.

*Table 6.7.* Summarized optimal solutions of CCP harvest scheduling models.

| Input/output | CCP 1 | CCP 2 | CCP 3 |
|---|---|---|---|
| $Y_1$ (1000 m$^3$) | 350 - 500 | 350 - 500 | ≤500 |
| $Y_2$ (1000 m$^3$) | | 500 - 650 | 500 - 650 |
| $Y_3$ (1000 m$^3$) | | 650 - 800 | 650 - 800 |
| $Y_4$ - $Y_{12}$ (1000 m$^3$) | | | 650 - 800 |
| $\alpha$ | .05 | .05 | .05 |
| Max. increase (%) | 100 | 100 | |
| Max. decrease (%) | 10 | 10 | |
| Total NPV (1000,000 Rp) | 271,824 | 263,770 | 255,847 |
| Total Volume (1000 m$^3$) | 10415 | 9771 | 8429 |
| Unmanaged land (%) | 0 | 4 | 20 |

*Note*: $Y_i$ = harvest volume in period $i$; empty cells = no relevant input/output

Another modification was to constrain harvest volumes in periods 2 and 3 (in addition to the volume in period 1) to be within explicit upper- and lower-bounds, while other constraints remained the same. The intention was to postpone some harvests to later periods. Thus, harvest volumes in periods 2 and 3 were restricted within the ranges of 500,000 - 650,000 and 650,000 - 800,000 m$^3$, respectively. These ranges are below the corresponding harvest volumes resulting from CCP 1. This modified model, labeled CCP 2, did result in a flatter harvest-flow trajectory compared to that of CCP 1 (Figure 6.3b). However, it also reduced the total NPV and left about 4% of the total forest area unmanaged (Table 6.7).

Finally, the model was modified by assigning explicit lower- and upper-bounds to the harvest volumes in all periods. Harvest volume in period 1 was restricted to be 500,000 m$^3$ or less, harvest volume in period 2 was bounded within 500,000 - 650,000 m$^3$ and harvest volumes starting in period 3 thereafter were restricted to be within 650,000 - 800,000 m$^3$. This model (CCP 3) resulted in a harvest flow in Figure 6.3c. Except for the declines in periods 8 and 11, harvest volumes are relatively constant starting in period 3. The total NPV, however, is lower than both CCP 1 and CCP 2, and about 20% percent of the forest is unmanaged. Moreover, the upper bounds were subjectively chosen, meaning the total NPV may not be the forest's maximum NPV.

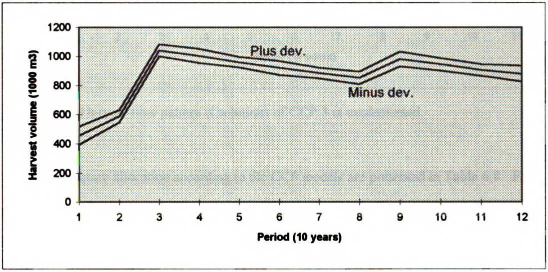



*Figure 6.3a*. Harvest-flow pattern if solutions of CCP 1 is implemented.

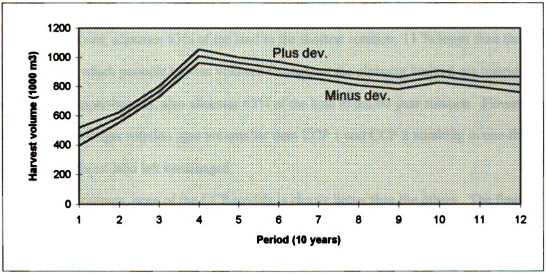



*Figure 6.4b*. Harvest-flow pattern if solutions of CCP 2 is implemented.

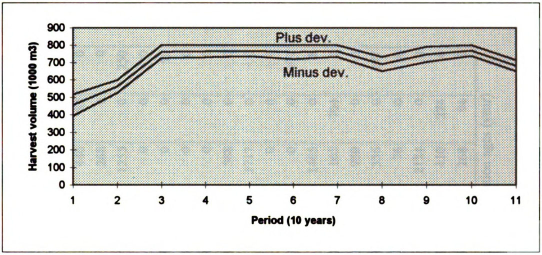



*Figure 6.3c.* Harvest-flow pattern if solutions of CCP 3 is implemented.

Optimal hectare allocation according to the CCP models are presented in Table 6.8. For comparison purposes, optimal hectare allocation according to LP 5 are also presented. LP 5 allocates about 60% of the forest to the shortest (60 years ) rotation. The other 40% is evenly distributed to rotation ages 70 and 80 years. In general, all CCP models follow a similar allocation pattern with CCP 1 allocation to the shortest rotation being the largest (74%). This higher portion of early harvests explains the highest NPV associated with CCP 1. CCP 2, in which some delays of harvests are imposed, allocates 63% of the land to the shortest rotation; 11 % lower than that of CCP 1. CCP 3, in which periodic harvest volumes throughout the planning horizon are restricted within lower- and upper-bounds, also allocates 63% of the land to the 60-year rotation. However, the allocation to the longer rotation ages are smaller than CCP 1 and CCP 2 resulting in one-fifth (20%) of the total forest land left unmanaged.

From their outputs, none of the CCP models is clearly better than the others. The final decision is decision makers. If attaining a stable harvest-flow is the main concern, CCP 3 may be the choice; however CCP 1 which gives the highest NPV. It also should be stated that many other modifications of the CCP are still possible.

*Table 6.8.* Optimal hectares allocations according to the LP 5 and CCP harvest scheduling models.

| Stand | LP 5 | | | CCP 1 | | | CCP 2 | | | CCP 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| type | 60 | 70 | 80 | 60 | 70 | 80 | 60 | 70 | 80 | 60 | 70 | 80 |
| 1A | 327 | 0 | 0 | 327 | 0 | 0 | 0 | 0 | 327 | 327 | 0 | 0 |
| 1B | 296 | 0 | 232 | 227 | 301 | 0 | 502 | 0 | 26 | 446 | 82 | 0 |
| 1C | 268 | 0 | 0 | 268 | 0 | 0 | 268 | 0 | 0 | 268 | 0 | 0 |
| 1D | 1631 | 0 | 0 | 1631 | 0 | 0 | 1263 | 0 | 368 | 1255 | 0 | 250 |
| 1E | 0 | 0 | 158 | 0 | 158 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2A | 496 | 0 | 0 | 154 | 253 | 88 | 0 | 282 | 214 | 0 | 0 | 90 |
| 2B | 0 | 135 | 249 | 0 | 63 | 321 | 0 | 340 | 44 | 0 | 0 | 0 |
| 2C | 0 | 0 | 122 | 0 | 0 | 122 | 2 | 88 | 33 | 0 | 0 | 0 |
| 2D | 0 | 0 | 588 | 278 | 103 | 208 | 318 | 133 | 137 | 588 | 0 | 0 |
| 2E | 616 | 0 | 1101 | 1717 | 0 | 0 | 1717 | 0 | 0 | 1717 | 0 | 0 |
| 2F | 1085 | 0 | 0 | 612 | 297 | 176 | 88 | 0 | 63 | 0 | 0 | 0 |
| 3A | 208 | 0 | 0 | 0 | 0 | 208 | 0 | 208 | 0 | 0 | 0 | 207 |
| 3B | 1473 | 0 | 0 | 1473 | 0 | 0 | 1445 | 0 | 28 | 1465 | 0 | 8 |
| 3C | 0 | 560 | 896 | 1193 | 0 | 263 | 1050 | 406 | 0 | 165 | 704 | 0 |
| 3D | 145 | 805 | 0 | 794 | 0 | 156 | 648 | 301 | 1 | 950 | 0 | 0 |
| 3E | 633 | 0 | 0 | 189 | 0 | 444 | 0 | 308 | 325 | 356 | 0 | 277 |
| 4A | 1069 | 1209 | 0 | 1424 | 0 | 854 | 1394 | 884 | 0 | 76 | 0 | 0 |
| 4B | 2124 | 0 | 0 | 2124 | 0 | 0 | 1739 | 0 | 385 | 2124 | 0 | 0 |
| 4C | 684 | 0 | 0 | 684 | 0 | 0 | 52 | 632 | 0 | 410 | 274 | 0 |
| 4D | 0 | 362 | 0 | 362 | 0 | 0 | 68 | 54 | 240 | 268 | 94 | 0 |

Stand-types are presented in Table 6.1 (e.g., 1A = age class 1, productivity class A); 60, 70, 80 are rotation ages (year).

*Table 6.8.* (cont'd).

| Stand type | | LP 5 | | | CCP 1 | | | CCP 2 | | | CCP 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 60 | 70 | 80 | 60 | 70 | 80 | 60 | 70 | 80 | 60 | 70 | 80 |
| 5A | | 628 | 0 | 0 | 628 | 0 | 0 | 628 | 0 | 0 | 628 | 0 | 0 |
| 5B | | 950 | 0 | 0 | 950 | 0 | 0 | 950 | 0 | 0 | 950 | 0 | 0 |
| 5C | | 476 | 0 | 0 | 476 | 0 | 0 | 476 | 0 | 0 | 476 | 0 | 0 |
| 6A | | 369 | 0 | 86 | 132 | 0 | 323 | 0 | 455 | 0 | 0 | 455 | 0 |
| 6B | | 269 | 233 | 211 | 194 | 519 | 0 | 576 | 0 | 137 | 461 | 0 | 252 |
| 6C | | 714 | 0 | 0 | 714 | 0 | 0 | 714 | 0 | 0 | 714 | 0 | 0 |
| 7A | | 0 | 0 | 274 | 274 | 0 | 0 | 274 | 0 | 0 | 274 | 0 | 0 |
| 7B | | 543 | 0 | 351 | 792 | 102 | 0 | 719 | 0 | 175 | 893 | 0 | 0 |
| 7C | | 0 | 0 | 200 | 0 | 200 | 0 | 0 | 0 | 200 | 0 | 0 | 200 |
| 7D | | 0 | 0 | 233 | 0 | 233 | 0 | 0 | 0 | 233 | 0 | 0 | 233 |
| 7E | | 0 | 0 | 337 | 0 | 337 | 0 | 0 | 0 | 337 | 0 | 0 | 337 |
| 8A | | 0 | 381 | 0 | 0 | 0 | 381 | 162 | 219 | 0 | 145 | 236 | 0 |
| 8B | | 0 | 601 | 0 | 601 | 0 | 0 | 601 | 0 | 0 | 601 | 0 | 0 |
| 8C | | 0 | 781 | 0 | 322 | 0 | 459 | 360 | 421 | 0 | 367 | 414 | 0 |
| 9A | | 229 | 0 | 0 | 229 | 0 | 0 | 140 | 0 | 89 | 48 | 0 | 181 |
| Total allocated to | Ha | 15223 | 5067 | 5038 | 18770 | 2565 | 4002 | 16153 | 4730 | 3363 | 15976 | 2259 | 2036 |
| each rotation | % | 60 | 20 | 20 | 74 | 10 | 16 | 63 | 19 | 13 | 63 | 9 | 8 |
| Total | Ha | 25328 | | | 25338 | | | 24246 | | | 20271 | | |
| managed | % | 100 | | | 100 | | | 96 | | | 80 | | |
| Total | Ha | 0 | | | 0 | | | 1092 | | | 5067 | | |
| unmanaged | % | 0 | | | 0 | | | 4 | | | 20 | | |

Stand-types are presented in Table 6.1 (e.g., 1A = age class 1, productivity class A); 60, 70, 80 are rotation ages (year).

## 6.4. Discussion

### 6.4.1. The Direct Cost of the 80-year Rotation Age

The total NPV is approximately doubled when alternative rotation ages were provided (i.e., LP 2). The NPVs obtained after imposing some form of harvest-flow constraint are lower with respect to that of LP 2, but still substantially higher compared to LP 1. As noted earlier, among the three models with harvest-flow constraints, LP 5 gives the highest NPV. The magnitude by which this NPV exceeds that of LP 1 can be roughly interpreted as the amount of revenue foregone under the current management approach. Moreover, if there is no requirement to maintain a stable or increasing harvest flow, the magnitude of lost revenue is even higher as indicated by the difference between the NPVs of LP 1 and LP 2.

While rotation-age options are exogenous in any forest-level harvest scheduling problem, all models with alternative rotation ages tend to allocate a major portion of the forest to the shortest rotation-age (i.e., 60 years). Thus, it may be inferred that the financial-maturity age of the stands must be closer to 60 years, and delaying harvests to age 80 years certainly incurs costs and reduces total profits. The NPV values in Table 6.4 give a similar indication. In addition, some earlier reports described below agree with this finding. Also, 60-year rotations provide more opportunities for 2 final harvests during the 120-year time horizon (Table 6.3).

Wiroatmodjo (1953) reported that Beekman (no year), a member of the team preparing the 1938-TFMI (Teak Forest Management Instruction), suggested that the economic rotation for teak plantations of site-classes 3 and 4 (of 1 - 6 scale) at 3 percent interest rate is between 50 - 60 years. Wiroatmodjo also reported that Helinga (no year), another local prominent forester of that time, suggested 60 - 65 years for the economic rotation for site-classes 2.5 - 3.5. Later, Wiroatmodjo and Effendi (1955) reviewed the work by Ferguson (no year) in which Ferguson suggested that the economic rotation for teak plantation of site 3.5 is 35 years at 5 percent interest rate, or 60 years at 3 percent interest rate. More recently, Sastrosumarto (1968) indicated that the economic rotation for teak plantations in Java may even as short as 40 years. These rotation-ages are close to those currently used in some other countries. Teak forests are cut at age 60 years in

India (Kumaravelu 1992), and between 40-60 years in Sri Lanka (Maddugoda 1992). The financial-maturity age of teak forests in Bangladesh is reported to be 40 years (Banik 1992). With this ample information, it should be apparent that the standard 80-year rotation currently used by Perhutani is very costly.

### 6.4.2. The Effect of NDEF Constraints

Figures 6.1a and 6.1b clearly reflect the role of the NDEF constraints. With the absence of such constraints, periodic harvest volumes fluctuate erratically regardless whether the forest is managed under a single rotation age as in LP 1, or with alternative rotation ages as in LP 2. In contrast, harvest flows under LP 3, LP 4 and LP 5 all show some form of regularity, with that of Model 5 showing the highest volume level.

The path of any harvest flow under a particular NDEF constraint is affected by the current age-class distribution of the forest. The levels of timber production of regenerated stands in comparison to those of existing stands also play a role. Regenerated stands usually produce more timber than their predecessors. This is reasonable because many existing stands have below-average stand density, whereas regenerated stands are assumed to start with an average number of trees per hectare, hence an average density. As shown in Figure 4.6, the current age-class distribution of the forest is very skewed toward the first four age classes. With this initial forest structure, and most model solutions cutting stands at age 60 years, it can be inferred that the portion of the forest which are ready for clearcutting (age 60 years or over) will be substantial in the future. With more stands available for harvest in the future, it is reasonable that allowing periodical harvest volume to increase without an upper-bound is not only feasible, but also gives the highest NPV.

The reduction of the total NPV due to the imposition of harvest-flow constraints can be explained using a simple model provided by Binkley (1980). Consider a forest with volume initially $V_1$ which must be liquidated in two periods and managed under an NDEF requirement. For simplicity assume that each period equals one year, and let $h_1$ be the harvested volume in year 1. Suppose that the annual growth of the forest is *r* percent and the discount rate is *i* percent per year. Also assume that timber price *P* is constant over time. The total NPV of the forest is given by:

$$NPV = P(h_1) + \left(\frac{(1+r)(V_1 - h_1)}{(1+i)}\right) \tag{6.12}$$

It is clear in this expression that if *r* is greater than *i*, the highest NPV is attained when $h_1 = 0$, meaning the entire forest is harvested in year 2. In this case, an NDEF requirement does not constrain profit maximization. In contrast, if *r* is lower than *i*, the highest NPV is obtained by setting $h_1 = V_1$ or harvesting the entire forest in period 1. Thus, the imposition of the NDEF constraint, which means setting $h_1 < V_1$, certainly results in a lower total NPV.

The cost (reduction in NPV) incurred by an NDEF constraint can be explained as follows. First, let *H* denotes the level of harvest volume that satisfies the NDEF constraint. Suppose that a slight departure from the NDEF is allowed, and $H$+$d$ is harvested in year 1. The cost due to the NDEF constraint is indicated by the difference between the total NPVs attained by harvesting *H* and $H$+$d$ in year 1. This difference is given by:

$$\Delta NPV = P\left[(H+d) + \left(\frac{(1+r)(H-d)}{(1+i)}\right)\right] - P\left[H - \frac{(1+r)H}{(1+i)}\right] \tag{6.13}$$

Rearranging terms in 6.13 gives:

$$\Delta NPV = P - \frac{P(1+r)}{(1+i)} = \frac{P(1-r)}{(1+i)} \tag{6.14}$$

Because *i* is greater than *r*, $\Delta NPV$ is positive. In other words, increasing the harvest volume in year 1 by the magnitude *d* does increase the total NPV. This increase, which is forgone because it is constrained to harvest only *H* in year 1, is the cost due to the NDEF constraint.

In this study, the NDEF constraints are relatively less costly because it is feasible to increase the periodic harvest volumes without an upper-bound. Obviously, the cost incurred is mainly due to the required upper-bound of the harvest volume in the first period. In fact, when no such upper bound was imposed (LP 2), the harvest volume in period 1 exceeds 600,000 cubic meters, substantially beyond the 440,000 upper bound.

