COMPARISON OF INVENTORY METHODS FOR TEAK PLANTATIONS AT THREE FOREST MANAGEMENT AREAS IN EAST JAVA, INDONESIA

By

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CHAPTER I

INTRODUCTION

Basic Idea

Several sample methods have been developed to estimate volumes and density (the number of trees per unit area) for forest inventories. Among these methods are fixed-radius circular plot sampling, point sampling and m-tree sampling. Fixed-radius circular plot sampling selects sample trees located within a fixed radius of the plot center. Point sampling selects sample trees that subtend (that is, their diameters are larger than) an angle of fixed magnitude whose vertex is a fixed point on the ground. M-tree sampling selects the m trees closest to a sample point on the ground. For example, 4-tree sampling selects the four trees closest to a fixed point or plot center on the ground. In m-tree sampling, the distance from the plot center to center of the tree which is farthest of m closest to the plot center (the m^{th} tree) is used as a plot radius to expand the sample to a unit area or forest level. Though the first method has long been implemented to inventory plantation forests in Java, the second and the third methods have rarely been applied in those areas.

In Java, Indonesia, plantation forests have been managed by Perum Perhutani (the state owned forest enterprise) since 1945. Fixed-radius circular plot sampling has been implemented to estimate volume and density of plantation forests of teak (Tectona grandis) since the early 1900's when Indonesia was being colonized by the Dutch. Although point sampling and m-tree sampling were proposed and developed for estimating volume and density of forest areas, fixed-radius circular plot sampling is still used exclusively in forest inventories of teak forests in Java, Indonesia.

Previous studies comparing point sampling to fixed-radius circular plot sampling have been conducted by Grosenbaugh and Stover (1957), Afanasiev (1958), Sukwong et al. (1971), Matérn (1972), and Oderwald (1981) in the United States. These studies generally indicated that point sampling could perform acceptably well compared to fixed-radius circular plot sampling in terms of variance, especially for basal area and volume estimation.

Studies comparing m-tree sampling with fixed-radius circular plot sampling have been conducted by Prodan (1968) in West Germany, Rusydi (1982) in Indonesia, Payandeh and Ek (1986) in Canada, Jonsson et al. (1992) in Sweden, Lessard et al. (1994a), and Lessard et al. (1994b) in the United States. These studies showed that m-tree sampling was competitive in terms of efficiency compared to fixed-radius circular plot sampling for estimating tree volume and density of the forest areas studied.

On the basis of the results of the studies mentioned above, point sampling and m-tree sampling showed promise for use in forest inventory. Successful applications of point sampling and m-tree sampling in several forest types suggested the potential utility of these methods for inventories of teak plantations in Java, Indonesia, in which fixed-radius circular plot sampling is still exclusively used .

Objective

In order to select an appropriate method for use in forest inventories of Javanese teak forests, efficiency in terms of practicality, economy and accuracy of inventory methods needs to be evaluated. Practicality and economy of the methods are reflected by the time and expense required for application of the methods. The accuracy is determined by the error of estimation associated with each method in conducting forest inventories. The error, time and the expense of each sample method are important since a sample method should make forest inventories more practical and economical without sacrificing accuracy. Very few, if any, studies comparing the efficiency of fixed-radius circular plot sampling to other sample methods have been conducted on mature teak plantations in Java, Indonesia. Hence, the objective of this study is to compare the relative efficiency of point sampling, m-tree sampling and fixed-radius circular plot sampling, using fixed-radius circular plot sampling as the standard of the comparison, for estimating the volume and density of mature teak plantations at three management areas of Perum Perhutani, East Java, Indonesia. In this way, the most efficient method in estimating volume and density of those forests can be ascertained.

Definitions

The following definitions will be used consistently through out the rest of this study:

1. KPH is a unit of forest management having a certain forest area ranging from 10,000 to 50,000 hectares that is managed by Perum Perhutani,

2. Perum Perhutani is the state-owned forest enterprise of Indonesia that manages plantation forests in Java,
3. Bonita is a type of a land fertility class according to the forest soil classification system used in Java,
4. Diameter (cm) will refer to the diameter of a circular cross-section of a tree bole at breast height (1.3 m),
5. Basal area (m^2) refers to the cross-sectional area of the tree stem at breast height (1.3 meters),
6. Tariff refers to a type of domestic volume table developed by Perum Perhutani used to convert the tree circumference or diameter to the tree volume in a certain forest area,
7. Age class (years) refers to the midpoint of a 10-year age classification for trees in teak forests,
8. The population means of interest are volume per hectare (V/ha) and density (the number) of trees per hectare (trees/ha) for the total forest areas considered in the study, and
9. The unit of measurement for the volume of the trees per hectare is m^3/ha (cubic meter per hectare; 1 hectare = 2.54 acres) and the unit of measurement for the density of the trees per hectare is trees/ha (trees per hectare).

CHAPTER II

REVIEW OF LITERATURE

Three Types of Sample Methods and their Application

Selection of sample units from forested areas has long been recognized as a means to gather data used in estimating yield potential of these areas. Fixed-radius circular plot sampling, point sampling and m-tree sampling are three types of sample methods which have been used in forest inventory. These sample methods have been applied in different countries. Associated with each method are different procedures for collecting data used to estimate volume and the density (number) of trees in forest areas. To decide which one of those sample methods should be implemented in certain forest stands, research which compares the advantages and disadvantages of each method is needed for forest inventory (Rusydi 1982).

Fixed-radius circular plot sampling

A fixed-radius circular plot is a type of sample unit that is limited by circumference with a certain radius as the distance between the center and the border of that plot. Trees contained in the plot are measured by using conventional tree measurement techniques (Loetsch et al. 1978). In teak plantation forests that have been managed in Java, this method is frequently used because applications of alternative methods have not been supported by comprehensive results of research for all age classes required.