6.4.3. The Effect of Incorporating Risk

Various harvest flows produced by the LP models will materialize only if the actual per-hectare yield of each stand-type under each rotation-age at each period (i.e., $a_{ijt}$) turn out to be exactly equal to their corresponding expected quantities. Because this is virtually impossible, the actual harvest flow under LP 5, for example may not be as regulated as it is shown in Figure 6.1b. Suppose for example a portion of the actual values of $a_{ij2}$, that is per-hectare yields of stand-type *i* under rotation *j* harvested in period 2, are lower than their expected quantities. If this causes the total harvest volume in period 2 to be lower than the total harvest volume in period 1, the path indicated in Figure 6.1b is no longer followed, and the NDEF condition may not be achieved.

The CCP models handle this risk by incorporating the variability of $a_{ijt}$ into the model and assures at a certain confidence level that certain levels of periodic harvest volumes (and therefore, a given NDEF condition) will be achieved and maintained. However, as discussed earlier, the CCP is not feasible with strict NDEF constraints included. Recall that in the deterministic LP models, a strict NDEF condition is imposed by requiring $Y_t - Y_{t+1} = \Delta Y_{t+1} \leq 0$, in which $Y_t$ and $Y_{t+1}$ being harvest volumes in period *t* and *t+1*, respectively. On the other hand, in the CCP models, the left-hand-side of the inequality is $(\Delta Y_{t+1} + \beta \mathrm{Var}(\Delta Y_{t+1}))$. If $\mathrm{Var}(\Delta Y_{t+1})$ turns out to be relatively large and are not identical for all *t*s the inequality requirement is harder to satisfy. This explains why imposing strict NDEF constraints alters the models' feasibility.

Given that requiring a strict NDEF condition is no longer feasible, the three CCP models (in which harvest volumes are allowed to decline by up to 10% relative to the volume in the previous period) offer the next best alternatives. With probability level $\alpha = 0.05$, these models assure at 95% confidence level that their corresponding projected outputs will materialize given their optimal solutions are fully implemented.

Incorporating the variability of $a_{ijt}$ indirectly affects the maximum value of the objective function. Theoretically, it may either increase or decrease the value depending upon how the variability in $a_{ijt}$ alters hectare allocation. One may anticipate to receive less revenues by being more conservative toward risk. However, the results of this study indicate that, except for CCP 3, the values of the CCP objective functions are higher than that of LP 5. This implies that accounting for the risk due to yield variability, other things being equal, earns revenues instead of incurs costs. A similar finding was reported by Brazee and Mendelsohn (1988) who developed a timber harvesting model that accounted for risk due to price fluctuation.

6.4.4. Ending Age-Class Distributions

The harvest scheduling models do not incorporate any explicit constraint representing ending inventory or ending age-class distribution. However, the fact that all stands must be replanted following clearcuttings ensures that there will be no bare land at the end of the planning horizon. Formally, it takes one period for a clearcut stand to become a stand of age-class 1; stands harvested in period $t$ become stands of age-class 1 (age 1 - 10 years) in period $t$+1. Therefore, stands harvested in the last period become stands of age-class 1 in the first period of the next planning horizon, which is beyond the time frame of the model in this study. Because of this, there is an age class labeled as age class 0 in the ending age-class distributions.

Figure 6.4a presents the ending age-class distribution if LP 5 is implemented. Apart from the fact that the associated total NPV and harvest-flow trajectory may not materialize (due to the deterministic treatment of yield), this age-class distribution will develop. Figures 6.4b - 6.4d, respectively, present the ending age-class distributions associated with CCP 1, CCP 2, and CCP 3. If CCP 1 is implemented, there will be no stand older than 60 years by the end of the planning horizon because CCP 1 leaves no stand unmanaged. In contrast, both CCP 2 and CCP 3 will create hectares of old growth, labeled as age-class OG.

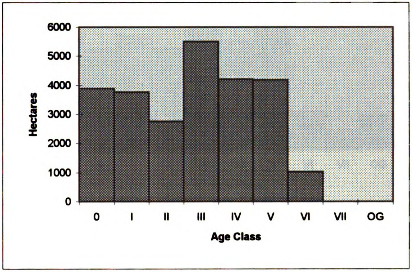



*Figure 6.4a*. Age-class distribution after the end of the planning horizon if LP 5 is implemented.

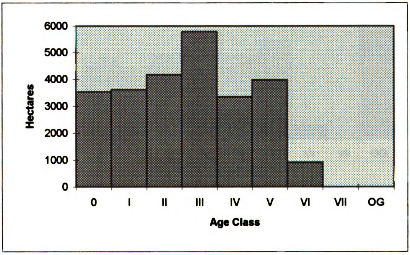



*Figure 6.4b*. Age-class distribution after the end of the planning horizon if CCP 1 is implemented.

*Note*: age-classes are in 10 year intervals (e.g., age class I = age 1 - 10); age-class 0 = stands just or being clearcut in period 12; OG = old growth (stands older than 70 years).

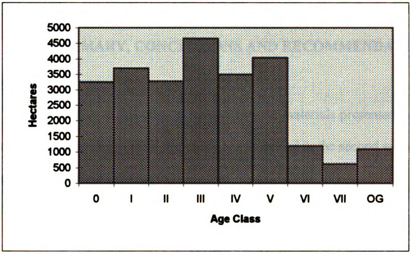



*Figure 6.4c*. Age-class distribution after the end of the planning horizon if CCP 2 is implemented.

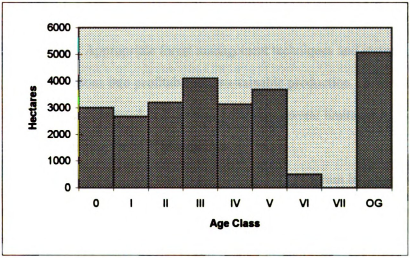



*Figure 6.4d*. Age-class distribution after the end of the planning horizon if CCP 1 is implemented.

*Note*: age-classes are in 10 year intervals (e.g., age class I = age 1 - 10); age-class 0 = stands just or being clearcut in period 12; OG = old growth (stands older than 70 years).

None of the models really result in a balanced ending age-class. However, this should not be a big concern, because, as cited in the beginning chapter, it is the main role of the managers to optimize yield from imbalanced forest structures.

# CHAPTER SEVEN:

# SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The first section of this chapter summarizes the materials presented in the preceding six chapters. Conclusions drawn from this study are presented in the second section, followed by some recommendations in the third section.

## 7.1. Summary

Foreseeing a possibility of timber shortages in the near future, the Indonesian government has recently launched a program for establishing large-scale industrial timber plantations, the HTI program. This HTI program bears critical implications for the Indonesian wood manufacturing industry, the conservation of Indonesian tropical rain forests, and the role of forestry in the Indonesian economy. Appropriate forest management techniques and instruments are necessary for bringing these plantations into profitable and sustainable production. A forest management approach currently implemented in Indonesia possesses several limitations, and therefore, may not be sufficient for managing the HTI plantations.

The purpose of this study was to support the HTI program by providing a prototype of a quantitative management approach for managing large-scale forest plantations in a profitable and sustainable manner. A package of quantitative models (consisting of (1) a set of growth and yield models and (2) harvest scheduling models) has been developed. This package was developed for teak plantations in Java because these plantations currently constitute the majority of established forest plantations in Indonesia. Nonetheless, the modeling framework can be implemented for developing similar quantitative management models for other species in other regions of Indonesia.

The growth and yield models were fitted using data collected on a number of permanent plots distributed across the main teak areas in Central and East Java. A teak forest district in Central Java was selected for developing the harvest scheduling models. The growth and yield models are:

(1) $$\ln B_2 = \left(\frac{A_1}{A_2}\right)\ln B_1 + 2.927\left(1-\frac{A_1}{A_2}\right) + .044\left(1-\frac{A_1}{A_2}\right)H_1$$

(2) $$\ln V_2 = 1.739 + .034\ln H_1 + .952\left(\frac{A_1}{A_2}\right)\ln B_1 + 1.796\left(1-\frac{A_1}{A_2}\right) + .092\left(1-\frac{A_1}{A_2}\right)H_1$$

(3) $$B_a = 1.074\left(\frac{N_a}{N_b}\right)B_b$$

(4) $$V_a = 1.048\left(\frac{N_a}{N_b}\right)V_b$$

(5) $$\ln H_1 = 2.575 - .143\ln\left(\frac{N_1}{A_1}\right) + .341\ln B_1$$

(6) $$\ln(B_2 - B_1) = .303\left(1-\frac{A_1}{A_1}\right)H_1$$

These growth and yield models were integrated into a computer routine specifically designed for generating part of the inputs in the development of the harvest scheduling models, specifically for predictions of future yields of a given stand, managed under different management regimes or rotation ages.

The harvest scheduling problem addressed in this study by and large represents a typical situation of forest plantation management in Indonesia. A forest district is managed to earn revenues, to maintain a sustained-yield condition, and to comply with a responsibility of continuously creating employment. The entire forest can be aggregated into several stand-types and there are alternative management regimes or rotation ages. The problem is to allocate hectares of each stand-type across the management regime alternatives in a way that will lead to the accomplishment of the management objectives.

This problem was formulated into a mathematical programming model following a Model I formulation (Johnson and Scheurman 1977). The first management objective was treated as an objective function of maximizing the total net-present-value (NPV) over a 120-year planning horizon. The second management objective (i.e., a sustained-yield condition), was represented as a set of non-declining even flow (NDEF) constraints. The employment objective was not explicitly represented in the model; to some extent, it is reflected in harvesting activities (i.e., employment is associated with thinning, girdling, clearcutting, replanting, and tending young trees).

The harvest scheduling problem was first solved in 5 different linear programming (LP) models. One of these LP models approximates the current management approach practiced on teak forests in Java which is characterized by a single 80-year rotation age. The other LP models incorporate multiple rotation ages with different sets of NDEF constraints. The following were observed from the outputs of these LP models:

1. The current practice of using a single 80-year rotation age is a costly management approach. The total NPV was less that 50% of the total NPV attained when shorter alternative rotation ages were provided.
2. Harvest flows over time fluctuate erratically if no NDEF constraints were included in the models. Including NDEF constraints effectively regulate the harvest flows with associated costs; the total NPV was reduced.
3. Models with alternative rotation ages tend to allocate a major portion of the forest into the shortest (60 years) rotation age.
4. Given an imbalanced initial age-class, the highest NPV was obtained by not allowing periodic harvest volumes to decline but allowing them to increase without an explicit upper bound.

A major limitation of these LP models is their treatment of risk associated with the non-deterministic nature of the yield predictions. The quantities representing the yield predictions in the models are the expected values of per-hectare yields of many individual stands, and therefore, contain variation. The LP models do not account for these variances. Consequently, there are possibilities that if the optimal solutions obtained (the hectare allocations) are implemented completely, they may not produce the total NPVs and harvest flows as indicated by the model solutions.

Considering the importance of attaining an NDEF condition, a harvest schedule that provides some degree of assurance of attaining this condition is more desirable. A possible approach is to incorporate the variances of the yield predictions in the models. In other words, the yield predictions are not considered as point estimates, but rather they are treated as range estimates. This can be accomplished by formulating the harvest scheduling problem as a chance-constrained programming or CCP problem.

Hence, one of the LP models (i.e., the one that simultaneously produces the highest NPV and a NDEF condition) was reformulated into a CCP. With CCP, NDEF constraints are required to hold with a certain level of probability but not necessarily with probability equal to one. In this manner, there is an assurance with a certain confidence level that a specific NDEF condition will be attained. The CCP formulation was solved by imposing a 95% confidence level. Imposing strict NDEF constraints, however, was not feasible. Three CCP models with different structures of NDEF constraints were solved. Each resulted in different total NPV and harvest flow trajectory. In general, harvest flows can be leveled off by lowering harvest volumes in early periods. Yet, this approach incurs costs in term of reduced NPV. Two of the three CCP problems resulted in higher total NPV compared to the deterministic LP 5, implying that including risk due to yield variation in the model does not necessarily incur costs.

## 7.2. Conclusions

Several conclusions can be drawn from the outcomes of this study. In general, this study has demonstrated the potential application of a particular modern forest management technique to forest plantations in Indonesia. This is a significant finding because modern forest management approaches currently receive little appreciation in Indonesia. This lack of appreciation can be attributed to insufficient recognition of the practical merits of the approaches, leading to *a priori* indictments that the approaches have little or no use. The fact that a typical Indonesian forest management situation has been successfully formulated into a package of quantitative models, indicates that such an attitude toward modern techniques should be discarded. In this context, this study has made a significant contribution to the improvement of forest plantation management in Indonesia.

Through comparisons, this study has revealed the limitations of the conventional forest management technique currently practiced to forest plantations in Indonesia. It was also shown that the technique proposed in this study mitigates those limitations. The existing conventional approach is neither economically efficient nor capable of maintaining a sustained-yield condition, and therefore, warrants replacement. More importantly, this finding provides a valid ground to justify that the existing conventional technique is not an appropriate technique for the management of the large-scale plantations established under the HTI program. Instead, it is more justifiable to adopt the technique proposed in this study.

The following conclusions are largely specific to the Cepu Forest District. Nonetheless, given the high similarity of teak forest districts, it may also holds to other teak forest districts in Central and East Java. These conclusions are:

1. Using several alternative rotation-ages is more economically efficient compared to using only a single rotation age. The opportunity cost of using a single 80-years rotation age is quite substantial; about 50% of the potential profit is forgone.
2. Given three alternative rotation ages (i.e., 60, 70, and 80 years), most stands are harvested at age 60 years. Roughly it can be inferred that the financial maturity of teak plantations in Java is about 60 years. Specific studies can be developed to substantiate or refute this conclusion.
3. Due to an imbalanced initial age-class distribution, a non-declining even flow (NDEF) condition can not be realized unless appropriate constraints are imposed. The appropriate and feasible structure of the NDEF constraints differs depending upon whether risk due to yield variability is excluded or included in the model. If it is excluded, a strict NDEF condition (does not allow any declines but allows increases without an explicit upper bound) gives the best result. If risk is included, the NDEF condition must be adjusted by allowing up to 10% periodical declines.
4. Imposing NDEF constraints always incurs costs in terms of reduced total NPV regardless risk is included or excluded in the model.

5. To a certain degree, accounting for risk by incorporating yield variability does not incur cost as the total NPV is slightly increased.

To some extent, these findings, particularly conclusions number one and three, may also hold for other species in other regions of Indonesia. It is generally discernible why using a single and relatively long rotation age is not economically efficient; unless the stands growth rate exceeds the interest rate, several stands must be harvested beyond their financial ages. Of course, if the single rotation age is the shortest one, or 60 years in the case of teak forests, using a single rotation age may result in a relatively high NPV. However, it is questionable whether an NDEF condition remains feasible.

Imposing NDEF constraints incurs a cost; this is theoretically consistent. Therefore, conclusion number three can be generalized to any species anywhere. What may vary across different species and regions is the magnitude of the cost incurred. An exception where this finding does not hold is when the initial age-class distribution is quite normal or relatively balanced. However, a forest with a balanced age-class distribution likely does not exist in Indonesia.

Another important point meriting mention is the critical role of growth and yield modeling in harvest scheduling. The mathematical growth and yield models developed for this study are the first for any species planted in Indonesia. Over time, models for other species can be developed and used in plantation management.

### 7.3. Recommendations

The results of this study leads to several recommendations. To Perum Perhutani, it is recommended to gradually replace the current forest management technique (i.e., the Burn's Method) using more modern, quantitative techniques. The technique presented in this study is a potential candidate. However, an elaboration and improvement of the harvest scheduling model may be necessary prior to its implementation. The necessary elaboration involves, but is not limited to, the following:

1. To use lower levels of spatial and temporal aggregation. More specifically, the number of stand-types should be increased in order to obtain more homogenous stand-types. In term of temporal aggregation, the 10-year planning period may need to be shortened into 5 years, at least for near-term management.
2. To include other relevant constraints. For example, a set of spatial constraints may be needed for insuring that harvesting activities are well distributed across the forest district.
3. To include minor sources of revenues, such as firewood production.
4. To include other sources of risk. A particularly relevant source of risk is timber theft. This source of risk is not included in the present study due to data unavailability. In the short run, perhaps allocating harvests at selected ages between theft and Perhutani may be possible.

In the long run, it is recommended to Perhutani to undertake studies for determining the economically optimal rotation-age of teak plantations in Java. The rotation ages used in this study, although formally *the* rotation ages for the teak plantations, are not based on any solid scientific investigation. It is also important for Perhutani to establish permanent plots for collecting new growth and yield data in various forest types. These new data can be used to develop new growth and yield models and to refine or re-estimate models obtained in this study.

The harvest scheduling approach presented in this study is under an indirect assumption that the long-run plan of each forest district is developed independently. Although forest districts are relatively independent management units, to some extent their long-run plans must be integrated. Therefore, given that Perhutani is to replace its current management approach using a modern approach, it may be important to develop the overall management plan in a hierarchical fashion. The implication to the forest-district level harvest scheduling is that there may be some form of hierarchically derived constraints that must be imposed, such as the total harvest volume in each period.

For the HTI Program, it is not recommended to adopt the current teak forest management technique as a model for the management of HTI plantations. In view of its limitations, clearly the conventional forest management technique is not capable of bringing HTI plantations into profitable and sustainable productions. Hence, it is recommended to the HTI Program to adopt a quantitative technique such as the one presented in this study.

Finally, Indonesian forestry researchers should carry out more studies on the development and application of modern forest management techniques. The approach presented in this study is only a small subset of a wide array of approaches offered by the present state-of-the-art of forest management.

# APPENDIX A:

## Growth and Yield Data and Yield Projections

*Table A.1.* Growth and yield data from permanent plots in Central and East Java.

| Plot # | A1 | A2 | H1 | B1 | B2 | V2 | Nb | Na | Bb | Ba | Vb | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C 4a | 21 | 26 | 24.3 | 14.9 | 18.1 | 195 | 518 | 466 | 15.7 | 14.9 | 148 | 141 |
| | 26 | 31 | 24.9 | 15.9 | 18.8 | 214 | 466 | 363 | 18.1 | 15.9 | 195 | 175 |
| | 31 | 38 | 26.9 | 15.5 | 19.4 | 245 | 363 | 267 | 18.8 | 15.6 | 214 | 181 |
| | 38 | 43 | 29 | 16.2 | 19.1 | 265 | 267 | 213 | 19.4 | 16.2 | 245 | 205 |
| | 43 | 48 | 30.5 | 17.7 | 21.1 | 310 | 213 | 187 | 19.1 | 17.7 | 265 | 247 |
| C 4b | 21 | 26 | 23 | 14.8 | 17.5 | 190 | 646 | 446 | 18.4 | 14.8 | 167 | 136 |
| | 26 | 31 | 25.8 | 14.6 | 16.9 | 206 | 446 | 334 | 17.5 | 14.6 | 190 | 161 |
| | 31 | 38 | 26.7 | 14.4 | 18.5 | 235 | 334 | 267 | 16.9 | 14.4 | 206 | 177 |
| | 38 | 43 | 28.8 | 13.5 | 17.4 | 239 | 268 | 180 | 18.5 | 13.5 | 235 | 171 |
| | 43 | 48 | 30 | 16.6 | 20.2 | 292 | 181 | 168 | 17.4 | 16.6 | 239 | 230 |
| C 5a | 40 | 45 | 25.3 | 18.7 | 21.3 | 230 | 393 | 374 | 19.2 | 18.7 | 187 | 183 |
| | 45 | 50 | 25.8 | 18.4 | 22.4 | 297 | 373 | 290 | 21.3 | 18.4 | 230 | 204 |
| | 50 | 57 | 27.2 | 21.7 | 25 | 338 | 291 | 272 | 22.4 | 21.7 | 272 | 264 |
| | 57 | 62 | 29.8 | 21.1 | 24.3 | 354 | 272 | 210 | 25 | 21.1 | 338 | 289 |
| C 5b | 40 | 45 | 26.6 | 19.9 | 22.8 | 283 | 343 | 326 | 20.5 | 19.9 | 221 | 215 |
| | 45 | 50 | 28 | 18.9 | 23 | 275 | 326 | 242 | 22.8 | 18.9 | 283 | 239 |
| | 50 | 57 | 29.6 | 21.5 | 25.4 | 358 | 241 | 219 | 23 | 21.5 | 275 | 258 |
| | 57 | 62 | 31.3 | 19.8 | 23 | 352 | 219 | 160 | 25.4 | 19.8 | 358 | 282 |
| C 6a | 30 | 35 | 26.9 | 18 | 21.7 | 262 | 465 | 376 | 19.8 | 18 | 202 | 187 |
| | 35 | 40 | 26.9 | 18.4 | 22.4 | 300 | 376 | 282 | 21.7 | 18.4 | 262 | 229 |
| | 40 | 47 | 28.6 | 20.7 | 24.3 | 335 | 283 | 245 | 22.4 | 20.7 | 300 | 282 |
| | 47 | 52 | 31.2 | 21.8 | 25 | 375 | 244 | 212 | 24.3 | 21.8 | 335 | 299 |
| C 6b | 30 | 35 | 25 | 15.4 | 19.3 | 222 | 470 | 343 | 18.5 | 15.4 | 183 | 157 |
| | 35 | 40 | 26.7 | 15.8 | 19.5 | 244 | 343 | 249 | 19.3 | 15.8 | 222 | 186 |
| | 40 | 47 | 28 | 17.3 | 21.2 | 306 | 250 | 208 | 19.5 | 17.3 | 244 | 217 |
| | 47 | 52 | 30.9 | 18.1 | 20.9 | 308 | 208 | 172 | 21.2 | 18.1 | 306 | 263 |
| C 7 | 35 | 40 | 27.6 | 19.1 | 22.5 | 282 | 326 | 283 | 20.6 | 19.1 | 243 | 228 |
| | 40 | 45 | 29 | 19.1 | 23.3 | 315 | 283 | 220 | 22.5 | 19.1 | 282 | 243 |

*Note:* A: age, H: height, B: basal area, V: volume, N: number of trees, 1: age 1, 2 = age 2, a: after-thinning, b: before-thinning.

*Table A.1.* (cont'd).

| Plot # | A1 | A2 | H1 | B1 | B2 | V2 | Nb | Na | Bb | Ba | Vb | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45 | 52 | 30.7 | 22 | 26.4 | 390 | 220 | 203 | 23.3 | 22 | 302 | 286 |
| | 52 | 57 | 32.8 | 20.3 | 23.6 | 371 | 206 | 149 | 26.4 | 20.3 | 390 | 305 |
| C 8a | 38 | 43 | 25.6 | 15.7 | 19.6 | 237 | 937 | 314 | 26.7 | 15.7 | 275 | 176 |
| | 43 | 48 | 27.8 | 16.8 | 20.3 | 262 | 314 | 231 | 19.6 | 16.8 | 237 | 206 |
| | 48 | 55 | 28.6 | 18.5 | 21.6 | 303 | 232 | 196 | 20.3 | 18.5 | 262 | 242 |
| | 55 | 60 | 31.4 | 18.4 | 20.7 | 312 | 195 | 154 | 21.7 | 18.4 | 303 | 257 |
| | 60 | 63 | 32.2 | 18.8 | 20.5 | 319 | 154 | 135 | 20.7 | 18.8 | 312 | 285 |
| C 11 | 52 | 57 | 28.2 | 21.6 | 23.9 | 307 | 272 | 207 | 25.7 | 21.6 | 328 | 280 |
| | 57 | 62 | 30.8 | 22.2 | 25.3 | 333 | 207 | 187 | 23.9 | 22.2 | 306 | 284 |
| | 62 | 70 | 31.1 | 23.1 | 26.8 | 414 | 187 | 169 | 25.3 | 23.1 | 333 | 301 |
| | 70 | 75 | 33.1 | 26 | 28.7 | 459 | 169 | 162 | 26.7 | 26 | 413 | 402 |
| C 12 | 61 | 66 | 34.6 | 29.3 | 31.2 | 510 | 147 | 125 | 32 | 29.3 | 462 | 425 |
| | 66 | 71 | 36.5 | 29.7 | 32 | 549 | 125 | 115 | 31.3 | 29.7 | 510 | 484 |
| | 71 | 79 | 37 | 29.5 | 33.4 | 604 | 115 | 103 | 32 | 29.5 | 549 | 512 |
| | 79 | 84 | 38.7 | 32.2 | 35.6 | 668 | 103 | 98 | 33.4 | 32.2 | 604 | 583 |
| C 13a | 15 | 20 | 21.8 | 17.1 | 22 | 227 | 727 | 502 | 19.9 | 17.1 | 155 | 137 |
| | 20 | 25 | 22.9 | 18.5 | 21.5 | 252 | 502 | 343 | 21.9 | 18.5 | 227 | 200 |
| | 25 | 33 | 26.4 | 20.1 | 23.9 | 317 | 342 | 301 | 21.5 | 20.1 | 252 | 238 |
| | 33 | 38 | 28.9 | 19 | 22.6 | 314 | 301 | 216 | 23.8 | 19 | 316 | 256 |
| C 14a | 40 | 45 | 28.9 | 17.3 | 20.6 | 281 | 374 | 177 | 26 | 17.3 | 311 | 221 |
| | 45 | 50 | 29.3 | 16.2 | 18.4 | 259 | 178 | 122 | 20.6 | 16.2 | 281 | 230 |
| | 50 | 57 | 30.8 | 17.9 | 21.5 | 328 | 121 | 116 | 18.4 | 17.9 | 259 | 254 |
| C 22 | 84 | 89 | 34.9 | 27.9 | 29.2 | 491 | 127 | 108 | 31.1 | 27.9 | 496 | 449 |
| | 89 | 94 | 35.6 | 27.9 | 29.8 | 506 | 108 | 101 | 29.2 | 27.9 | 491 | 470 |
| | 94 | 99 | 36.1 | 29.3 | 31.5 | 516 | 101 | 99 | 29.8 | 29.3 | 506 | 498 |
| C 31a | 33 | 38 | 24.2 | 13.8 | 16.8 | 191 | 473 | 283 | 18.3 | 13.8 | 198 | 156 |
| | 38 | 43 | 25.4 | 15.8 | 18.1 | 211 | 283 | 253 | 16.8 | 15.8 | 192 | 181 |
| | 43 | 51 | 26.3 | 17.2 | 20.9 | 265 | 252 | 236 | 18.1 | 17.2 | 211 | 201 |
| | 51 | 59 | 29.4 | 17.1 | 21 | 306 | 236 | 176 | 21 | 17.1 | 265 | 214 |

*Note:* A: age, H: height, B: basal area, V: volume, N: number of trees, 1: age 1, 2 = age 2, a: after-thinning, b: before-thinning.

*Table A.1.* (cont'd).

| Plot # | A1 | A2 | H1 | B1 | B2 | V2 | Nb | Na | Bb | Ba | Vb | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 59 | 68 | 31.9 | 19.8 | 21 | 329 | 176 | 162 | 21 | 19.8 | 305 | 289 |
| C 33 | 33 | 38 | 18.8 | 14.9 | 17.3 | 148 | 833 | 609 | 17.3 | 14.9 | 137 | 121 |
| | 38 | 43 | 19.7 | 15.9 | 17.9 | 174 | 608 | 512 | 17.3 | 15.9 | 148 | 137 |
| | 43 | 50 | 21 | 16.1 | 19.1 | 194 | 512 | 425 | 17.9 | 16.1 | 174 | 160 |
| | 50 | 56 | 23.3 | 17.1 | 20 | 218 | 425 | 360 | 19.1 | 17.1 | 194 | 176 |
| C 37a | 41 | 46 | 26.1 | 16.4 | 19.5 | 243 | 422 | 242 | 20.4 | 16.4 | 229 | 193 |
| | 46 | 51 | 27.6 | 18.4 | 21.1 | 258 | 242 | 218 | 19.5 | 18.4 | 242 | 230 |
| | 51 | 58 | 30.1 | 19.7 | 22.5 | 324 | 218 | 197 | 21.1 | 19.7 | 258 | 241 |
| | 58 | 63 | 31.6 | 18.7 | 21.4 | 324 | 197 | 152 | 22.4 | 18.7 | 324 | 275 |
| C 40 | 49 | 54 | 28.2 | 21.8 | 24.1 | 320 | 249 | 215 | 24 | 21.8 | 296 | 269 |
| | 54 | 59 | 31.2 | 22.7 | 25.6 | 347 | 215 | 195 | 24.1 | 22.7 | 319 | 304 |
| | 59 | 67 | 31.3 | 23.9 | 26.9 | 370 | 195 | 178 | 25.6 | 23.9 | 347 | 326 |
| | 67 | 72 | 34.1 | 23.6 | 27 | 440 | 178 | 152 | 27 | 23.6 | 421 | 370 |
| | 72 | 79 | 34.7 | 24.4 | 27.2 | 450 | 152 | 129 | 27 | 24.4 | 440 | 402 |
| C 42 | 15 | 20 | 16.2 | 13.8 | 16.9 | 125 | 1634 | 1013 | 17.9 | 13.8 | 109 | 91 |
| | 20 | 25 | 17.8 | 15.3 | 17.1 | 140 | 1014 | 866 | 16.9 | 15.3 | 125 | 115 |
| | 25 | 32 | 18.9 | 14.4 | 18.5 | 162 | 866 | 664 | 17.1 | 14.4 | 140 | 122 |
| | 32 | 38 | 20.9 | 14.2 | 17.8 | 178 | 664 | 441 | 18.5 | 14.2 | 162 | 128 |
| C 43 | 28 | 33 | 18.8 | 13.7 | 17.3 | 153 | 898 | 599 | 17.1 | 13.7 | 135 | 114 |
| | 33 | 38 | 20.3 | 16.5 | 18.5 | 165 | 599 | 552 | 17.2 | 16.5 | 153 | 147 |
| | 38 | 45 | 21.9 | 16.9 | 20 | 209 | 552 | 453 | 18.6 | 16.9 | 165 | 151 |
| | 45 | 53 | 24.2 | 17.4 | 21.2 | 241 | 453 | 354 | 20 | 17.4 | 209 | 186 |
| | 53 | 62 | 25.8 | 18.1 | 22.2 | 310 | 354 | 266 | 21.1 | 18.1 | 241 | 211 |
| | 62 | 70 | 30.4 | 19.6 | 23.4 | 329 | 250 | 206 | 22.3 | 19.6 | 311 | 277 |
| C 44 | 21 | 26 | 15.6 | 13.7 | 16.6 | 117 | 1882 | 1158 | 16.9 | 13.7 | 93 | 83 |
| | 26 | 31 | 16.6 | 13.8 | 16.1 | 135 | 1158 | 844 | 16.6 | 13.8 | 117 | 102 |
| | 31 | 38 | 18.6 | 13.6 | 19.3 | 177 | 844 | 634 | 16.1 | 13.6 | 135 | 119 |
| | 38 | 46 | 22.2 | 16.5 | 21.4 | 227 | 633 | 464 | 19.3 | 16.5 | 177 | 156 |
| | 46 | 55 | 24.6 | 16.1 | 20.7 | 252 | 464 | 311 | 21.5 | 16.1 | 227 | 173 |

*Note:* A: age, H: height, B: basal area, V: volume, N: number of trees, 1: age 1, 2 = age 2, a: after-thinning, b: before-thinning.

*Table A.1.* (cont'd).

| Plot # | A1 | A2 | H1 | B1 | B2 | V2 | Nb | Na | Bb | Ba | Vb | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 55 | 63 | 27.8 | 18 | 20.4 | 273 | 290 | 230 | 20.7 | 18 | 252 | 223 |
| C 45 | 15 | 20 | 21 | 15.5 | 19.9 | 203 | 852 | 423 | 24.1 | 15.5 | 213 | 142 |
| | 20 | 25 | 22.6 | 18.4 | 20.5 | 210 | 423 | 374 | 20 | 18.4 | 203 | 189 |
| | 25 | 32 | 23.7 | 15.9 | 18.4 | 215 | 374 | 273 | 20.5 | 15.9 | 240 | 192 |
| | 32 | 38 | 25.5 | 15.6 | 18.3 | 229 | 273 | 221 | 18.4 | 15.6 | 215 | 184 |
| C 46 | 8 | 13 | 16.2 | 11.6 | 20 | 174 | 1936 | 989 | 17 | 11.6 | 100 | 76 |
| | 13 | 18 | 20.5 | 15.1 | 22 | 211 | 989 | 610 | 20 | 15.1 | 174 | 136 |
| C 47 | 52 | 57 | 22.5 | 15.3 | 18 | 185 | 534 | 354 | 19 | 15.3 | 189 | 159 |
| | 57 | 62 | 23.2 | 17.3 | 18.6 | 206 | 353 | 326 | 17.9 | 17.3 | 185 | 180 |
| | 62 | 69 | 24.5 | 18 | 20.8 | 247 | 326 | 305 | 18.5 | 18 | 206 | 201 |
| C 48 | 26 | 31 | 28.9 | 15.1 | 19.6 | 266 | 378 | 196 | 22.8 | 15.1 | 284 | 195 |
| | 31 | 36 | 29.9 | 19 | 22.7 | 326 | 203 | 192 | 19.6 | 19 | 266 | 258 |
| | 36 | 43 | 32.1 | 18.7 | 24.1 | 387 | 192 | 151 | 22.7 | 18.7 | 326 | 272 |
| | 43 | 51 | 35.1 | 18.6 | 22.2 | 379 | 151 | 107 | 24.1 | 18.6 | 387 | 305 |
| | 51 | 60 | 37.1 | 19 | 25 | 456 | 107 | 85 | 22.2 | 19 | 379 | 329 |
| | 60 | 68 | 39.4 | 23.6 | 25.4 | 474 | 84 | 79 | 25 | 23.6 | 456 | 432 |
| C 50 | 15 | 20 | 23.1 | 15 | 18.2 | 201 | 598 | 404 | 19 | 15 | 186 | 151 |
| | 20 | 25 | 23.8 | 17 | 19.3 | 229 | 404 | 360 | 18.2 | 17 | 200 | 188 |
| | 25 | 32 | 25.4 | 16.2 | 18.9 | 231 | 360 | 280 | 19.3 | 16.2 | 229 | 195 |
| | 32 | 38 | 27.3 | 17.3 | 22.2 | 293 | 280 | 249 | 18.9 | 17.3 | 231 | 213 |
| C 52 | 17 | 22 | 23.7 | 14.8 | 20.4 | 239 | 946 | 364 | 23.1 | 14.8 | 221 | 155 |
| | 22 | 27 | 26.7 | 18.1 | 21.2 | 285 | 364 | 299 | 20.5 | 18.1 | 239 | 213 |
| | 27 | 35 | 27.4 | 17.2 | 22.6 | 322 | 299 | 226 | 21.3 | 17.2 | 285 | 234 |
| | 35 | 40 | 31.6 | 18.6 | 22.3 | 341 | 226 | 171 | 22.6 | 18.6 | 322 | 270 |
| | 40 | 48 | 33.5 | 19.6 | 23.5 | 371 | 172 | 143 | 22.3 | 19.6 | 342 | 303 |
| | 48 | 57 | 33.5 | 22.2 | 25.4 | 418 | 143 | 135 | 23.5 | 22.2 | 370 | 349 |
| | 57 | 60 | 36.4 | 22.3 | 27.1 | 440 | 132 | 114 | 25.4 | 22.3 | 418 | 367 |
| C 53 | 21 | 26 | 24.1 | 16 | 20 | 229 | 565 | 349 | 21.2 | 16 | 221 | 176 |

*Note:* A: age, H: height, B: basal area, V: volume, N: number of trees, 1: age 1, 2 = age 2, a: after-thinning, b: before-thinning.