To inventory teak plantations in this region, the locations of fixed-radius circular plot samples are selected systematically with a random start. The distance between the center of a sampling location and the following sampling location (the closest sampling location) is 200 meters. Plot volumes are determined by summing the volumes of all trees in each plot. Tree volumes are calculated by measurement of circumference and reference to a tariff or local volume table. Area and intensity of the plot are established according to age classes of the forest stands as shown by Table 1 (Perum Perhutani 1979).

Table 1. Area and intensity of fixed-radius circular plot sampling according to age classes of teak plantation forests of Perum Perhutani in Java, Indonesia.

Age classes	Fixed-radius circular plot		Intensity (%)
	Area/size (hectares)	Radii (meters)	
I - II	0.02	7.94	0.5
III - IV	0.04	11.28	1.0
V and greater	0.10	17.84	2.5

The volume of forest stands per hectare for each sample plot is estimated by using the following procedures (Perum Perhutani 1979):

$$Y_i = \frac{\Sigma V_j}{L_i}$$

where: j = an index for individual tree number on the plot,

V_j = the volume of the j^{th} tree in the plot,

L_i = the area of the i^{th} plot in hectares,

i = an index for the sample plot in a population, and

Y_i = volume per hectare of the i^{th} sample plot.

Further, when n_h fixed-radius circular plot samples are selected randomly or systematically with random start from a certain forest area (or a stratum), the volume per hectare of the forest is estimated through the following formula (Loetsch et al. 1978):

$$Y_h = \frac{\Sigma Y_i}{n_h}$$

where: Y_h = the volume per hectare of the h^{th} stratum,

Y_i = the volume per hectare of the i^{th} sample plot in that stratum,

i = 1, 2, 3, ..., n_h, and

n_h = the number of sample plots observed in the h^{th} stratum.

The density (number) of trees of forest stands per hectare based on a fixed-radius circular plot sampling is estimated by the following formula (Perum Perhutani 1979) :

$$Z_i = T_i/L_i$$

where: L_i = the area of the i^{th} fixed-radius plot sample in hectares,

T_i = the density (number) of trees in the i^{th} plot sample,

i = an index for the sample plot in a population, and

Z_i = the density (number) of trees per hectare, based on the i^{th} plot.

When n_h fixed-radius circular plot samples are located randomly or systematically with random start in a certain forest area, the density (number) of trees of forest stands per hectare (ha) is estimated by using the following formula (Perum Perhutani 1979):

$$Z_h = \frac{\Sigma Z_i}{n_h}$$

where: Z_i = the density of trees per hectare based on the i^{th} fixed-radius circular plot,

Z_h = the density of trees per hectare in the h^{th} stratum,

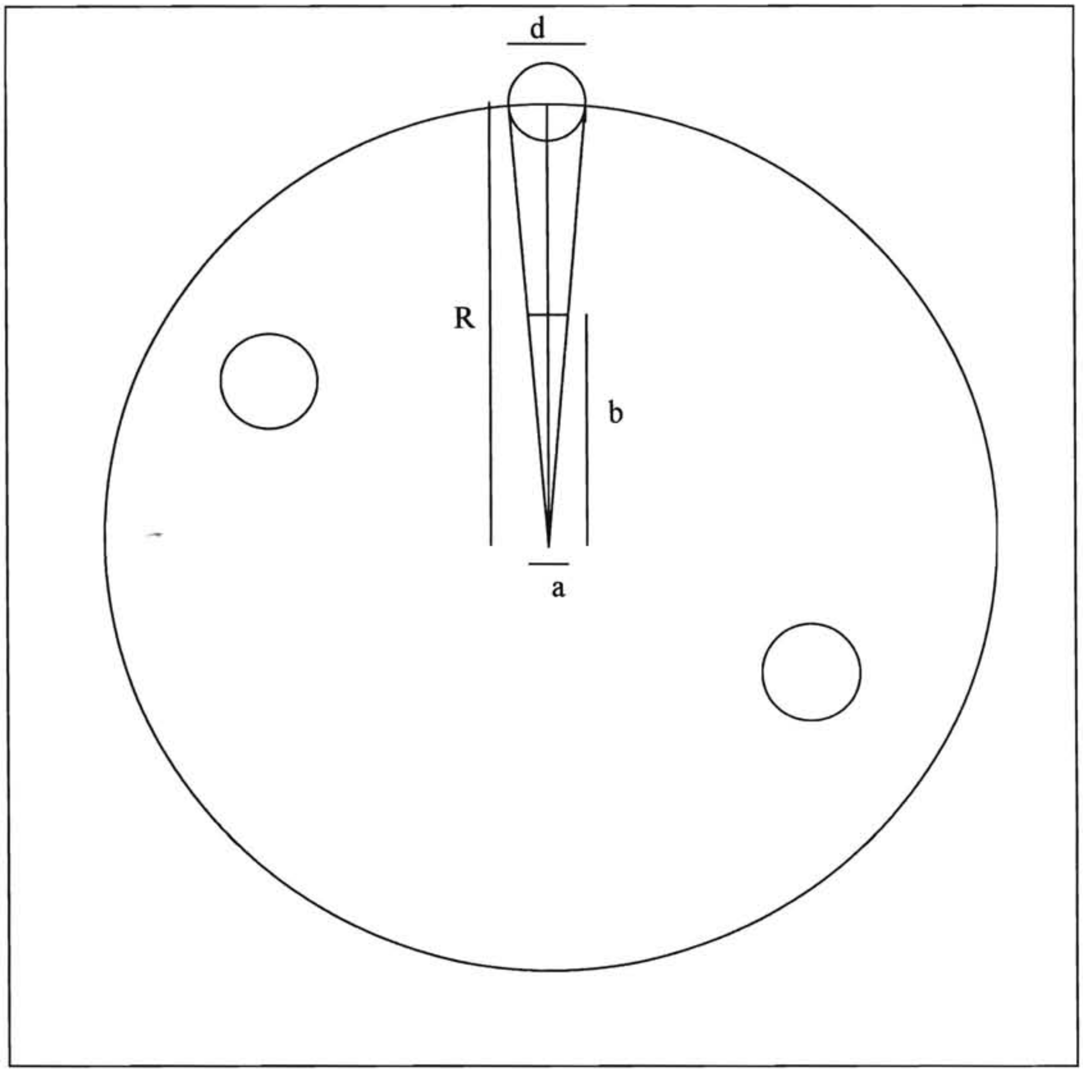
n_h = the sample size or the number of sample plots in that stratum, and

i = 1, 2, 3, ..., n_h.

Point sampling

Point sampling is also called the Bitterlich method based on the results of his research conducted in 1931 (Bitterlich 1947, Soekiman 1954). The basic idea of this method is practical and ingenious because this method eliminates diameter measurements for basal area estimation and plot boundary establishment, so that it is also called inventory design without sample plot.

The basal area of forest stands is measured at breast height with a Bitterlich stick or spiegel relascope which projects an angle to the trees around the position of the measurement center. A tree that has the same width or wider than the view target of the instrument is determined as a tally tree. A tree that has less width than that is not included in the sample. The sum of trees selected is multiplied by basal area factor of the instrument, in order to obtain basal area per hectare of the forest stand. The concept of this method is based on Figure 1.



a = the width of the view target of Bitterlich stick or spiegel relascope,
b = the length of Bitterlich stick (the distance between the eye of user and view target of the Bitterlich Stick),
d = the diameter of the k^{th} tree (at breast height = 1.3 meters) in centimeters,
R= the distance between the measurement position and the center of the circular cross-section of the k^{th} tree bole, or, the radius of imaginary circle.

Figure 1. The measurement according to the Bitterlich method to the k^{th} tree in order to obtain basal area of a certain forest area.

Suppose the measurement is focused on one tree (tree k) among the trees measured in a sampling location in the forest (Figure 1). It can be stated that:

$a/b = d/R$

where: a = the width of the view target of Bitterlich stick or spiegel relascope,

b = the length of Bitterlich stick (the distance between the eye of user and view target of the Bitterlich stick),

d = the diameter of the k^{th} tree (at breast height = 1.3 meters) in centimeters, and

R = the distance between the measurement position and the center of the circular cross-section of the k^{th} tree bole, or radius of imaginary circle in meters.

Then: $R = (b \times d) / a$.

The area of imaginary circle (point sample area) is: $\pi R^2 = \pi (b \times d)^2/a^2$.

The basal area of the k^{th} tree is: $\pi d^2 /4$.

The ratio between the basal area of the k^{th} tree and the area of imaginary circle (point sample area) is:

$$\frac{\pi d^2 /4}{\pi (b \times d)^2 /a^2} = a^2 /4b^2.$$

Since there are some trees to be measured in the forest stand with various basal areas in every imaginary circle, then the sum of basal areas of the trees per unit of ground area according to their diameter will be:

$G_1 = n_1 \times (a^2/4b^2)$

$G_2 = n_2 \times (a^2/4b^2)$

$G_3 = n_3 \times (a^2/4b^2)$

$\vdots \quad \vdots \quad \vdots$

$G_k = n_k \times (a^2/4b^2)$

where: $n_1, n_2, n_3, \ldots\ldots, n_k$ are the numbers of trees having the same measured diameter indicated by 1, 2, 3, ..., k.

When the ground area and basal area are measured in the same units, the total basal area per unit of ground area is:

$G = G_1 + G_2 + G_3 + \ldots\ldots\ldots + G_k = (n_1 + n_2 + n_3 + \ldots\ldots\ldots\ldots\ldots + n_k)(a^2/4b^2).$

When the units of the basal area are square meters per hectare, the conversion factor 10^4 (the number of square meters per hectare) must be used in the basal area estimation formula as follows:

$G = (n_1 + n_2 + n_3 + \ldots\ldots\ldots\ldots\ldots\ldots + n_k)\ 10^4 \times (a^2/4b^2).$

When it is noted $N = n_1 + n_2 + n_3 + \ldots\ldots\ldots\ldots\ldots + n_k$, then the formula becomes:

$G = N \times 10^4 \times a^2/4b^2 = N \times 2500 \times a^2/b^2.$

Since $2500 \times (a^2/b^2)$ is constant, it is called the basal area factor (BAF). The formula can be expressed as follows:

$G = N \times BAF$

where: G = basal area of forest stands per hectare,

N = the number of trees selected by the projection of the Bitterlich stick, and

BAF = the basal area factor of the Bitterlich stick or spiegel relascope.

When one point sample is used to measure a certain forest, the density (number) of trees per hectare based on that point is estimated by the following procedure (Avery and Burkhart 1994):

$$Z_i = \sum_{j=1}^{k} \frac{BAF}{b_{ij}}$$

where: Z_i = the number of trees per hectare based on the i^{th} point sample,

b_{ij} = basal area of tree j accounted at the i^{th} point sample,

i = an index for point sample number in a population,

j = 1, 2, ..., k,

k = the number of trees tallied at the i^{th} point sample, and

BAF = basal area factor of the Bitterlich stick or spiegel relascope.

If n_h point samples are selected randomly or systematically with random start from a certain forest area or a stratum, then the density (number) of trees per hectare is determined by the formula (Avery and Burkhart 1994):

$$Z_h = \frac{\Sigma Z_i}{n_h}$$

where: Z_i = the density of trees per hectare based on the i^{th} point sample,

Z_h = the density of trees per hectare of the h^{th} stratum,

i = 1, 2, 3, ..., n_h, and

n_h = the sample size of point samples observed in that forest.