*Table A.1.* (cont'd).

| Plot # | A1 | A2 | H1 | B1 | B2 | V2 | Nb | Na | Bb | Ba | Vb | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 26 | 31 | 25.5 | 18.2 | 20.8 | 270 | 349 | 299 | 20 | 18.2 | 229 | 212 |
| | 31 | 39 | 27.3 | 16.1 | 21.6 | 295 | 299 | 219 | 20.7 | 16.1 | 270 | 220 |
| | 39 | 43 | 29.8 | 17.1 | 20.5 | 298 | 218 | 163 | 21.6 | 17.1 | 295 | 236 |
| | 43 | 52 | 31.6 | 18.8 | 23 | 349 | 163 | 144 | 20.5 | 18.8 | 299 | 275 |
| | 52 | 61 | 32.6 | 21.2 | 25 | 397 | 144 | 127 | 23.1 | 21.2 | 349 | 322 |
| | 61 | 64 | 34.4 | 22 | 23.7 | 393 | 125 | 108 | 25 | 22 | 398 | 350 |
| C 54 | 14 | 19 | 15 | 11 | 12.7 | 90 | 933 | 855 | 11.4 | 11 | 67 | 65 |
| | 19 | 24 | 16.2 | 11.9 | 14.1 | 107 | 855 | 750 | 12.7 | 11.9 | 90 | 85 |
| | 24 | 31 | 17.7 | 13.3 | 16.2 | 134 | 750 | 666 | 14.1 | 13.3 | 107 | 101 |
| C 56 | 47 | 52 | 33.4 | 16.6 | 19.1 | 317 | 97 | 89 | 17.6 | 16.6 | 278 | 264 |
| | 52 | 60 | 35.1 | 16.8 | 21.3 | 357 | 90 | 76 | 19.2 | 16.8 | 318 | 280 |
| | 60 | 69 | 35.2 | 20 | 21.8 | 379 | 75 | 70 | 21.3 | 20 | 357 | 336 |
| | 69 | 72 | 37.5 | 18.7 | 21 | 382 | 71 | 60 | 21.8 | 18.7 | 378 | 325 |
| C 58 | 28 | 33 | 22.2 | 12.9 | 16.6 | 179 | 689 | 415 | 18 | 12.9 | 171 | 127 |
| | 33 | 38 | 23.9 | 14.1 | 16.1 | 191 | 416 | 328 | 16.6 | 14.1 | 179 | 154 |
| | 38 | 45 | 25.3 | 11.9 | 15.9 | 199 | 327 | 220 | 16.1 | 11.9 | 192 | 144 |
| | 45 | 50 | 27.8 | 14.4 | 17.1 | 229 | 220 | 186 | 15.9 | 14.4 | 199 | 183 |
| C 60 | 16 | 21 | 17 | 12.7 | 16.8 | 143 | 1499 | 850 | 17.4 | 12.7 | 112 | 92 |
| | 21 | 26 | 19.7 | 14.2 | 16.7 | 155 | 850 | 627 | 16.9 | 14.2 | 143 | 125 |
| | 26 | 33 | 21.6 | 11.1 | 16.5 | 179 | 628 | 349 | 16.7 | 11.1 | 155 | 108 |
| | 33 | 38 | 24.8 | 14 | 17.3 | 204 | 348 | 268 | 16.5 | 14 | 178 | 154 |
| C 63 | 22 | 27 | 22.9 | 13 | 16.6 | 186 | 360 | 294 | 14.5 | 13 | 142 | 128 |
| | 27 | 32 | 24.9 | 14.9 | 17.9 | 222 | 294 | 253 | 16.6 | 14.9 | 186 | 168 |
| | 32 | 38 | 27.1 | 13.5 | 16.5 | 225 | 253 | 176 | 17.9 | 13.5 | 222 | 171 |
| | 38 | 45 | 30.1 | 13.6 | 16.9 | 245 | 176 | 137 | 16.5 | 13.6 | 225 | 188 |
| C 72 | 17 | 22 | 21.4 | 19 | 19.8 | 193 | 605 | 437 | 22.7 | 19 | 199 | 172 |
| | 22 | 27 | 22.6 | 17.5 | 19.4 | 205 | 437 | 359 | 19.8 | 17.5 | 192 | 170 |
| | 27 | 32 | 23.6 | 15.1 | 17.8 | 200 | 359 | 260 | 19.4 | 15.1 | 206 | 163 |

*Note:* A: age, H: height, B: basal area, V: volume, N: number of trees, 1: age 1, 2 = age 2, a: after-thinning, b: before-thinning.

*Table A.1.* (cont'd).

| Plot # | A1 | A2 | H1 | B1 | B2 | V2 | Nb | Na | Bb | Ba | Vb | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 32 | 38 | 24.4 | 16.8 | 20.2 | 239 | 260 | 238 | 17.8 | 16.8 | 200 | 190 |
| | 38 | 46 | 26.1 | 17.5 | 23.3 | 307 | 238 | 199 | 20.2 | 17.5 | 239 | 209 |
| C 77 | 19 | 24 | 20.5 | 16.6 | 18.2 | 168 | 980 | 613 | 22.1 | 16.6 | 192 | 151 |
| | 24 | 31 | 21.8 | 13.9 | 17.5 | 179 | 613 | 412 | 18.2 | 13.9 | 168 | 133 |
| | 31 | 36 | 23.1 | 15.6 | 19.5 | 220 | 412 | 350 | 17.4 | 15.6 | 178 | 161 |
| | 36 | 41 | 25.3 | 14.6 | 18.5 | 231 | 350 | 258 | 19.4 | 14.6 | 221 | 167 |
| C 79 | 43 | 48 | 31.9 | 22.6 | 26.5 | 384 | 305 | 244 | 25.2 | 22.6 | 339 | 308 |
| | 48 | 56 | 33 | 19.7 | 25 | 402 | 244 | 166 | 26.5 | 19.7 | 384 | 286 |
| | 56 | 61 | 34.7 | 20.9 | 23.7 | 398 | 166 | 130 | 24.9 | 20.9 | 402 | 338 |
| | 61 | 68 | 36.7 | 21.3 | 25.6 | 448 | 130 | 111 | 23.7 | 21.3 | 398 | 361 |
| C 81 | 26 | 31 | 27.6 | 17.5 | 20 | 249 | 325 | 255 | 19.8 | 17.5 | 239 | 215 |
| | 31 | 39 | 30.3 | 16.6 | 21.6 | 313 | 255 | 190 | 20 | 16.6 | 258 | 209 |
| | 39 | 44 | 31.5 | 19.9 | 23.3 | 358 | 190 | 171 | 21.5 | 19.9 | 313 | 290 |
| | 44 | 52 | 32.9 | 21.8 | 25.9 | 402 | 171 | 154 | 23.2 | 21.8 | 358 | 338 |
| C 82 | 9 | 14 | 17.9 | 17.3 | 26.4 | 235 | 2784 | 1055 | 27.5 | 17.3 | 182 | 132 |
| | 14 | 21 | 21.5 | 18.4 | 26.3 | 279 | 1055 | 600 | 26.4 | 18.4 | 235 | 168 |
| | 21 | 26 | 24.8 | 18 | 23.3 | 276 | 600 | 345 | 26.3 | 18 | 280 | 199 |
| | 26 | 31 | 26.4 | 16.8 | 22 | 288 | 345 | 231 | 23.3 | 16.8 | 275 | 203 |
| C 86 | 12 | 17 | 20.7 | 12.6 | 19.7 | 201 | 1061 | 623 | 17.4 | 12.6 | 151 | 115 |
| | 17 | 24 | 24.1 | 12.4 | 21.3 | 264 | 623 | 328 | 19.7 | 12.4 | 201 | 132 |
| | 24 | 30 | 28.4 | 15.4 | 21.2 | 295 | 328 | 204 | 21.3 | 15.4 | 264 | 197 |
| C 90 | 23 | 28 | 18 | 12.9 | 16.2 | 150 | 814 | 571 | 15.4 | 12.9 | 124 | 109 |
| | 28 | 36 | 19.9 | 15 | 19.7 | 197 | 571 | 497 | 16.1 | 15 | 151 | 142 |
| | 36 | 42 | 23.8 | 17.5 | 20.7 | 226 | 497 | 405 | 19.7 | 17.5 | 197 | 178 |
| C 96 | 80 | 85 | 38 | 27 | 29.6 | 496 | 150 | 139 | 28.3 | 27 | 488 | 468 |
| | 85 | 88 | 37.8 | 24 | 24.6 | 464 | 139 | 110 | 29.5 | 24 | 496 | 404 |
| C 98 | 7 | 12 | 15.3 | 11.1 | 18.8 | 154 | 3411 | 1249 | 19.5 | 11.1 | 94 | 70 |
| | 12 | 18 | 19.6 | 10.4 | 19.1 | 191 | 1249 | 552 | 18.8 | 10.4 | 154 | 89 |

*Note:* A: age, H: height, B: basal area, V: volume, N: number of trees, 1: age 1, 2 = age 2, a: after-thinning, b: before-thinning.

*Table A.1.* (cont'd).

| Plot # | A1 | A2 | H1 | B1 | B2 | V2 | Nb | Na | Bb | Ba | Vb | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 18 | 23 | 23.6 | 15.2 | 20.4 | 231 | 552 | 395 | 19.1 | 15.2 | 192 | 157 |
| C 101 | 21 | 26 | 17 | 11 | 15.5 | 139 | 1602 | 736 | 17.2 | 11 | 110 | 80 |
| | 26 | 31 | 19.9 | 10.1 | 14.6 | 145 | 736 | 418 | 15.5 | 10.1 | 139 | 94 |
| | 31 | 37 | 22.9 | 13 | 17.2 | 188 | 418 | 348 | 14.6 | 13 | 145 | 130 |
| C 113e | 6 | 13 | 12.1 | 9.3 | 15.7 | 94 | 2404 | 1525 | 12.8 | 9.3 | 49 | 44 |
| | 13 | 17 | 15.7 | 9.3 | 11.7 | 82 | 1525 | 735 | 15.6 | 9.3 | 94 | 62 |
| C 125 | 20 | 25 | 22.8 | 12.6 | 17.4 | 186 | 688 | 381 | 17.3 | 12.6 | 165 | 128 |
| | 25 | 31 | 25.1 | 13.7 | 19.2 | 231 | 381 | 280 | 17.4 | 13.7 | 186 | 150 |
| C 161 a | 26 | 36 | 27.6 | 18.5 | 22.4 | 319 | 312 | 219 | 23.6 | 18.5 | 293 | 233 |
| | 36 | 40 | 31.1 | 19.4 | 21.9 | 323 | 198 | 164 | 22.4 | 19.4 | 320 | 278 |
| | 40 | 45 | 32.5 | 17.1 | 18.9 | 286 | 164 | 120 | 21.9 | 17.1 | 323 | 255 |
| C 161 b | 26 | 36 | 27.6 | 19.6 | 24.8 | 357 | 281 | 215 | 23.4 | 19.6 | 291 | 246 |
| | 36 | 40 | 30.9 | 18.8 | 21.3 | 315 | 205 | 155 | 24.8 | 18.8 | 357 | 270 |
| | 40 | 45 | 32.8 | 15.8 | 17.6 | 275 | 155 | 102 | 21.3 | 15.8 | 315 | 239 |
| C 161 d | 26 | 36 | 26.5 | 18.9 | 24 | 337 | 314 | 237 | 22.5 | 18.9 | 264 | 225 |
| | 36 | 40 | 30.9 | 21 | 24 | 338 | 230 | 199 | 24 | 21 | 336 | 295 |
| | 40 | 45 | 31.7 | 17.8 | 19.2 | 286 | 199 | 136 | 23.8 | 17.8 | 338 | 253 |
| | 45 | 50 | 32.7 | 17.6 | 22 | 342 | 135 | 118 | 19.2 | 17.6 | 287 | 265 |
| C 161 e | 26 | 36 | 26.4 | 21.4 | 29 | 402 | 380 | 297 | 25 | 21.4 | 292 | 254 |
| | 36 | 40 | 31.1 | 22.6 | 26.4 | 374 | 291 | 218 | 29 | 22.6 | 402 | 312 |
| | 40 | 45 | 31.6 | 18.7 | 21.2 | 317 | 218 | 142 | 26.4 | 18.7 | 374 | 267 |
| | 45 | 50 | 32.7 | 19.6 | 23.9 | 370 | 142 | 129 | 21.2 | 19.6 | 318 | 295 |
| C 161 f | 26 | 36 | 27.3 | 18.5 | 24.7 | 356 | 279 | 210 | 22.4 | 18.5 | 273 | 228 |
| | 36 | 40 | 31.5 | 22.3 | 25.3 | 376 | 200 | 177 | 24.7 | 22.3 | 356 | 322 |
| | 40 | 45 | 32.3 | 20 | 21.8 | 342 | 177 | 125 | 25.3 | 20 | 376 | 304 |
| C 161 g | 16 | 21 | 21.8 | 16.9 | 25 | 265 | 1090 | 593 | 23.2 | 16.9 | 202 | 156 |
| | 21 | 26 | 24.5 | 20.3 | 23.5 | 269 | 592 | 407 | 25 | 20.3 | 265 | 222 |
| | 26 | 36 | 26.3 | 19.2 | 26.6 | 370 | 407 | 311 | 23.6 | 19.2 | 269 | 222 |

*Note:* A: age, H: height, B: basal area, V: volume, N: number of trees, 1: age 1, 2 = age 2, a: after-thinning, b: before-thinning.

*Table A.1.* (cont'd).

| Plot # | A1 | A2 | H1 | B1 | B2 | V2 | Nb | Na | Bb | Ba | Vb | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 36 | 40 | 31.8 | 21.4 | 24.9 | 354 | 304 | 225 | 26.6 | 21.4 | 365 | 301 |
| | 40 | 45 | 32.3 | 17.3 | 19.6 | 297 | 225 | 139 | 24.9 | 17.3 | 354 | 249 |
| | 45 | 50 | 33.1 | 18.9 | 23.8 | 373 | 139 | 132 | 19.6 | 18.9 | 296 | 286 |
| C 161 h | 16 | 21 | 22.2 | 15.9 | 24 | 262 | 917 | 468 | 22.1 | 15.9 | 198 | 152 |
| | 21 | 26 | 24.9 | 18.7 | 22.4 | 267 | 469 | 316 | 24 | 18.7 | 262 | 209 |
| | 26 | 36 | 26.8 | 18.5 | 25.6 | 366 | 316 | 243 | 22.4 | 18.5 | 267 | 222 |
| | 36 | 40 | 31.7 | 21.9 | 26.6 | 390 | 232 | 189 | 25.6 | 21.9 | 367 | 317 |
| | 40 | 45 | 32.3 | 19.6 | 20.7 | 317 | 189 | 123 | 26.6 | 19.6 | 390 | 293 |
| | 45 | 50 | 33.3 | 19.9 | 24.6 | 390 | 123 | 120 | 20.7 | 19.9 | 318 | 306 |
| C 161 i | 26 | 36 | 28.3 | 20.7 | 28.2 | 414 | 350 | 252 | 25.9 | 20.7 | 330 | 268 |
| | 36 | 40 | 32.9 | 22.8 | 28.2 | 432 | 245 | 178 | 28.2 | 22.8 | 414 | 341 |
| | 40 | 45 | 33.8 | 20.3 | 22.3 | 362 | 178 | 117 | 28.2 | 20.3 | 431 | 313 |
| C 161 j | 16 | 21 | 23.4 | 21 | 29.3 | 337 | 1096 | 584 | 25.8 | 21 | 237 | 209 |
| | 21 | 26 | 25.7 | 22.4 | 26.6 | 337 | 584 | 349 | 29.7 | 22.4 | 337 | 267 |
| | 26 | 36 | 28.6 | 20.9 | 27.8 | 404 | 349 | 223 | 26.6 | 20.9 | 337 | 273 |
| | 36 | 40 | 32.5 | 24.4 | 29.5 | 449 | 223 | 187 | 27.8 | 24.4 | 404 | 357 |
| | 40 | 45 | 33.8 | 25.6 | 27.3 | 438 | 187 | 151 | 29.2 | 25.4 | 449 | 395 |
| | 45 | 50 | 34.7 | 24.1 | 31.2 | 501 | 151 | 133 | 27.3 | 24.1 | 438 | 387 |
| C 161l | 16 | 21 | 21.6 | 16.9 | 24.2 | 256 | 1557 | 576 | 23.4 | 16.9 | 187 | 157 |
| | 21 | 26 | 23.8 | 19.6 | 23.6 | 277 | 576 | 395 | 24.2 | 19.6 | 257 | 214 |
| | 26 | 36 | 26.2 | 17.4 | 23.7 | 333 | 395 | 257 | 23.6 | 17.4 | 277 | 208 |
| | 36 | 40 | 31.4 | 20.1 | 25 | 360 | 253 | 205 | 23.7 | 20.1 | 333 | 284 |
| | 40 | 45 | 31.8 | 19.2 | 21.5 | 327 | 205 | 143 | 25 | 19.2 | 360 | 281 |
| | 45 | 50 | 32.9 | 20.3 | 24.8 | 388 | 143 | 129 | 21.5 | 20.3 | 327 | 311 |
| C 161m | 16 | 21 | 21.8 | 18.8 | 26.9 | 283 | 1634 | 656 | 26.5 | 18.8 | 348 | 174 |
| | 21 | 26 | 23.8 | 21.4 | 25.4 | 294 | 656 | 415 | 26.9 | 21.4 | 468 | 234 |
| | 26 | 36 | 26.2 | 18.8 | 26 | 363 | 415 | 268 | 25.4 | 18.8 | 446 | 223 |

*Note:* A: age, H: height, B: basal area, V: volume, N: number of trees, 1: age 1, 2 = age 2, a: after-thinning, b: before-thinning.