The volume per hectare of the forest based on one point sample is estimated by the following formula (Avery and Burkhart 1994) :

$$Y_i = \sum_{j=1}^{k} \frac{BAF \times v_{ij}}{b_{ij}}$$

where: Y_i = the volume per hectare based on the i^{th} point sample,

v_{ij} = the volume of tree j accounted at the i^{th} point sample,

b_{ij} = the basal area of tree j accounted at the i^{th} point sample,

j = 1, 2, ..., k,

k = the number of trees tallied at the i^{th} point sample,

i = an index for point sample number in a population, and

BAF = the basal area factor of the Bitterlich stick or spiegel relascope.

If there are n_h point samples located randomly or systematically with random start in a certain forest stand or a stratum, the volume per hectare of the forest area will be (Avery and Burkhart 1994):

$$Y_h = \frac{\Sigma Y_i}{n_h}$$

where: Y_h = the volume per hectare of the forest or the h^{th} stratum,

Y_i = the volume per hectare based on the i^{th} point sample,

i = 1, 2, 3, ..., n_h, and

n_h = the sample size or number of point samples observed in that area.

To evaluate this method, several studies have been performed in the U.S and Europe. Grosenbaugh and Stover (1957) conducted extensive field trials in which point sampling was compared to fixed-radius circular plot sampling in the context of the U.S. Forest Service Forest Survey. Point samples and fixed-radius plot samples were located in 12 counties in southeast Texas. From the center of each of more than 600 fixed-radius circular plot samples, point samples were conducted by selecting trees with an angle gauge so that comparisons could be made. Estimates obtained from point sampling were not significantly different than those obtained from fixed-radius circular plot sampling. Though the study indicated that 20% more points would be needed to achieve an accuracy equal to that obtained by the fixed-radius circular plot sampling, the time required for point sampling was much less. For this reason, Grosenbaugh and Stover (1957) concluded that point sampling would often be more efficient than fixed-radius circular plot sampling. Afanasiev (1958) conducted another field trial in an even-aged longleaf pine (Pinus palustris) stand in southern Mississippi. The estimated results from fixed-radius circular plot sampling and point sampling were compared to the results of 100% inventory (census of the forest population). Afanasiev also found that the results obtained from point sampling compared favorably with those obtained from fixed-radius circular plot sampling. However, point sampling was not as time consuming as fixed-radius circular plot sampling.

Sukwong et al. (1971) compared point sampling to fixed-radius circular plot sampling by using computer simulation. Assumptions concerning forest tree diameter distributions and spatial distributions were made in order to perform the study. Both random and clumped spatial distributions were considered, but square lattice spatial distributions were not considered. Generally, their results indicated that point sampling was more efficient for estimating basal area of trees per unit area than fixed-radius circular plot sampling. The estimation of volume per unit area was not considered explicitly in these simulations, but the authors speculated that comparisons for volume estimation might be expected to roughly parallel their results for estimation of basal area of trees per unit area for the forest types considered in their study.

Probability theory was used by several researchers to compare point sampling with fixed-radius circular plot sampling. Holgate (1967) demonstrated that point sampling would estimate basal area of trees per unit area more precisely than fixed-radius circular plot sampling in forests that have a random spatial pattern. Matérn (1972) found that point sampling gave a basal area per unit area estimate that was more precise than fixed-radius circular plot sampling in forests having either random or clumped spatial pattern. Oderwald (1981) showed that though the point sampling basal area per unit area estimate was more precise than that of fixed-radius circular plot sampling in forests having clumped or random spatial distributions, plot sampling was more efficient for forests having square lattice spatial distributions.

M-Tree Sampling

According to Loetsch et al. (1978), this method was reported by Konig and US Federal Surveyors in 1935 and Prodan (1968) further developed this method to estimate volumes and the number of trees of forest areas in Germany (Prodan 1968, Loetsch et al. 1978). The trees measured at every sample location are the m closest trees from the center of every sample location. Unlike fixed-radius circular plot sampling, m-tree sampling has variable radii which are determined as the distance between the center of the sample location and the farthest tree among the m closest trees from that center plus a half diameter of that farthest tree.

Suppose a 6-tree sampling method is used to inventory a given forest area, then the application of this method is illustrated by Figure 2. To inventory a given area, six trees which are closest to the center of the 6-tree sample plot are measured. The 6th tree (the furthest among the six closest trees from the center of the sample unit) is obvious. Then, the distance between this tree (the 6th tree) and the center of the 6-tree sample plot is measured in addition to measuring diameter at breast height and any other parameters required. The area of this sample plot is determined by the formula:

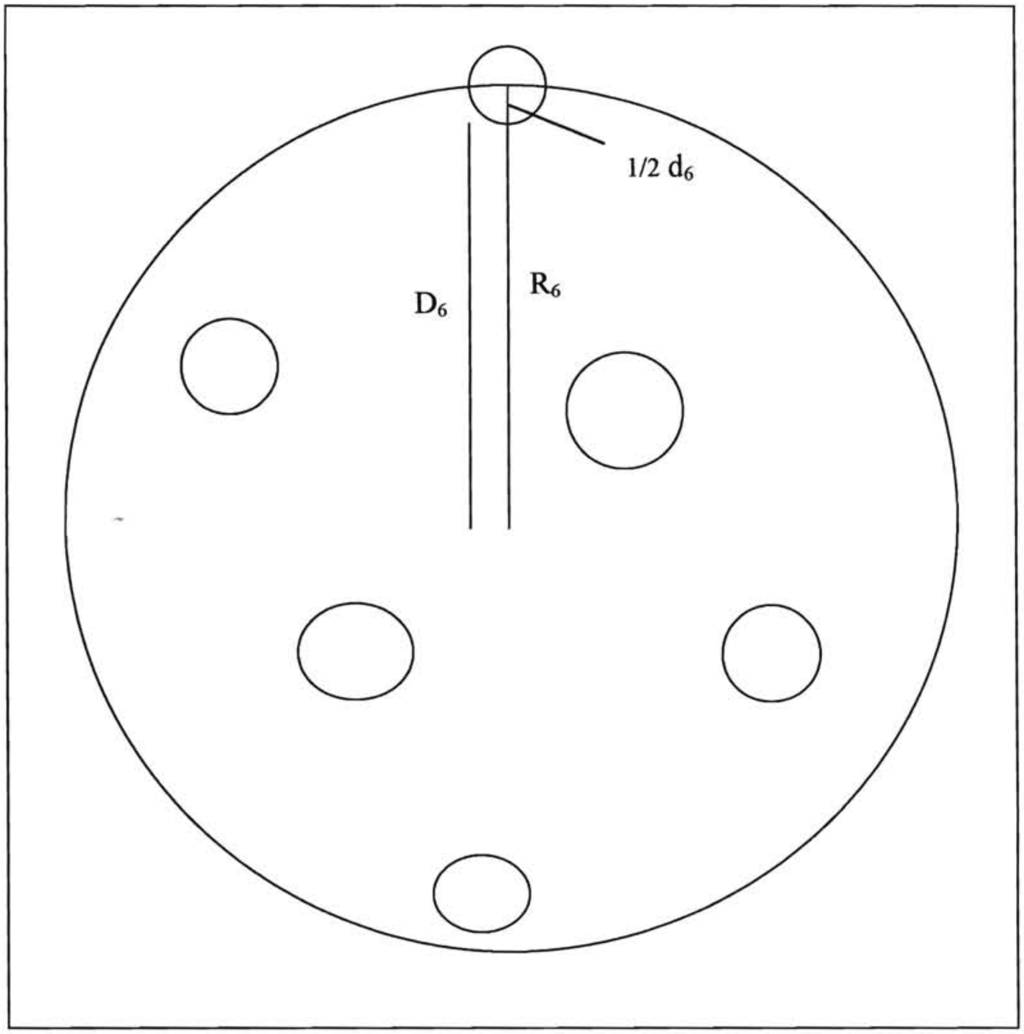
$L = \pi (R_6)^2$

where: $R_6 = a_6 + 1/2 \times (d_6)$,

a_6 = the distance between the inside edge of 6th tree (the furthest) and the center of the sample, and

d_6 = the diameter of the 6th tree.

There are two ways to estimate the volume of trees of the forest stand (Figure 2). First, the estimated volume of trees is based on the trees included in the area of the m-tree sample plot, in which the volume of the trees per plot is determined by adding a half of the volume of the farthest tree to volumes of all other trees in the plot. Second, the estimated volume of the trees for every plot is ascertained by multiplying the total volumes of all (m)



d_6 = the diameter of the 6th tree,
D_6 = the distance between the inside edge of the 6th tree (the furthest) and the center of the sample,
R6 = the radius of the sample.

Figure 2. Determination of radius, sample area and trees included in a 6-tree sampling method.

trees considered in the plot by a correction factor. These procedures are also used analogically to estimate density (the number) of trees of the forest stand.

Method 1.

Sutarahardja (1976) estimated the volume of a m-tree sample as $\Sigma v_i = v_1 + v_2 + \ldots + (1/2 \times v_m)$. The volume per hectare of the forest based on one sample of m-tree sampling method is determined by the following formula:

$$Y_i = \frac{\Sigma v_{ij}}{L_i}$$

where: Y_i = the volume per hectare of the forest based on the i^{th} sample location,

Σv_{ij} = $v_1 + v_2 + \ldots + (1/2 \times v_m)$ or the total volume of the trees included in the i^{th} sample location,

L_i = the area of the i^{th} sample location,

i = an index for sample location number observed in a population,

j = 1, 2, ...,m, and

m = an index for individual tree number tallied in the i^{th} sample location.

When n_h m-tree samples are selected randomly or systematically with random start from a certain forest or a stratum, then the volume of trees per hectare of that area is estimated by the formula:

$$Y_h = \frac{\Sigma Y_i}{n_h}$$

where: Y_h = volume per hectare of the h^{th} stratum or the forest,

Y_i = volume per hectare based on the i^{th} sample location,

i = 1, 2, 3, ..., n_h, and

n_h = the number of sample locations observed in the h^{th} stratum.

The density (number) of trees according to the Figure 2 for a 6-tree sample is 5.5 trees. It means that there are 5.5 trees in the area $L = 1/4 \times \pi R^2 \times 10^{-4}$ hectares. So, the density (number) of trees per hectare based on that sample location is:

$$Z = \frac{5.5}{1/4 \times \pi R^2 \times 10^{-4}} = 5.5/L$$

where: Z = the density (number) of trees per hectare based on one 6-tree sample,

L = the area of that sample location, and

R = the distance between the central point of the sample and the inside edge of 6^{th} tree (the furthest tree from the center of the sample among six trees included in the sample) plus a half diameter of the 6^{th} tree in that sample location.

When m-tree sampling is used to estimate the density (number) of trees in a certain forest area, then the density of trees per hectare based on one sample unit is estimated through the following formula:

$$Z_i = (m - 0.5)/L_i$$

where: Z_i = the density of trees per hectare based on the i^{th} sample location,

L_i = the area of the i^{th} sample location,

m = the total number of trees accounted in the i^{th} sample location, and

i = an index for sample location number in a population.

If n_h m-tree samples are used to estimated a particular forest area or a stratum of the forest, the density of trees per hectare of the forest area is:

$$Z_h = \frac{\Sigma Z_i}{n_h}$$

where: Z_h = the density of trees per hectare of the h^{th} stratum,

n_h = the sample size or the number of observations in the h^{th} stratum,

Z_i = the density of trees per hectare based on the i^{th} sample location, and

$i = 1, 2, 3, \ldots\ldots\ldots\ldots, n_h$.

Method 2.

Moore (1954) discussed bias in m-tree sampling for density in the case where distance was measured to only one tree nearest each point located randomly on the ground. Thompson (1956) derived the distribution of distance to the m^{th} individual (where m may be greater than one) when individuals have a Poisson spatial distribution (randomly distributed). Eberhardt (1967) derived the correction factor ((m-1)/m) to estimate density (number) of the trees for sample locations for m-tree sampling when m is greater than one. This factor has been shown to give unbiased estimates in a forest having a Poisson spatial distribution (randomly distributed) and a Negative binomial (clumped forests). However, it may be biased for other spatial distributions, such as uniform (plantations).

The density (number) of the trees based on one m-tree sampling (method 2) using the correction factor is determined by using the following formula:

$Z_i = ((m - 1)/m) \times m\,(1/L_i)$ or $Z_i = (m - 1)/L_i$

where: Z_i = the density of the trees based on the i^{th} sample location, m = the number of trees accounted in that sample location,

L_i = the area of the sample location, and

i = an index for sample location number in a population.

When n_h m-tree samples are used to estimate the density of trees per hectare in a certain (the hth) stratum, then the estimated density of trees/hectare for that stratum is determined by the following formula:

$$Z_h = \frac{\Sigma Z_i}{n_h}$$

where: Z_h = the density of trees per hectare in the hth stratum,

Z_i = the density of trees per hectare based on the ith sample location, and

n_h = the sample size or the number of observations in the hth stratum.

Jonsson et al. (1992) and Lessard et al. (1994a) used the correction factor ((m - 1)/m) to estimate the volume of the trees for every sample unit. By using this correction factor, m-tree sampling gave the best performance for estimating volume of forests having spatial distribution with Poisson pattern in Lapland, Sweden (Jonsson et al. 1992). However, m-tree sampling using this procedure might give greater bias than point and fixed-radius circular plot sampling for forests having other spatial distributions as studied by Lessard et al. (1994a) in the clumped hardwood stands.

The volume of the trees for one sample location is determined as:

$(v_1 + v_2 + \ldots v_m)$ ((m - 1)/m) or $\Sigma v_j \times ((m - 1)/m)$.

Therefore, the volume of the trees per hectare based on one sample location is determined by the formula:

$$Y_i = \frac{((m - 1)/m)\ \Sigma v_{ij}}{L_i}$$

where: Y_i = the volume per hectare of the forest based on the i^{th} sample location,

Σv_{ij} = $(v_{i1} + v_{i2} + ... + v_{im})$ or the total volume of all trees accounted in the i^{th} sample location,

L_i = the area of the i^{th} sample location,

j = 1, 2, ..., m,

m = the number of trees considered in the sample location, and

i = an index for sample location number in a population.

The volume of the trees per hectare in a certain stratum (h) of the forest based on m-tree sampling with method 2 is estimated by the formula:

$$Y_h = \frac{\Sigma\ Y_i}{n_h}$$

where: Y_h = volume per hectare of the h^{th} stratum or the forest,

Y_i = volume per hectare based on the i^{th} sample location,

i = 1, 2, 3, ..., n_h, and

n_h = the sample size or the number of sample units observed in the h^{th} stratum.

The applications of m-tree sampling have been esearched in several countries. Prodan (1968) compared this method with fixed-radius circular plot sampling for estimating volumes of mixed-forests in southern West Germany. The results of the study showed that m-tree sampling (6-tree sampling) had smaller standard deviation (10%) than fixed-radius circular plot sampling (0.1 hectares). Rusydi (1982) applied m-tree sampling and fixed-radius circular plot sampling to estimate volumes of growing teak plantations in Bojonegoro, East Java, Indonesia. The study found that the m-tree sampling was more efficient than fixed-radius circular plot sampling (plot size = 0.04 hectares for age classes III - IV). Payandeh and Ek (1986) tested a variety of density estimators based on distance measurements in randomly patterned, clustered, and uniformly distributed forests. Their results showed good performance of m-tree sampling with a ratio estimator for m >10 for estimating density in most of forest types examined. A variant of Prodan's method (method 1) worked well for randomly distributed forests, but tended to overestimate density for other spatial distributions. Jonsson et al. (1992) conducted studies comparing m-tree sampling with fixed-radius circular plot sampling for estimating volumes of mixed-forests in Vastergotland and Lapland, Sweden. The study indicated that m-tree sampling had an insignificant amount of bias in forests they studied. The researchers also concluded that long-term prognoses related to timber assessment calculations can be of high quality when based on inventory data from the m-tree sampling. Lessard et al. (1994a) demonstrated the utility of m-tree sampling as an alternative to the more common point sampling and fixed-radius plot sampling in northern hardwoods, red pine and clumped hardwoods of northern Michigan, U.S.A. The study was conducted to estimate board foot volume, cord volume, basal area and number of trees per acre produced by those methods. The results of the study showed that the error, cost efficiency index and time required for 3-tree sampling were generally better than the other methods tested in estimating cord volume, basal area and number of trees per acre. The researchers concluded that 3-tree sampling was competitive on a cost effective basis with point and fixed-radius circular plot sampling in randomly patterned forests. Further, the researchers also concluded that m-tree sampling provided the parameters of the spatial pattern of tree location which were unavailable from point and fixed-radius plot sampling, and which would become more necessary as emphasis was placed on ecosystem management rather than just management of timber resources.

The Principles of Stratified Systematic Sampling

Stratified systematic sampling is a method of sampling in which the population is divided into h classes that are called strata. In each stratum, n_h samples are selected systematically in which only the first sample is drawn randomly. Stratification is used to reduce the heterogeneity and to increase the precision of the estimate of the population parameters (Sukhatme 1963).

The Systematic sample in each stratum offers great advantages in organizing control over field work. This method is extensively used on account of its low cost and simplicity in the selection of the samples (Spurr 1952). The relative position in the population of the different units included in the sample is fixed, so that there is consequently no risk that any large contiguous part of the population will fail to be represented (Cochran 1977). The systematic locations of the samples also provide good estimates of the population and are usually easier and faster to execute for forest inventory than random sampling (Husch et al. 1982).