*Table A.1.* (cont'd).

| Plot # | A1 | A2 | H1 | B1 | B2 | V2 | Nb | Na | Bb | Ba | Vb | Va |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 36 | 40 | 30.9 | 21 | 26 | 381 | 246 | 192 | 26 | 21 | 594 | 297 |
| | 40 | 45 | 31.7 | 19.8 | 21.6 | 332 | 192 | 125 | 26 | 19.8 | 598 | 299 |
| | 45 | 50 | 32.8 | 20.1 | 25.4 | 402 | 125 | 112 | 21.6 | 20.1 | 624 | 312 |
| C 162f | 16 | 21 | 22.7 | 12.3 | 17.8 | 199 | 797 | 352 | 17.6 | 12.3 | 161 | 122 |
| | 21 | 24 | 24.5 | 13.6 | 15.3 | 180 | 352 | 251 | 17.8 | 13.6 | 199 | 154 |
| E 68 | 54 | 59 | 32.1 | 18.5 | 20.7 | 328 | 197 | 157 | 21.3 | 18.5 | 326 | 287 |
| | 59 | 64 | 33.2 | 20.4 | 22.4 | 371 | 157 | 154 | 20.7 | 20.4 | 327 | 323 |
| | 64 | 71 | 33.7 | 17.7 | 23 | 339 | 154 | 114 | 22.4 | 17.7 | 370 | 295 |
| | 71 | 81 | 35.1 | 18.9 | 21.5 | 363 | 114 | 103 | 23 | 18.9 | 340 | 320 |
| | 81 | 88 | 36.4 | 19.5 | 21.7 | 381 | 102 | 91 | 21.5 | 19.5 | 364 | 331 |
| | 88 | 95 | 38.7 | 19.7 | 25.1 | 461 | 94 | 83 | 21.7 | 19.7 | 380 | 346 |
| E 69 | 25 | 30 | 25.6 | 14.2 | 18.1 | 232 | 500 | 332 | 17.9 | 14.2 | 205 | 167 |
| | 30 | 35 | 27.2 | 15 | 17 | 232 | 332 | 247 | 18.1 | 15 | 232 | 196 |
| | 35 | 42 | 27.4 | 13.1 | 16.5 | 227 | 247 | 174 | 17 | 13.1 | 231 | 178 |
| | 42 | 47 | 30 | 15.4 | 17.7 | 255 | 174 | 159 | 16.5 | 15.4 | 227 | 213 |
| | 47 | 51 | 31.8 | 16.6 | 18.3 | 272 | 158 | 143 | 17.7 | 16.6 | 255 | 241 |
| | 51 | 59 | 32.8 | 17.1 | 21.3 | 339 | 143 | 134 | 18.3 | 17.1 | 272 | 255 |
| | 59 | 66 | 34.6 | 20 | 23.6 | 397 | 134 | 122 | 21.3 | 20 | 338 | 319 |
| E 70 | 17 | 22 | 17.9 | 12.1 | 16.1 | 140 | 1313 | 673 | 16.5 | 12.1 | 122 | 97 |
| | 22 | 27 | 20.7 | 13.2 | 15.5 | 156 | 673 | 480 | 16.1 | 13.2 | 139 | 116 |
| | 27 | 34 | 21.1 | 10.1 | 13.9 | 147 | 480 | 279 | 15.5 | 10.1 | 156 | 103 |
| | 34 | 39 | 23.4 | 12.5 | 15.3 | 169 | 279 | 249 | 13.9 | 12.5 | 147 | 132 |
| | 39 | 44 | 24.6 | 13.8 | 15.6 | 184 | 249 | 218 | 15.3 | 13.8 | 169 | 154 |
| | 44 | 51 | 25.7 | 14.3 | 16.8 | 212 | 218 | 198 | 15.6 | 14.3 | 184 | 168 |
| E 75 | 29 | 34 | 24.5 | 16.5 | 20.2 | 227 | 414 | 352 | 18.4 | 16.5 | 203 | 184 |
| E 118a | 13 | 18 | 19.1 | 8.3 | 15.2 | 130 | 1247 | 675 | 11.4 | 8.3 | 73 | 60 |
| E 135 | 10 | 15 | 18.4 | 8.2 | 14.4 | 135 | 1816 | 375 | 15.8 | 8.2 | 92 | 63 |
| | 15 | 20 | 21.4 | 12.7 | 16.2 | 167 | 375 | 324 | 14.4 | 12.7 | 135 | 120 |
| | 20 | 24 | 23.4 | 12.8 | 16.2 | 185 | 324 | 238 | 16.2 | 12.8 | 168 | 135 |

*Note:* A: age, H: height, B: basal area, V: volume, N: number of trees, 1: age 1, 2 = age 2, a: after-thinning, b: before-thinning.

*Table A.2.* Yield projections of the Cepu Forest District; mean and variance of per-hectare yield of each stand-type under each management regime in each period throughout the planning horizon.

| Stand-type/ | Period 1 | | Period 2 | | Period 3 | | Period 4 | | Period 5 | | Period 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mgt. regime | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance |
| 1A80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1B80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1C80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 22.51 | 14.31 | 11.52 | 26.54 | 21.73 | 11.96 |
| 1D80 | 0.00 | 0.00 | 23.09 | 36.07 | 20.12 | 10.36 | 15.62 | 3.54 | 9.59 | 6.11 | 16.00 | 4.70 |
| 1E80 | 26.81 | 26.98 | 28.04 | 22.90 | 20.19 | 7.44 | 15.88 | 3.12 | 9.58 | 7.61 | 16.93 | 5.38 |
| 2A80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2B80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2C80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 28.61 | 96.61 |
| 2D80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 16.47 | 42.15 | 20.01 | 20.29 | 19.90 | 103.20 |
| 2E80 | 0.00 | 0.00 | 23.86 | 36.32 | 20.78 | 19.73 | 11.33 | 18.58 | 19.44 | 9.29 | 17.93 | 75.59 |
| 2F80 | 28.45 | 186.19 | 28.00 | 35.48 | 20.29 | 10.06 | 12.25 | 15.46 | 19.23 | 9.96 | 15.42 | 56.83 |
| 3A80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 160.84 | 71.85 |
| 3B80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 176.54 | 93.28 |
| 3C80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 20.74 | 99.65 | 177.44 | 97.85 |
| 3D80 | 0.00 | 0.00 | 0.00 | 0.00 | 14.84 | 33.57 | 20.51 | 8.37 | 15.76 | 65.26 | 176.02 | 61.12 |
| 3E80 | 0.00 | 0.00 | 23.65 | 25.15 | 14.28 | 25.97 | 22.15 | 10.06 | 12.46 | 15.41 | 190.91 | 55.86 |
| 4A80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 165.38 | 89.75 | 16.74 | 125.57 |
| 4B80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 16.37 | 55.74 | 183.56 | 96.81 | 25.27 | 132.02 |
| 4C80 | 0.00 | 0.00 | 14.24 | 23.30 | 21.16 | 12.00 | 12.12 | 11.79 | 186.65 | 81.36 | 33.84 | 147.53 |
| 4D80 | 24.57 | 75.13 | 13.86 | 54.87 | 20.64 | 23.69 | 11.07 | 5.94 | 177.49 | 55.63 | 34.07 | 139.50 |
| 5A80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 120.07 | 74.25 | 0.00 | 0.00 | 23.07 | 60.35 |
| 5B80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 185.82 | 63.12 | 31.49 | 141.30 | 29.03 | 25.25 |
| 5C80 | 0.00 | 0.00 | 0.00 | 0.00 | 15.17 | 39.81 | 167.18 | 95.12 | 0.00 | 0.00 | 31.26 | 16.63 |
| 6A80 | 0.00 | 0.00 | 0.00 | 0.00 | 102.75 | 41.54 | 0.00 | 0.00 | 23.94 | 48.13 | 19.32 | 2.84 |
| 6B80 | 0.00 | 0.00 | 0.00 | 0.00 | 172.83 | 64.19 | 28.19 | 157.90 | 33.32 | 14.78 | 22.95 | 4.63 |
| 6C80 | 0.00 | 0.00 | 0.00 | 0.00 | 159.49 | 42.88 | 39.62 | 105.14 | 26.38 | 6.29 | 19.49 | 2.33 |
| 7A80 | 0.00 | 0.00 | 84.43 | 204.26 | 0.00 | 0.00 | 29.65 | 3.20 | 20.64 | 1.66 | 16.28 | 0.63 |
| 7B80 | 0.00 | 0.00 | 138.69 | 389.08 | 25.36 | 74.48 | 32.07 | 9.56 | 22.28 | 3.66 | 17.28 | 1.32 |
| 7C80 | 0.00 | 0.00 | 77.49 | 224.00 | 31.50 | 103.26 | 24.31 | 5.00 | 18.29 | 1.84 | 14.42 | 0.98 |
| 7D80 | 0.00 | 0.00 | 115.48 | 35.37 | 36.53 | 16.75 | 24.79 | 1.35 | 18.60 | 0.52 | 14.73 | 0.54 |
| 7E80 | 0.00 | 0.00 | 146.55 | 386.42 | 41.40 | 74.07 | 26.47 | 9.51 | 19.48 | 2.13 | 15.05 | 3.23 |

*Table A.2.* (cont'd).

| Stand-type/ | Period 7 | | Period 8 | | Period 9 | | Period 10 | | Period 11 | | Period 12 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mgt. regime | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance |
| 1A80 | 0.00 | 0.00 | 243.97 | 109.26 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1B80 | 0.00 | 0.00 | 321.66 | 172.60 | 0.00 | 0.00 | 20.00 | 50.20 | 19.29 | 2.35 | 17.01 | 1.39 |
| 1C80 | 19.61 | 119.47 | 180.55 | 653.62 | 0.00 | 0.00 | 20.17 | 36.03 | 18.68 | 2.89 | 16.56 | 1.63 |
| 1D80 | 15.20 | 53.04 | 141.22 | 405.99 | 0.00 | 0.00 | 20.61 | 65.75 | 19.43 | 2.47 | 17.13 | 1.37 |
| 1E80 | 13.12 | 39.84 | 151.15 | 448.97 | 30.21 | 122.86 | 27.57 | 19.52 | 20.06 | 4.49 | 17.70 | 2.57 |
| 2A80 | 210.20 | 984.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2B80 | 228.44 | 602.47 | 0.00 | 0.00 | 18.04 | 57.13 | 19.40 | 2.55 | 15.02 | 1.16 | 13.18 | 0.80 |
| 2C80 | 195.05 | 830.97 | 0.00 | 0.00 | 19.92 | 48.09 | 18.82 | 2.55 | 14.71 | 1.14 | 12.91 | 0.82 |
| 2D80 | 174.93 | 696.31 | 0.00 | 0.00 | 20.02 | 63.34 | 19.37 | 2.11 | 15.11 | 0.96 | 13.27 | 0.67 |
| 2E80 | 165.35 | 705.35 | 0.00 | 0.00 | 21.99 | 55.91 | 19.19 | 2.99 | 15.08 | 1.46 | 13.22 | 0.99 |
| 2F80 | 171.98 | 796.92 | 0.00 | 0.00 | 27.28 | 38.57 | 20.16 | 4.44 | 15.77 | 1.70 | 13.76 | 1.44 |
| 3A80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3B80 | 9.75 | 192.57 | 19.04 | 55.97 | 19.22 | 2.85 | 14.96 | 1.29 | 8.30 | 10.04 | 12.30 | 24.35 |
| 3C80 | 0.00 | 0.00 | 23.57 | 56.45 | 19.42 | 3.67 | 15.30 | 1.74 | 9.49 | 11.03 | 10.42 | 26.31 |
| 3D80 | 0.00 | 0.00 | 26.74 | 19.73 | 19.69 | 2.86 | 15.55 | 1.53 | 9.41 | 10.61 | 11.42 | 33.54 |
| 3E80 | 28.84 | 123.53 | 29.82 | 11.06 | 21.14 | 3.47 | 16.57 | 1.47 | 10.87 | 10.71 | 10.09 | 34.67 |
| 4A80 | 22.54 | 57.37 | 18.58 | 3.07 | 14.60 | 1.49 | 9.05 | 10.74 | 15.34 | 2.48 | 13.70 | 37.93 |
| 4B80 | 28.37 | 20.04 | 20.38 | 5.21 | 16.05 | 2.32 | 10.01 | 12.06 | 17.05 | 4.39 | 15.15 | 32.35 |
| 4C80 | 30.72 | 35.79 | 21.74 | 5.54 | 16.69 | 2.05 | 10.14 | 12.35 | 16.75 | 2.78 | 14.16 | 9.72 |
| 4D80 | 32.27 | 16.62 | 22.60 | 5.31 | 17.52 | 1.79 | 11.76 | 11.55 | 18.94 | 3.55 | 16.64 | 2.41 |
| 5A80 | 19.53 | 4.01 | 15.31 | 1.88 | 8.95 | 11.23 | 16.30 | 2.88 | 12.99 | 38.56 | 146.54 | 316.94 |
| 5B80 | 21.10 | 2.93 | 16.54 | 1.28 | 10.83 | 9.62 | 17.59 | 3.80 | 11.48 | 20.92 | 59.54 | 292.92 |
| 5C80 | 21.76 | 6.45 | 16.95 | 2.45 | 12.31 | 6.03 | 17.55 | 6.52 | 13.47 | 31.46 | 30.79 | 426.60 |
| 6A80 | 15.22 | 1.41 | 9.45 | 10.99 | 15.86 | 1.70 | 14.02 | 45.34 | 142.39 | 301.95 | 0.00 | 0.00 |
| 6B80 | 17.59 | 1.49 | 13.27 | 2.01 | 17.78 | 12.12 | 11.11 | 18.38 | 160.59 | 223.50 | 22.70 | 68.41 |
| 6C80 | 15.47 | 1.47 | 6.03 | 0.11 | 17.53 | 3.62 | 11.12 | 17.77 | 163.06 | 296.69 | 25.85 | 54.64 |
| 7A80 | 12.61 | 0.27 | 16.23 | 2.01 | 13.07 | 38.31 | 146.20 | 284.60 | 0.00 | 0.00 | 30.08 | 105.48 |
| 7B80 | 13.29 | 0.60 | 17.88 | 2.71 | 9.76 | 4.50 | 160.14 | 61.03 | 25.36 | 74.48 | 39.83 | 50.35 |
| 7C80 | 6.14 | 0.12 | 16.49 | 3.13 | 11.98 | 35.26 | 149.71 | 310.93 | 31.50 | 103.26 | 29.96 | 7.80 |
| 7D80 | 6.18 | 0.01 | 17.05 | 0.63 | 8.82 | 0.37 | 158.57 | 39.56 | 36.53 | 16.75 | 30.43 | 2.25 |
| 7E80 | 6.76 | 6.18 | 17.71 | 2.74 | 9.69 | 2.36 | 166.83 | 252.15 | 41.40 | 74.07 | 32.74 | 19.38 |

*Table A.2.* (cont'd).