If the population consists of N units and h strata, and each stratum has N_h units in which n_h samples are selected systematically with random start, the mean of the population is determined by the following formula (Cochran 1977, Sukhatme 1963):

$$\overline{Y} = \frac{\Sigma(N_h \times Y_h)}{N}$$

where: $\overline{Y}$ = the estimated mean of the population,

Y_h = the estimated mean of the h^{th} stratum,

N_h = the size or the area of the h^{th} stratum, and

N = the size or the area of the population.

The estimated variance of the population mean is determined by the following formula (Cochran 1977):

$$S_{\overline{Y}}^{2} = \frac{1}{N^2}\sum\left[N_h^2 \frac{S_h^2}{n_h}\right]$$

where: $S_{\overline{Y}}^{2}$ = the estimated variance of the population mean,

N_h = the size or area of the h^{th} stratum,

N = the size or area of the population,

n_h = the number of observations in the h^{th} stratum, and

$$S_h^2 = \frac{\Sigma y_i^2 - (\Sigma y_i)^2 / n_h}{n_h - 1}.$$

Efficiency

The relative efficiency of a sampling method is often used as the criterion to choose an appropriate method that will provide information for management. To select among several methods, the main factors that affect efficiency need to be considered (Riyadi 1975). According to Munawardi (1960), the guidelines in measuring efficiency consist of two considerations:

1. If two methods yield the same expected result, then the method having the lower cost or the shorter time is more appropriate for use.
2. If two methods have the same expense, then the method having better results (such as precision, quality, strength, etc.) should be chosen.

In sampling technique, the definition of the efficiency is the success level of a method in terms of its error and time or expense (Nasution and Barizi 1976). Husch et al. (1982) suggested the relative efficiency calculated by multiplying sampling error with the time or expense to compare between methods used. This comparison was expressed in the following formula:

$$Ef_{m-p} = \frac{[(C_m)^2 / n_m] \times T_m}{[(C_p)^2 / n_p\ ] \times T_p}$$

where: C_m = the coefficient of variation of the estimated mean for the m method,

C_p = the coefficient of variation of the estimated mean for the p method,

T_m = the time of measurement or expense of the m method,

T_p = the time of measurement or expense of the p method,

$C_m = (S_{ym} / \bar{y}_m) \times 100\ \%$,

$C_p = (S_{yp} / \bar{y}_p) \times 100\ \%$,

n_m = the sample size (the number of observations) of the m method,

n_p = the sample size (the number of observations) of the p method, and

$Ef_{m\text{-}p}$ = the relative efficiency of the m method compared to the p method.

If $Ef_{m\text{-}p}$ is less than one, then the m method is more efficient than the p method and vice versa.

CHAPTER III

METHODS

Population and Sampling Technique

The population of this study is teak plantation forests at KPH Bojonegoro, KPH Madiun and KPH Saradan of Perum Perhutani in East Java, Indonesia. The population has age class 8 (71 - 80 years) and is divided into five strata according to bonita (forest land fertility class). This stratification is intended to reduce variability caused by differences in land fertility in which growth and dimension (diameter, height and volume) of the trees are different for every bonita, so that the stratification might be expected to increase the accuracy or the precision of the estimation.

To estimate the mean of the population of interest (the volume per hectare and density per hectare of the trees), stratified systematic sampling was applied as the sampling design. From each stratum, the central points of sampling locations were selected systematically in which the first central point of sampling locations was drawn randomly using a random number table. The area and stratification of the population, and the number of samples for each method studied in each stratum are expressed by Table 2.

Table 2. Area and stratification of the population of the study, and the number of samples for each method studied in each stratum.