| Stand-type/ | Period 1 | | Period 2 | | Period 3 | | Period 4 | | Period 5 | | Period 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mgt. regime | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance |
| 8A80 | 74.96 | 536.87 | 0.00 | 0.00 | 28.31 | 8.79 | 20.11 | 2.52 | 15.85 | 1.28 | 10.89 | 8.90 |
| 8B80 | 111.85 | 53.46 | 0.00 | 0.00 | 29.69 | 9.89 | 21.08 | 2.96 | 16.54 | 1.30 | 10.83 | 10.84 |
| 8C80 | 149.20 | 427.89 | 35.99 | 77.24 | 31.85 | 14.08 | 22.44 | 4.13 | 17.41 | 1.49 | 11.27 | 12.38 |
| 9A80 | 92.62 | 354.89 | 30.95 | 171.62 | 24.62 | 6.52 | 18.48 | 2.47 | 14.69 | 1.58 | 6.01 | 0.13 |
| 1A70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1B70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1C70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 22.50 | 14.31 | 11.52 | 26.54 | 21.73 | 11.96 |
| 1D70 | 0.00 | 0.00 | 23.09 | 36.07 | 20.12 | 10.36 | 15.62 | 3.55 | 9.59 | 6.11 | 16.00 | 4.70 |
| 1E70 | 26.81 | 121.96 | 28.04 | 22.90 | 20.19 | 7.44 | 15.88 | 3.13 | 9.58 | 7.61 | 16.93 | 5.38 |
| 2A70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 186.99 | 98.95 |
| 2B70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 202.55 | 55.26 |
| 2C70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 195.54 | 154.59 |
| 2D70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 16.48 | 44.05 | 20.01 | 20.30 | 167.97 | 561.17 |
| 2E70 | 0.00 | 0.00 | 23.86 | 36.32 | 20.78 | 19.74 | 11.33 | 18.59 | 19.44 | 9.29 | 156.69 | 83.29 |
| 2F70 | 33.31 | 176.08 | 28.00 | 35.37 | 20.29 | 10.43 | 12.25 | 17.57 | 19.23 | 21.44 | 160.19 | 53.12 |
| 3A70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 132.00 | 106.64 | 0.00 | 0.00 |
| 3B70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 152.43 | 128.52 | 24.65 | 153.77 |
| 3C70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 170.70 | 57.65 | 0.00 | 0.00 |
| 3D70 | 0.00 | 0.00 | 0.00 | 0.00 | 14.84 | 33.57 | 20.51 | 8.37 | 164.19 | 40.96 | 0.00 | 0.00 |
| 3E70 | 0.00 | 0.00 | 23.65 | 25.15 | 14.28 | 25.97 | 22.15 | 10.06 | 174.68 | 47.42 | 28.84 | 123.53 |
| 4A70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 143.39 | 90.85 | 27.60 | 125.57 | 23.93 | 57.37 |
| 4B70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 171.91 | 68.58 | 30.12 | 0.00 | 28.37 | 20.04 |
| 4C70 | 0.00 | 0.00 | 14.24 | 23.30 | 21.16 | 12.00 | 170.00 | 69.47 | 35.59 | 147.53 | 30.72 | 35.79 |
| 4D70 | 25.57 | 425.16 | 13.86 | 54.87 | 20.64 | 23.69 | 160.94 | 85.18 | 34.07 | 139.50 | 32.27 | 16.62 |
| 5A70 | 0.00 | 0.00 | 0.00 | 0.00 | 96.44 | 66.21 | 0.00 | 0.00 | 22.54 | 71.04 | 19.08 | 12.59 |
| 5B70 | 0.00 | 0.00 | 0.00 | 0.00 | 161.18 | 87.46 | 26.80 | 52.05 | 29.03 | 25.25 | 21.10 | 2.93 |
| 5C70 | 0.00 | 0.00 | 0.00 | 0.00 | 155.22 | 81.08 | 0.00 | 0.00 | 31.26 | 16.63 | 21.76 | 6.45 |
| 6A70 | 0.00 | 0.00 | 82.83 | 189.10 | 0.00 | 0.00 | 23.94 | 48.13 | 19.32 | 2.84 | 15.22 | 1.41 |
| 6B70 | 0.00 | 0.00 | 148.06 | 687.22 | 32.31 | 53.14 | 33.45 | 21.71 | 22.37 | 14.49 | 17.13 | 7.89 |
| 6C70 | 0.00 | 0.00 | 135.40 | 458.30 | 39.62 | 115.66 | 26.38 | 8.12 | 19.49 | 2.35 | 15.47 | 1.50 |
| 7A70 | 66.83 | 153.42 | 21.38 | 174.82 | 29.65 | 3.22 | 20.64 | 1.69 | 16.28 | 0.64 | 12.61 | 0.29 |

*Table A.2.* (cont'd).

| Stand-type/ | Period 7 | | Period 8 | | Period 9 | | Period 10 | | Period 11 | | Period 12 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mgt. regime | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance |
| 8A80 | 16.48 | 1.56 | 11.48 | 29.91 | 150.17 | 221.84 | 0.00 | 0.00 | 28.31 | 8.79 | 23.29 | 4.11 |
| 8B80 | 17.64 | 1.72 | 10.05 | 8.72 | 160.20 | 123.26 | 0.00 | 0.00 | 29.69 | 9.89 | 24.49 | 4.61 |
| 8C80 | 18.92 | 2.04 | 10.30 | 1.41 | 167.14 | 46.94 | 35.99 | 77.24 | 31.85 | 14.08 | 26.19 | 6.61 |
| 9A80 | 16.57 | 4.47 | 14.26 | 41.60 | 148.14 | 506.37 | 30.95 | 171.62 | 24.62 | 6.52 | 21.11 | 4.37 |
| 1A70 | 223.90 | 343.62 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1B70 | 297.59 | 176.28 | 0.00 | 0.00 | 20.00 | 50.20 | 19.29 | 2.35 | 14.99 | 1.23 | 8.12 | 9.39 |
| 1C70 | 172.85 | 607.52 | 0.00 | 0.00 | 20.17 | 36.03 | 18.68 | 2.90 | 14.56 | 1.33 | 7.14 | 6.95 |
| 1D70 | 131.79 | 246.83 | 0.00 | 0.00 | 20.61 | 65.75 | 19.43 | 2.48 | 15.18 | 1.14 | 9.61 | 10.17 |
| 1E70 | 138.22 | 272.49 | 30.21 | 122.86 | 27.57 | 19.51 | 20.06 | 4.49 | 15.77 | 2.24 | 9.74 | 12.08 |
| 2A70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2B70 | 0.00 | 0.00 | 18.04 | 57.13 | 19.41 | 2.56 | 15.02 | 1.16 | 8.62 | 10.51 | 15.93 | 0.82 |
| 2C70 | 0.00 | 0.00 | 19.92 | 48.09 | 18.82 | 2.55 | 14.71 | 1.14 | 8.29 | 10.54 | 15.32 | 1.09 |
| 2D70 | 0.00 | 0.00 | 20.02 | 63.34 | 19.37 | 2.11 | 15.11 | 0.97 | 9.48 | 10.14 | 15.49 | 1.06 |
| 2E70 | 0.00 | 0.00 | 21.99 | 55.91 | 19.19 | 2.99 | 15.08 | 1.46 | 8.93 | 10.73 | 15.76 | 2.12 |
| 2F70 | 0.00 | 0.00 | 27.28 | 39.21 | 20.16 | 4.39 | 15.77 | 1.74 | 9.96 | 11.95 | 16.00 | 11.49 |
| 3A70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 180.94 | 0.02 |
| 3B70 | 19.04 | 55.97 | 19.22 | 2.85 | 14.96 | 1.30 | 8.30 | 10.05 | 15.91 | 1.32 | 131.42 | 73.30 |
| 3C70 | 23.57 | 56.45 | 19.42 | 3.68 | 15.30 | 1.74 | 9.49 | 11.03 | 15.82 | 2.76 | 130.61 | 134.09 |
| 3D70 | 26.74 | 19.73 | 19.69 | 2.86 | 15.55 | 1.53 | 9.41 | 10.61 | 16.55 | 3.40 | 136.08 | 163.43 |
| 3E70 | 29.82 | 11.06 | 21.14 | 3.47 | 16.57 | 1.48 | 10.87 | 10.71 | 17.71 | 2.69 | 143.49 | 102.39 |
| 4A70 | 19.72 | 3.07 | 15.50 | 1.49 | 9.61 | 10.74 | 16.28 | 2.48 | 134.17 | 123.11 | 27.60 | 125.57 |
| 4B70 | 20.38 | 5.22 | 16.05 | 2.33 | 10.01 | 12.06 | 17.05 | 4.39 | 138.76 | 177.03 | 30.12 | 0.00 |
| 4C70 | 21.74 | 5.54 | 16.69 | 2.05 | 10.64 | 12.35 | 18.07 | 2.77 | 148.34 | 192.11 | 35.59 | 147.53 |
| 4D70 | 22.60 | 5.31 | 17.52 | 1.79 | 11.76 | 11.55 | 18.94 | 3.55 | 149.25 | 84.23 | 34.07 | 139.50 |
| 5A70 | 14.97 | 7.18 | 8.74 | 12.79 | 15.94 | 8.86 | 135.15 | 175.10 | 27.74 | 215.53 | 22.54 | 71.04 |
| 5B70 | 16.54 | 1.28 | 10.83 | 9.62 | 17.59 | 3.80 | 142.62 | 166.16 | 26.80 | 252.05 | 29.03 | 25.25 |
| 5C70 | 16.95 | 2.45 | 12.31 | 6.03 | 17.55 | 6.52 | 140.06 | 210.51 | 23.13 | 276.59 | 31.26 | 16.63 |
| 6A70 | 9.45 | 10.99 | 15.86 | 1.70 | 131.22 | 93.11 | 0.00 | 0.00 | 23.94 | 48.13 | 19.32 | 2.84 |
| 6B70 | 13.13 | 2.39 | 17.34 | 17.87 | 143.14 | 173.10 | 32.31 | 953.14 | 33.45 | 21.71 | 22.37 | 14.49 |
| 6C70 | 6.03 | 0.86 | 17.53 | 9.82 | 147.38 | 210.88 | 39.62 | 115.66 | 26.38 | 8.12 | 19.49 | 2.35 |
| 7A70 | 16.23 | 2.10 | 133.57 | 97.96 | 21.38 | 428.20 | 29.65 | 3.22 | 20.64 | 1.69 | 16.28 | 0.64 |

*Table A.2.* (cont'd).

| Stand-type/ | Period 1 | | Period 2 | | Period 3 | | Period 4 | | Period 5 | | Period 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mgt. regime | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance |
| 7B70 | 115.84 | 381.29 | 25.36 | 84.27 | 32.07 | 9.42 | 22.28 | 3.62 | 17.28 | 1.30 | 13.29 | 0.59 |
| 7C70 | 59.56 | 141.71 | 31.50 | 103.26 | 24.31 | 5.00 | 18.29 | 1.84 | 14.42 | 0.98 | 6.14 | 0.12 |
| 7D70 | 91.99 | 26.21 | 36.53 | 16.75 | 24.79 | 1.35 | 18.60 | 0.52 | 14.73 | 0.54 | 6.18 | 0.01 |
| 7E70 | 119.98 | 356.90 | 41.40 | 74.07 | 26.47 | 9.51 | 19.48 | 2.13 | 15.05 | 3.23 | 6.76 | 6.18 |
| 8A70 | 67.63 | 357.46 | 0.00 | 0.00 | 24.23 | 1.87 | 18.26 | 0.74 | 14.46 | 0.57 | 6.08 | 0.05 |
| 8B70 | 98.53 | 65.35 | 0.00 | 0.00 | 25.72 | 3.11 | 19.18 | 1.18 | 15.30 | 0.97 | 6.12 | 0.04 |
| 8C70 | 133.49 | 375.96 | 44.66 | 23.76 | 27.54 | 4.52 | 20.29 | 1.59 | 16.19 | 0.78 | 6.26 | 0.13 |
| 9A70 | 131.98 | 181.58 | 41.52 | 95.66 | 26.67 | 13.94 | 19.68 | 7.33 | 15.68 | 4.69 | 6.13 | 0.69 |
| 1A60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 201.83 | 44.83 |
| 1B60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 271.38 | 137.80 |
| 1C60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 17.10 | 43.62 | 11.52 | 26.54 | 176.80 | 83.73 |
| 1D60 | 0.00 | 0.00 | 21.79 | 36.07 | 20.12 | 10.36 | 15.62 | 3.55 | 9.59 | 6.11 | 130.45 | 53.97 |
| 1E60 | 26.81 | 121.96 | 28.04 | 22.90 | 20.19 | 7.44 | 15.88 | 3.13 | 9.58 | 7.61 | 135.31 | 64.95 |
| 2A60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 162.22 | 73.54 | 0.00 | 0.00 |
| 2B60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 174.75 | 67.15 | 0.00 | 0.00 |
| 2C60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 180.65 | 150.80 | 0.00 | 0.00 |
| 2D60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 10.39 | 42.15 | 170.93 | 67.12 | 0.00 | 0.00 |
| 2E60 | 0.00 | 0.00 | 17.04 | 53.36 | 20.78 | 19.74 | 11.33 | 18.59 | 158.49 | 59.92 | 13.07 | 99.11 |
| 2F60 | 28.45 | 183.20 | 28.00 | 35.37 | 20.29 | 10.43 | 12.25 | 15.28 | 159.98 | 50.38 | 21.31 | 63.53 |
| 3A60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 108.23 | 88.51 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3B60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 127.19 | 96.25 | 0.00 | 0.00 | 19.04 | 55.97 |
| 3C60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 162.36 | 54.59 | 0.00 | 0.00 | 23.57 | 56.45 |
| 3D60 | 0.00 | 0.00 | 9.07 | 59.65 | 14.84 | 33.57 | 164.69 | 43.77 | 0.00 | 0.00 | 26.74 | 19.73 |
| 3E60 | 0.00 | 0.00 | 23.65 | 25.15 | 14.28 | 25.97 | 173.28 | 54.61 | 28.84 | 123.48 | 29.82 | 11.06 |
| 4A60 | 0.00 | 0.00 | 0.00 | 0.00 | 117.20 | 41.80 | 16.74 | 125.57 | 22.54 | 13.12 | 18.58 | 3.75 |
| 4B60 | 0.00 | 0.00 | 0.00 | 0.00 | 159.92 | 75.36 | 0.00 | 0.00 | 28.37 | 20.04 | 20.38 | 5.22 |
| 4C60 | 0.00 | 0.00 | 13.85 | 26.12 | 166.91 | 82.47 | 33.84 | 26.31 | 30.72 | 35.79 | 21.74 | 5.54 |
| 4D60 | 24.57 | 17.43 | 13.86 | 54.87 | 158.41 | 61.40 | 34.07 | 139.50 | 32.27 | 16.62 | 22.60 | 5.31 |
| 5A60 | 0.00 | 0.00 | 75.27 | 493.99 | 0.00 | 0.00 | 22.54 | 71.04 | 19.08 | 12.59 | 14.97 | 7.18 |
| 5B60 | 0.00 | 0.00 | 135.03 | 540.75 | 0.00 | 0.00 | 29.03 | 25.25 | 21.10 | 2.93 | 16.54 | 1.28 |

*Table A.2.* (cont'd).

| Stand-type/ | Period 7 | | Period 8 | | Period 9 | | Period 10 | | Period 11 | | Period 12 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mgt. regime | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance |
| 7B70 | 17.88 | 2.68 | 142.92 | 49.69 | 25.36 | 84.27 | 32.07 | 9.42 | 22.28 | 3.62 | 17.28 | 1.30 |
| 7C70 | 16.49 | 3.13 | 135.78 | 142.73 | 31.50 | 103.26 | 24.31 | 5.00 | 18.29 | 1.84 | 14.42 | 0.98 |
| 7D70 | 17.05 | 0.63 | 140.74 | 41.45 | 36.53 | 16.75 | 24.79 | 1.35 | 18.60 | 0.52 | 14.73 | 0.54 |
| 7E70 | 17.71 | 2.74 | 149.35 | 270.03 | 41.40 | 74.07 | 26.47 | 9.51 | 19.48 | 2.13 | 15.05 | 3.23 |
| 8A70 | 16.48 | 1.56 | 136.32 | 94.71 | 0.00 | 0.00 | 24.23 | 1.87 | 18.26 | 0.74 | 14.46 | 0.57 |
| 8B70 | 17.64 | 1.72 | 145.31 | 97.84 | 0.00 | 0.00 | 25.72 | 3.11 | 19.18 | 1.18 | 15.30 | 0.97 |
| 8C70 | 18.92 | 2.04 | 153.93 | 68.59 | 44.66 | 23.76 | 27.54 | 4.52 | 20.29 | 1.59 | 16.19 | 0.78 |
| 9A70 | 18.22 | 7.57 | 149.26 | 257.59 | 41.52 | 95.66 | 26.67 | 13.94 | 19.68 | 7.33 | 15.68 | 4.69 |
| 1A60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 161.02 | 0.00 |
| 1B60 | 0.00 | 0.00 | 20.00 | 50.20 | 19.29 | 2.35 | 14.99 | 1.23 | 8.12 | 9.39 | 129.42 | 75.09 |
| 1C60 | 0.00 | 0.00 | 20.17 | 36.03 | 18.68 | 2.90 | 14.56 | 1.33 | 7.14 | 6.95 | 128.16 | 65.86 |
| 1D60 | 0.00 | 0.00 | 20.61 | 65.75 | 19.43 | 2.48 | 15.18 | 1.14 | 9.61 | 10.17 | 126.79 | 15.42 |
| 1E60 | 22.70 | 16.33 | 27.57 | 19.51 | 20.06 | 4.49 | 15.77 | 2.24 | 9.74 | 12.08 | 133.66 | 94.78 |
| 2A60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 161.00 | 0.02 | 0.00 | 0.00 |
| 2B60 | 18.04 | 57.13 | 19.41 | 2.56 | 15.02 | 1.16 | 8.62 | 10.51 | 127.83 | 8.69 | 0.00 | 0.00 |
| 2C60 | 19.92 | 48.09 | 18.82 | 2.55 | 14.71 | 1.14 | 8.29 | 10.54 | 125.76 | 9.69 | 0.00 | 0.00 |
| 2D60 | 20.02 | 63.34 | 19.37 | 2.11 | 15.11 | 0.97 | 9.48 | 10.14 | 126.35 | 10.21 | 0.00 | 0.00 |
| 2E60 | 21.99 | 55.91 | 19.19 | 2.99 | 15.08 | 1.46 | 8.93 | 10.73 | 128.43 | 58.90 | 13.07 | 199.11 |
| 2F60 | 27.28 | 39.21 | 20.16 | 4.38 | 15.77 | 1.74 | 9.96 | 10.58 | 133.56 | 135.00 | 21.31 | 153.42 |
| 3A60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 161.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3B60 | 19.22 | 2.85 | 14.96 | 1.30 | 8.30 | 10.05 | 128.36 | 29.01 | 0.00 | 0.00 | 19.04 | 55.97 |
| 3C60 | 19.42 | 3.68 | 15.30 | 1.74 | 9.49 | 11.03 | 129.10 | 73.05 | 0.00 | 0.00 | 23.57 | 56.45 |
| 3D60 | 19.69 | 2.86 | 15.55 | 1.53 | 9.41 | 10.61 | 132.96 | 118.44 | 0.00 | 0.00 | 26.74 | 19.73 |
| 3E60 | 21.14 | 3.47 | 16.57 | 1.48 | 10.87 | 10.71 | 138.73 | 102.82 | 28.84 | 167.85 | 29.82 | 11.06 |
| 4A60 | 14.60 | 2.00 | 9.05 | 11.37 | 132.80 | 90.29 | 19.10 | 125.57 | 24.81 | 13.12 | 20.07 | 3.75 |
| 4B60 | 16.05 | 2.33 | 10.01 | 12.06 | 135.70 | 129.26 | 0.00 | 0.00 | 28.37 | 20.04 | 20.38 | 5.22 |
| 4C60 | 16.69 | 2.05 | 10.14 | 16.22 | 143.01 | 142.23 | 33.84 | 26.31 | 30.72 | 35.79 | 21.74 | 5.54 |
| 4D60 | 17.52 | 1.79 | 11.76 | 11.55 | 145.00 | 117.52 | 34.07 | 139.50 | 32.27 | 16.62 | 22.60 | 5.31 |
| 5A60 | 8.74 | 12.79 | 131.73 | 101.80 | 0.00 | 0.00 | 23.25 | 60.46 | 19.60 | 4.12 | 15.36 | 1.96 |
| 5B60 | 10.83 | 9.62 | 138.69 | 147.03 | 0.00 | 0.00 | 29.03 | 25.25 | 21.10 | 2.93 | 16.54 | 1.28 |

*Table A.2.* (cont'd).

| Stand-type/ | Period 1 | | Period 2 | | Period 3 | | Period 4 | | Period 5 | | Period 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mgt. regime | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance |
| 7E60 | 112.62 | 221.16 | 27.72 | 166.33 | 32.74 | 19.38 | 22.56 | 4.92 | 17.31 | 1.15 | 13.48 | 1.35 |
| 8A60 | 67.63 | 357.46 | 0.00 | 0.00 | 29.84 | 2.59 | 20.81 | 1.33 | 16.39 | 0.50 | 12.70 | 0.21 |
| 8B60 | 98.53 | 65.35 | 0.00 | 0.00 | 31.66 | 4.97 | 22.05 | 2.13 | 17.14 | 0.79 | 13.15 | 0.29 |
| 8C60 | 133.49 | 375.96 | 31.83 | 43.28 | 34.01 | 7.73 | 23.52 | 2.76 | 18.03 | 0.97 | 13.74 | 0.55 |
| 5C60 | 0.00 | 0.00 | 138.13 | 735.30 | 0.00 | 0.00 | 31.26 | 16.63 | 21.76 | 6.45 | 16.95 | 2.45 |
| 6A60 | 62.99 | 137.93 | 0.00 | 0.00 | 23.94 | 48.13 | 19.32 | 2.84 | 15.22 | 1.41 | 9.45 | 10.99 |
| 6B60 | 123.22 | 507.99 | 28.19 | 157.90 | 33.32 | 14.78 | 22.95 | 4.63 | 17.59 | 1.49 | 13.27 | 2.01 |
| 6C60 | 106.90 | 362.20 | 25.85 | 161.50 | 32.60 | 13.77 | 22.51 | 4.54 | 17.34 | 1.47 | 13.16 | 1.63 |
| 7A60 | 54.61 | 124.31 | 0.00 | 0.00 | 29.65 | 3.22 | 20.64 | 1.69 | 16.28 | 0.64 | 12.61 | 0.29 |
| 7B60 | 98.06 | 336.34 | 25.36 | 84.27 | 32.07 | 9.42 | 22.28 | 3.62 | 17.28 | 1.30 | 13.29 | 0.59 |
| 7C60 | 55.55 | 130.34 | 15.59 | 120.87 | 29.96 | 7.80 | 20.84 | 3.21 | 16.40 | 1.16 | 12.74 | 0.62 |
| 7D60 | 86.32 | 20.97 | 20.74 | 31.55 | 30.43 | 2.25 | 21.27 | 0.96 | 16.67 | 0.36 | 12.91 | 0.10 |
| 9A60 | 90.45 | 106.70 | 15.97 | 207.87 | 30.44 | 9.70 | 21.11 | 4.37 | 16.56 | 1.61 | 12.77 | 0.77 |

*Table A.2.* (cont'd).

| Stand-type/ | Period 7 | | Period 8 | | Period 9 | | Period 10 | | Period 11 | | Period 12 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mgt. regime | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance | Mean | Variance |
| 7E60 | 138.92 | 75.35 | 27.72 | 166.33 | 32.74 | 19.38 | 22.56 | 4.92 | 17.31 | 1.15 | 13.48 | 1.35 |
| 8A60 | 131.34 | 31.44 | 0.00 | 0.00 | 29.84 | 2.59 | 20.81 | 1.33 | 16.39 | 0.50 | 12.70 | 0.21 |
| 8B60 | 137.08 | 42.74 | 0.00 | 0.00 | 31.66 | 4.97 | 22.05 | 2.13 | 17.14 | 0.79 | 13.15 | 0.29 |
| 8C60 | 143.26 | 41.68 | 31.83 | 43.28 | 34.01 | 7.73 | 23.52 | 2.76 | 18.03 | 0.97 | 13.74 | 0.55 |
| 9A60 | 132.29 | 90.33 | 15.97 | 207.87 | 30.44 | 9.70 | 21.11 | 4.37 | 16.56 | 1.61 | 12.77 | 0.77 |
| 5C60 | 12.31 | 6.03 | 137.60 | 166.07 | 0.00 | 0.00 | 31.26 | 16.63 | 21.76 | 6.45 | 16.95 | 2.45 |
| 6A60 | 128.73 | 35.89 | 0.00 | 0.00 | 23.94 | 48.13 | 19.32 | 2.84 | 15.22 | 1.41 | 12.67 | 0.21 |
| 6B60 | 140.52 | 79.67 | 28.19 | 157.90 | 33.32 | 14.78 | 22.95 | 4.63 | 17.59 | 1.49 | 13.27 | 2.01 |
| 6C60 | 138.67 | 80.92 | 25.85 | 161.50 | 32.60 | 13.77 | 22.51 | 4.54 | 17.34 | 1.47 | 13.16 | 1.63 |
| 7A60 | 130.44 | 40.94 | 0.00 | 0.00 | 29.65 | 3.22 | 20.64 | 1.69 | 16.28 | 0.64 | 12.61 | 0.29 |
| 7B60 | 137.91 | 62.33 | 25.36 | 84.27 | 32.07 | 9.42 | 22.28 | 3.62 | 17.28 | 1.30 | 13.29 | 0.59 |
| 7C60 | 131.23 | 59.58 | 15.59 | 120.87 | 29.96 | 7.80 | 20.84 | 3.21 | 16.40 | 1.16 | 12.74 | 0.62 |
| 7D60 | 133.70 | 19.69 | 20.74 | 31.55 | 30.43 | 2.25 | 21.27 | 0.96 | 16.67 | 0.36 | 12.91 | 0.10 |

# APPENDIX B:

## The Yield-Projection Computer Routine

Appendix B. The yield-projection computer routine.

Putera Parthama 5/10/94
A yield projection computer routine (written in QuickBASIC)
For predicting timber yield and NPV of teak stands

```
First Part
CLS

DIM A(10, 16), B(10, 2), D(10, 2), N(24), AA(10, 16), NR(24), NRN(24), BA(24), BAR(24)
DIM V(24), VT(24), H(24), NNorm(24), Age(24), Naver(10), AVD(24), Pr(24)
no = 1:Rot = 16: Harvage = 80:Q = 40000 / 3.141592654#

OPEN "c:\teak\comdat1.csv" FOR INPUT AS #1
OPEN "c:\teak\nrntab80.csv" FOR INPUT AS #2
OPEN "c:\teak\H-coef1.csv" FOR INPUT AS #5
OPEN "c:\teak\BA-coef.csv" FOR INPUT AS #8
OPEN "c:\teak\n-norm80.csv" FOR INPUT AS #7
OPEN "c:\teak\naverage.csv" FOR INPUT AS #10
OPEN "c:\teak\comres81.csv" FOR OUTPUT AS #3
OPEN "c:\teak\combin80.csv" FOR OUTPUT AS #20
OPEN "c:\teak\Price80.csv" FOR OUTPUT AS #22

FOR R = 1 TO 10
  FOR C = 1 TO Rot
    INPUT #2, A(R, C)
    INPUT #7, AA(R, C)
  NEXT C
NEXT R
CLOSE #2
CLOSE #7

FOR G = 1 TO 10
  INPUT #10, Naver(G)
NEXT G
CLOSE #10

FOR RR = 1 TO 10
  FOR CC = 1 TO 2
    INPUT #5, B(RR, CC)
    INPUT #8, D(RR, CC)
  NEXT CC
NEXT RR
CLOSE #5
CLOSE #8

DO

INPUT #1, no$, Stand$, Hectares, Initage, InitN, Bonita, InitH, InitBA
Row = Bonita * 2 - 1
FOR Col = 1 TO 16
  NRN(Col) = A(Row, Col): NNorm(Col) = AA(Row, Col)
NEXT Col
```

Appendix B. (cont'd).

```
Alpha = B(Row, 1): Beta = B(Row, 2): Alpha1 = D(Row, 1): Beta1 = D(Row, 2)
IF Initage > 80 THEN
   Projage = Initage: Period = 2:  Rot2 = 2: Period2 = 17: Rot3 = 18
ELSEIF Initage > 75 AND Initage <= 80 THEN
   Projage = 80: Period = 2:  Rot2 = 2: Period2 = 17: Rot3 = 18
ELSEIF Initage >= 1 AND Initage <= 75 THEN
   FOR I = 1 TO (Rot - 1)
      Upper = I * 5: Lower = Upper - 5
      IF Initage > Lower AND Initage <= Upper THEN
         Projage = Upper: Period = Rot + 1 - I: Rot2 = Period + 1: Per2 = Period + Rot
         IF Per2 < 24 THEN
            Period2 = Per2: Rot3 = Period2 + 1
         ELSEIF Per2 >= 24 THEN
            Period2 = 24: Rot3 = 24
         END IF
      END IF
   NEXT I
END IF

IF Projage > Harvage THEN
   K = Rot
ELSEIF Projage <= Harvage THEN
   K = Projage / 5
END IF
NormalN = NNorm(K)

IF InitH > 0 THEN
   InitH = InitH
ELSEIF InitH = 0 THEN
   InitH = EXP(Alpha + Beta * LOG(Initage))
END IF

IF InitBA > 0 THEN
   InitBA = InitBA
ELSEIF InitBA = 0 THEN
   Relba = InitN / NormalN: InitBA = Relba * (Alpha1 + Beta1 * LOG(Initage))
END IF

Agerat = Initage / Projage
N(1) = InitN
BA(1) = EXP(Agerat * LOG(InitBA) + 2.927 * (1 - Agerat) + .044 * (1 - Agerat) * InitH)
Envelope = EXP(.303 * (1 - Agerat) * InitH)
BAGrow = BA(1) - InitBA
IF BAGrow > Envelope THEN
   BA(1) = InitBA + Envelope
END IF

H(1) = EXP(2.575 - .143 * LOG(N(1) / Projage) + .341 * LOG(BA(1)))
V(1) = EXP(1.739 + .034 * LOG(InitH) + .952 * Agerat * LOG(InitBA) + 1.796 * (1 - Agerat) + .092 *
         (1 - Agerat)*InitH)
NR(1) = NRN(K)
AvBA = BA(1) / N(1)
AVD(1) = (Q * AvBA) ^ .5
IF AVD(1) >= 30 THEN
   Pr(1) = .53
```

Appendix B. (cont'd).

```
ELSEIF AVD(1) < 30 AND AVD(1) >= 20 THEN
  Pr(1) = .275
ELSEIF AVD(1) < 20 AND AVD(1) >= 4 THEN
  Pr(1) = .155
ELSEIF AVD(1) < 4 THEN
  Pr(1) = 0
END IF

IF Bonita > 2 THEN
  IF N(1) > 1.1 * NR(1) THEN
    Nrat = NR(1) / N(1):  BAR(1) = 1.074 * Nrat * BA(1):  VT(1) = V(1) - (1.048 * Nrat * V(1))
  ELSEIF N(1) <= 1.1 * NR(1) THEN
    BAR(1) = BA(1): VT(1) = 0
  END IF
ELSEIF Bonita <= 2 THEN
  BAR(1) = BA(1):  VT(1) = 0
END IF

FOR P = 2 TO Period
  IF Bonita > 2 THEN
    IF N(P - 1) > 1.1 * NR(P - 1) THEN
      N(P) = NR(P - 1):  BA(P - 1) = BAR(P - 1)
    ELSEIF N(P - 1) <= 1.1 * NR(P - 1) THEN
      N(P) = N(P - 1):  BA(P - 1) = BA(P - 1)
    END IF
  ELSEIF Bonita <= 2 THEN
    N(P) = N(P - 1):  BA(P - 1) = BA(P - 1)
  END IF

  Agerat = Projage / (Projage + 5)
  LnBA = Agerat * LOG(BA(P - 1)) + 2.927 * (1 - Agerat) + .044 * (1 - Agerat) * H(P - 1)
  BA(P) = EXP(LnBA)
  Envelope = EXP(.303 * (1 - Agerat) * H(P - 1))
  BAGrow = BA(P) - BA(P - 1)
  IF BAGrow > Envelope THEN
    BA(P) = BA(P - 1) + Envelope
  END IF

  H(P) = EXP(2.575 - .143 * LOG(N(P) / (Projage + 5)) + .341 * LOG(BA(P)))
  V(P) = EXP(1.739 + .034 * LOG(H(P - 1)) + .952 * Agerat * LOG(BA(P - 1)) + 1.796 * (1 - Agerat) + .092 * (1 -
         Agerat) * H(P - 1))

  IF (Projage + 5) > Harvage THEN
    K = Rot
  ELSEIF (Projage + 5) <= Harvage THEN
    K = (Projage + 5) / 5
  END IF

  NR(P) = NRN(K)
  AvBA = BA(P) / N(P)
  AVD(P) = (Q * AvBA) ^ .5
  IF AVD(P) >= 30 THEN
    Pr(P) = .53
  ELSEIF AVD(P) < 30 AND AVD(P) >= 20 THEN
    Pr(P) = .275
```

Appendix B. (cont'd).

```
  ELSEIF AVD(P) < 20 AND AVD(P) >= 4 THEN
    Pr(P) = .155
  ELSEIF AVD(P) < 4 THEN
    Pr(P) = 0
  END IF

 IF Bonita > 2 THEN
    IF N(P) > 1.1 * NR(P) THEN
      Nrat = NR(P) / N(P): BAR(P) = 1.074 * Nrat * BA(P):  VT(P) = V(P) - (1.048 * Nrat * V(P))
    ELSEIF N(P) <= 1.1 * NR(P) THEN
      BAR(P) = BA(P): VT(P) = 0
    END IF
 ELSEIF Bonita <= 2 THEN
    BAR(P) = BA(P): VT(P) = 0
 END IF
  Projage = Projage + 5
NEXT P

NormalN = NNorm(1)
Age(Rot2) = 5
N(Rot2) = Naver(Row)
NR(Rot2) = NRN(1)
H(Rot2) = EXP(Alpha + Beta * LOG(Age(Rot2)))
Relba = N(Rot2) / NormalN
BA(Rot2) = Relba * (Alpha1 + Beta1 * LOG(Age(Rot2)))
V(Rot2) = EXP(-1.4 + 1.248 * LOG(H(Rot2)) + .922 * LOG(BA(Rot2)))
AvBA = BA(Rot2) / N(Rot2)
AVD(Rot2) = (Q * AvBA) ^ .5
IF AVD(Rot2) >= 30 THEN
  Pr(Rot2) = .53
ELSEIF AVD(Rot2) < 30 AND AVD(Rot2) >= 20 THEN
  Pr(Rot2) = .275
ELSEIF AVD(Rot2) < 20 AND AVD(Rot2) >= 4 THEN
  Pr(Rot2) = .155
ELSEIF AVD(Rot2) < 4 THEN
  Pr(Rot2) = 0
END IF

IF Bonita > 2 THEN
  IF N(Rot2) > (1.1 * NR(Rot2)) THEN
    Nrat = NR(Rot2) / N(Rot2)
    BAR(Rot2) = 1.074 * Nrat * BA(Rot2)
    VT(Rot2) = V(Rot2) - (1.048 * Nrat * V(Rot2))
  ELSEIF N(Rot2) < (1.1 * NR(Rot2)) THEN
    BAR(Rot2) = BA(Rot2)
    VT(Rot2) = 0
  END IF
ELSEIF Bonita < 2 THEN
  BAR(Rot2) = BA(Rot2)
  VT(Rot2) = 0
END IF

M = 1
```

Appendix B. (cont'd).

```
FOR PP = (Rot2 + 1) TO Period2
  Age(PP) = 5 * M + 5:  Kol = Age(PP) / 5:  NR(PP) = NRN(Kol)
  IF Bonita > 2 THEN
    IF N(PP - 1) > (1.1 * NR(PP - 1)) THEN
      N(PP) = NR(PP - 1): BA(PP - 1) = BAR(PP - 1)
    ELSEIF N(PP - 1) < (1.1 * NR(PP - 1)) THEN
      N(PP) = N(PP - 1): BA(PP - 1) = BA(PP - 1)
    END IF
  ELSEIF Bonita <= 2 THEN
    N(PP) = N(PP - 1): BA(PP - 1) = BA(PP - 1)
  END IF

  Agerat = Age(PP - 1) / Age(PP)
  LnBA = Agerat * LOG(BA(PP - 1)) + 2.927 * (1 - Agerat) + .044 * (1 - Agerat) * H(PP - 1)
  BA(PP) = EXP(LnBA)
  Envelope = EXP(.303 * (1 - Agerat) * H(PP - 1))
  BAGrow = BA(PP) - BA(PP - 1)
  IF BAGrow > Envelope THEN
    BA(PP) = BA(PP - 1) + Envelope
  END IF

  H(PP) = EXP(2.575 - .143 * LOG(N(PP) / Age(PP)) + .341 * LOG(BA(PP)))
  V(PP) = EXP(1.739 + .034 * LOG(H(PP - 1)) + .952 * Agerat * LOG(BA(PP - 1)) + 1.796 * (1 - Agerat) + .092 *
        (1 - Agerat) * H(PP - 1))
  AvBA = BA(PP) / N(PP)
  AVD(PP) = (Q * AvBA) ^ .5
  IF AVD(PP) >= 30 THEN
    Pr(PP) = .53
  ELSEIF AVD(PP) < 30 AND AVD(PP) >= 20 THEN
    Pr(PP) = .275
  ELSEIF AVD(PP) < 20 AND AVD(PP) >= 4 THEN
    Pr(PP) = .155
  ELSEIF AVD(PP) < 4 THEN
    Pr(PP) = 0
  END IF

  IF Bonita > 2 THEN
    IF N(PP) > (1.1 * NR(PP)) THEN
      Nrat = NR(PP) / N(PP):  BAR(PP) = 1.074 * Nrat * BA(PP):  VT(PP) = V(PP) - (1.048 * Nrat * V(PP))
    ELSEIF N(PP) < (1.1 * NR(PP)) THEN
      VT(PP) = 0
      BAR(PP) = BA(PP)
    END IF
  ELSEIF Bonita <= 2 THEN
    VT(PP) = 0
    BAR(PP) = BA(PP)
  END IF
  M = M + 1
NEXT PP

IF Period2 < 24 THEN
  FOR PPP = Rot3 TO 24
    V(PPP) = V(PPP - Rot):  VT(PPP) = VT(PPP - Rot): Pr(PPP) = Pr(PPP - Rot)
  NEXT PPP
END IF
```

Appendix B. (con't).

```
PRINT "Stand No."; no
PRINT
PRINT no$; "   "; Stand$; USING "####.##"; V(1); VT(1); V(2); VT(2); V(3); VT(3); V(4); VT(4)
PRINT
PRINT
no = no + 1
PRINT #3, USING "\  \\      \#.# ###.# ##"; no$; Stand$; Bonita; Hectares; Initage;
FOR P = 1 TO 8
   PRINT #3, USING "####.## "; V(P); VT(P);
NEXT P
PRINT #3, ""
PRINT #20, USING "#.# ###.# ##"; Bonita; Hectares; Initage;
FOR P = 1 TO 24
   PRINT #20, USING "####.## "; V(P); VT(P);
NEXT P
PRINT #20, ""
PRINT #22, USING "#.# ###.# ##"; Bonita; Hectares; Initage;
FOR P = 1 TO 24
   PRINT #22, USING "####.## "; Pr(P);
NEXT P
PRINT #22, ""

LOOP WHILE NOT EOF(1)
END


Second Part
CLS

DIM V(48), VX(48), VT(48), VTX(48), X(51), Y(48), Pr(48), PrX(48)
DIM R(48), C(48), TCost(48), M3(24), Rp(24), t(24), PNV(24)
PCost = .19: GCost = .055: HCost = .022
Rot = 16: R = .09: NO = 0

OPEN "c:\teak\Combin80.csv" FOR INPUT AS #1
OPEN "c:\teak\Price80.csv" FOR INPUT AS #2
OPEN "c:\teak\Volume81.csv" FOR OUTPUT AS #3
OPEN "c:\teak\Volume83.csv" FOR OUTPUT AS #5
OPEN "c:\teak\Value81.csv" FOR OUTPUT AS #6
OPEN "c:\teak\Value83.csv" FOR OUTPUT AS #8

DO
TotPNV = 0
FOR I = 1 TO 51
   INPUT #1, X(I)
NEXT I

Bonita = X(1): Hectares = X(2): Initage = X(3)

FOR I = 2 TO 25
   VX(I - 1) = X(I * 2):  VTX(I - 1) = X(I * 2 + 1): VX(I + 23) = 0: VTX(I + 23) = 0
NEXT I
```

Appendix B. (cont'd).

```
FOR I = 1 TO 24
   INPUT #2, PrX(I): PrX(I + 24) = 0
NEXT I

FOR I = 1 TO 24
   V(I + 7) = VX(I): VT(I + 7) = VTX(I):  Pr(I + 7) = PrX(I)
NEXT I

FOR I = 1 TO 7
   V(I) = 0: VT(I) = 0: Pr(I) = 0
NEXT I
FOR I = 32 TO 48
   V(I) = 0: VT(I) = 0: Pr(I) = 0
NEXT I

FOR I = 1 TO 48
   IF VT(I) > 0 THEN
      TCost(I) = .065
   ELSEIF VT(I) = 0 THEN
      TCost(I) = 0
   END IF
NEXT I

IF Initage > 1 AND Initage <= 80 THEN
   FOR I = 1 TO Rot
      Up = I * 5:  Low = Up - 5
      IF Initage > Low AND Initage <= Up THEN
         Harv1 = Rot + 1 - I + 7   '7 is the trick to avoid neg. period
         A751 = Harv1 - 1:  A701 = Harv1 - 2:  A551 = Harv1 - 5
         A501 = Harv1 - 6:  A451 = Harv1 - 7
         Rot2 = Harv1 + 1
         Harv2 = Harv1 + Rot: A752 = A751 + Rot:  A702 = A701 + Rot
         A552 = A551 + Rot: A502 = A501 + Rot: A452 = A451 + Rot
         Rot3 = Harv2 + 1:  A453 = A452 + Rot
      END IF
   NEXT I

ELSEIF Initage > 80 THEN
   Low = Up - 5:  Harv1 = 1 + 7
   A751 = Harv1 - 1:  A701 = Harv1 - 2:  A551 = Harv1 - 5: A501 = Harv1 - 6:  A451 = Harv1 - 7
   Rot2 = Harv1 + 1:  Harv2 = Harv1 + Rot:  A752 = A751 + Rot:  A702 = A701 + Rot
   A552 = A551 + Rot:  A502 = A501 + Rot:  A452 = A451 + Rot:
   Rot3 = Harv2 + 1:  A453 = A452 + Rot
END IF

IF Bonita > 2 THEN
   FOR I = 1 TO A451
      Y(I) = VT(I): R(I) = Y(I) * Pr(I): C(I) = TCost
   NEXT I
   FOR I = A501 TO A701 STEP 2
      Y(I) = VT(I): R(I) = Y(I) * Pr(I): C(I) = TCost
   NEXT I
   FOR I = A551 TO A751 STEP 2
      Y(I) = 0: R(I) = 0:  C(I) = 0
```

Appendix B. (cont'd).

```
NEXT I
  Y(Harv1) = V(Harv1): R(Harv1) = Y(Harv1) * Pr(Harv1): C(Harv1) = GCost + CCost
  Y(Rot2) = VT(Rot2):  R(Rot2) = Y(Rot2) * Pr(Rot2): C(Rot2) = PCost + TCost
  FOR I = (Rot2 + 1) TO A452
    Y(I) = VT(I):  R(I) = Y(I) * Pr(I): C(I) = TCost
  NEXT I
  FOR I = A502 TO A702 STEP 2
    Y(I) = VT(I): R(I) = Y(I) * Pr(I): C(I) = TCost
  NEXT I
    FOR I = A552 TO A752 STEP 2
    Y(I) = 0: R(I) = 0: C(I) = 0
  NEXT I
  Y(Harv2) = V(Harv2):  R(Harv2) = Y(Harv2) * Pr(Harv2):  C(Harv2) = GCost + CCost
  Y(Rot3) = VT(Rot3):  R(Rot3) = Y(Rot3) * Pr(Rot3):  C(Rot3) = PCost + TCost
  FOR I = (Rot3 + 1) TO A453
    Y(I) = VT(I):  R(I) = Y(I) * Pr(I):  C(I) = TCost
  NEXT I

ELSEIF Bonita <= 2 THEN
  FOR I = 1 TO (Harv1 - 1)
    Y(I) = 0:  R(I) = 0:  C(I) = 0
  NEXT I
  Y(Harv1) = V(Harv1):  R(Harv1) = Y(Harv1) * Pr(Harv1):  C(Harv1) = GCost + CCost
  Y(Rot2) = 0: R(Rot2) = 0:  C(Rot2) = PCost
  FOR I = (Rot2 + 1) TO (Harv2 - 1)
    Y(I) = 0:  R(I) = 0:  C(I) = 0
  NEXT I
  Y(Harv2) = V(Harv2): R(Harv2) = Y(Harv2) * Pr(Harv2):  C(Harv2) = GCost + CCost
  Y(Rot3) = 0:  R(Rot3) = 0:  C(Rot3) = PCost
  FOR I = (Rot3 + 1) TO A453
    Y(I) = 0:  R(I) = 0:  C(I) = 0
  NEXT I
END IF

IF Initage > 1 AND Initage <= 15 THEN
  RemV = V(24) - VT(24):  RemVal = RemV * Pr(24)
ELSEIF Initage > 15 AND Initage <= 20 THEN
  RemV = V(24):   RemVal = V(24) * Pr(24)
ELSEIF Initage > 20 AND Initage <= 25 THEN
  RemV = V(24) - VT(24):  RemVal = RemV * Pr(24)
ELSEIF Initage > 25 AND Initage <= 30 THEN
  RemV = V(24):  RemVal = V(24) * Pr(24)
ELSEIF Initage > 30 AND Initage <= 35 THEN
  RemV = V(24) - VT(24):  RemVal = RemV * Pr(24)
ELSEIF Initage > 35 AND Initage <= 40 THEN
  RemV = V(24):  RemVal = V(24) * Pr(24)
ELSEIF Initage > 40 AND Initage <= 45 THEN
  RemV = 0:  RemVal = 0
ELSEIF Initage > 45 THEN
  RemV = V(24) - VT(24):  RemVal = RemV * Pr(24)
END IF

FOR I = 1 TO 24
  M3(I) = Y(I + 7): Rp(I) = R(I + 7) - C(I + 7): t(I) = 5 * I:  PNV(I) = Rp(I) / ((1 + R) ^ t(I))
```

Appendix B. (cont'd).

```
 TotPNV = TotPNV + PNV(I)
NEXT I

PRINT #3, USING "#.# ###.# ##"; Bonita; Hectares; Initage;
FOR P = 1 TO 12
   PRINT #3, USING "####.##"; M3(P);
NEXT P
PRINT #3, ""
FOR P = 13 TO 24
   PRINT #5, USING "####.##"; M3(P);
NEXT P
PRINT #5, RemV
PRINT #6, USING "#.# ###.# ##"; Bonita; Hectares; Initage;
FOR P = 1 TO 12
   PRINT #6, USING "####.##"; Rp(P);
NEXT P
PRINT #6, ""
FOR P = 13 TO 24
   PRINT #8, USING "####.##"; Rp(P);
NEXT P
PRINT #8, USING "####.## ####.###"; RemVal; TotPNV
NO = NO + 1
PRINT NO
FOR P = 13 TO 18
   PRINT USING "####.##"; Rp(P);
NEXT P
PRINT USING "####.##  ####.###"; RemVal; TotPNV

LOOP WHILE NOT EOF(1)
END
```

# APPENDIX C:

# The CCP SOLVER Spreadsheet

Appendix C. The CCP SOLVER spreadsheet.

The CCP SOLVER spreadsheet is structured as shown in Figure 6.2. It can be partitioned into several sections.

*Section I*: model inputs.

| | |
|---|---|
| Column A: | decision-variable coefficients $c_{ij}$. |
| Column B: | total hectares available for each stand-type (the right-hand-sides $L_i$ of the land-area constraints). |
| Cells C1, C2, C3: | respectively, parametersβ, $u$, and $l$. |
| Columns D to O: | per-hectare yield $a_{ijt}$. |
| Columns P to AA: | Var($a_{ijt}$). |

*Section II*: objective function, land-area constraints, and periodic harvest volumes.

| | |
|---|---|
| Column AB: | decision variables $x_{ij}$ (i.e., hectares of stand-type $i$ allocated to management regime or rotation-age $j$). |
| Cell AB106: | sum of cells AB1 to AB105 (i.e., the total hectares of all stand-types allocated across the rotation-age alternatives). |
| Column AC: | objective-function components $c_{ij}x_{ij}$. |
| Cell AC106: | sum of cells AC1 to AC105, the objective function. |
| Column AD: | total hectares of stand type $i$ allocated to rotation-age $j$. Since there are 35 stand-types and three rotation-ages, the first 35 cells of column AB contain hectares of stand-type $i$ ($i$ = 1, 2 ... 35) allocated to rotation-age $j$ = 1 (i.e., 60 years). Likewise, the next 35 cells are for those allocated to rotation-age $j$ = 2 or 70 years), and the last 35 cells are for those allocated to rotation-age $j$ = 3 or 80 years. Hence, values contained in column AD (total hectares of stand type $i$ allocated to rotation-age $j$) are give by AB($i$) + AB($i$+35) + AB($i$ +70) for $i$ = 1,2..., 35. |

Appendix C. (cont'd)

Columns AE to AP: $a_{ijt}x_{ij}$, (total yield produced in period $t$ (t = 1, ... ,12)) from stand-type $i$ under rotation-age $j$. Cells in row 106 contain the sums of their respective columns indicating total periodic harvest volumes of the corresponding period. Thus, cell AE106 is the sum of cells AE1 to AE105; the total harvest volume in period 1.

*Section III*: chance-constraint components.

Columns AQ to BB: $\mathrm{Var}(a_{ijt})\,x_{ij}^2$.

Columns BC to BM: $(1+u)a_{ijt}x_{ij} - a_{ij(t+1)}x_{ij}$

Columns BN to BX: $\mathrm{Var}((1+u)a_{ijt} - a_{ij(t+1)})x_{ij}^2$

Columns BY to CJ: $(1-l)a_{ijt}x_{ij} - a_{ij(t+1)}x_{ij}^2$

Columns CK to CV: $\mathrm{Var}((1-l)a_{ijt} - a_{ij(t+1)})x_{ij}^2$

Column totals are located in row 106. Thus,

$\Sigma$ [$\mathrm{Var}(a_{ijt})\,x_{ij}^2$)] ( $t$ = 1,...,12) are contained in cells AQ106 to BB106. Likewise,

$\Sigma$ [$(1+u)a_{ijt}x_{ij} - a_{ij(t+1)}x_{ij}$ ] ($t$ = 1, ...,12) are in cells BC106 to BN106,

$\Sigma$ [$\mathrm{Var}((1+u)a_{ijt} - a_{ij(t+1)})x_{ij}^2$] ($t$ = 1,...,12) are in cells BO106 to BZ106,

$\Sigma$ [$(1-l)a_{ijt}x_{ij} - a_{ij(t+1)}x_{ij}^2$] (t = 1,... ,12) are in cells CA106 to CL106, and

$\Sigma$ [$\mathrm{Var}((1-l)a_{ijt} - a_{ij(t+1)})x_{ij}^2$ ] (t = 1,... ,12) are in cells CM106 to CX106.

These column totals are used to form the left-hand-sides (LHS) of chance constraints 6.7 ... 6.10. First, the quantity $\beta(K(x^2))^{.5}$ — in which K = $\mathrm{Var}(a_{ijt})$ or $\mathrm{Var}((1+u)a_{ijt} - a_{ij(t+1)})$ or $\mathrm{Var}((1-l)a_{ijt} - a_{ij(t+1)})$ — are computed in row 107. LHS of constraints are given in row 108 and 109. For $t$ = 1, the LHSs of constraints 6.7 ... 6.10 are, respectively, given by:

AE108 - AQ108,

AE109 + AQ109,

BC108 - BO108, and

Appendix C. (cont'd)

BY108 + CK 108.

The CCP now can be expressed as follow:

| | |
|---|---|
| Maximize cell: | AC106 |
| By changing cells: | AB1:AB105 |
| Subject to constraints: | AB1:AB105 ≥ 0 (non-negative constraints) |
| | AD1:AD35 ≤ B1:B35 (area constraints) |
| | AQ108 ≥ 0 (constraint 6.7) |
| | AQ109 ≤ 0 (constraint 6.8) |
| | BO108:BX108 ≥ 0 (set of constraints 6.9) |
| | CK108:CV108 ≤ 0 (set of constraints 6.10). |

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