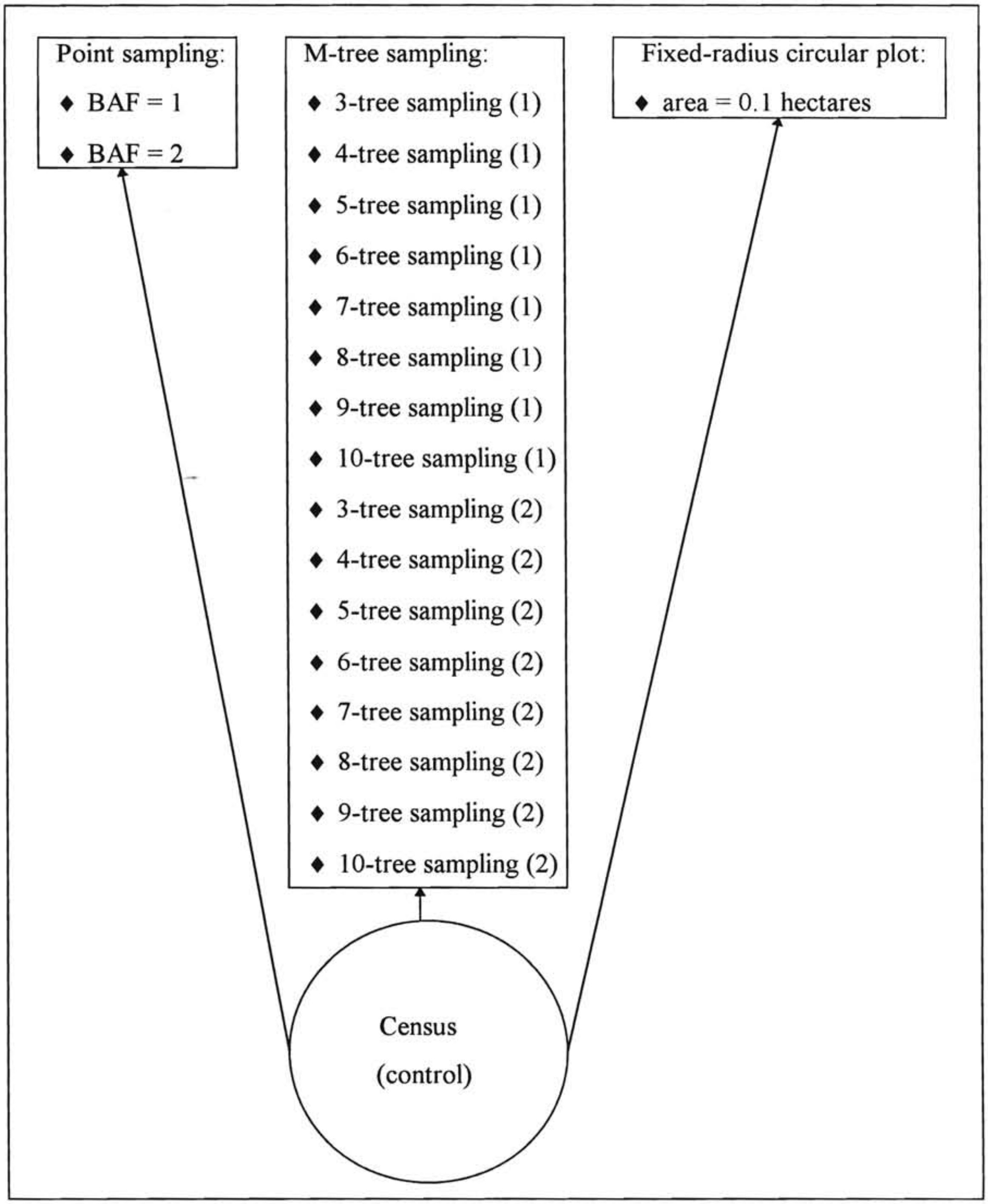
Stratum	Bonita	Age class	The area of the stratum for each site/KPH (in ha)				Samples for each method studied
			Madiun	B.negoro	Saradan	Total	
I	2.0	8	24.0	5.4	35.9	65.3	18
II	2.5	8	16.2	25.4	80.3	121.9	30
III	3.0	8	67.9	26.8	-	94.7	24
IV	3.5	8	29.4	21.7	-	51.1	12
V	4.0	8	-	34.4	-	34.4	9
Total			137.5	113.7	116.2	367.4	93

Sample Methods to be Compared

In order to estimate the volume and density of trees of teak forests studied, nineteen sample methods were applied to select sample units for estimation and comparisons. These methods consisted of two methods of point sampling, sixteen methods of m-tree sampling and one method of fixed-radius circular plot sampling (Figure 3). The two methods of point sampling were point sampling with basal area factor (BAF) = 1 m^2/hectare/tree selected, and point sampling with BAF = 2 m^2/hectare/tree selected. M-tree sampling methods used were divided into two groups, namely, eight methods of m-tree sampling (1) and eight methods of m-tree sampling (2). Eight methods of m-tree sampling (1) consisted of 3-tree to 10-tree sampling which estimate the volume (or density) of trees by using a half volumes (or a half trees) of the m^{th} tree plus the total volumes (or the total number) of other trees included in each sample in accordance with procedures of calculation method 1 as explained in Chapter II. Eight methods of m-tree sampling (2) comprised of 3-tree to 10-tree sampling which estimate the volume and density of the trees in each sample by using multiplicative correction factor ((m-1)/m) which is mentioned as m-tree sampling with calculation method 2 in Chapter II above. For fixed-radius-circular plot sampling, this study used plot sampling with the area of 0.1 hectares which is currently used for inventories of mature teak plantations by Perum Perhutani in Java.

The central points of the sample methods were located at the same points that had been selected systematically with a random start in sample drawing. In detail, the methods that were compared consisted of:

1. Point sampling with BAF (basal area factor) = 1 m^2/ha/tree selected,
2. Point sampling with BAF = 2 m^2/ha/tree selected,
3. 3-tree sampling (1) or 3-tree sampling with calculation method 1,
4. 3-tree sampling (2) or 3-tree sampling with calculation method 2,
5. 4-tree sampling (1) or 4-tree sampling with calculation method 1,
6. 4-tree sampling (2) or 4-tree sampling with calculation method 2,
7. 5-tree sampling (1) or 5-tree sampling with calculation method 1,
8. 5-tree sampling (2) or 5-tree sampling with calculation method 2,
9. 6-tree sampling (1) or 6-tree sampling with calculation method 1,



BAF = basal area factor, 1 = 1 m^2/ha/tree selected, 2 = 2 m^2/ha/tree selected,

(1) = using calculation method 1 (by adding volume or number of actual portions of trees included) in each sample,

(2) = using calculation method 2 (by multiplying correction factor (m-1)/m to the total volume or total number of m trees) for each sample.

Figure 3. Sample methods to be compared in the study.

10. 6-tree sampling (2) or 6-tree sampling with calculation method 2,
11. 7-tree sampling (1) or 7-tree sampling with calculation method 1,
12. 7-tree sampling (2) or 7-tree sampling with calculation method 2,
13. 8-tree sampling (1) or 8-tree sampling with calculation method 1,
14. 8-tree sampling (2) or 8-tree sampling with calculation method 2,
15. 9-tree sampling (1) or 9-tree sampling with calculation method 1,
16. 9-tree sampling (2) or 9-tree sampling with calculation method 2,
17. 10-tree sampling (1) or 10-tree sampling with calculation method 1,
18. 10-tree sampling (2) or 10-tree sampling with calculation method 2, and
19. Fixed-radius circular plot sampling with area = 0.1 hectares (radii = 17.84 m).

In order to evaluate the estimated means of the population obtained from each method compared, the results of a census conducted by Perum Perhutani (two years before felling the forest) is used as additional material to analyze data in this study. Since the forest management practice in this area is to girdle trees two years prior to felling, no growth occured after the census.

Time, Locations and Instruments

The survey was conducted during the three-month period between May 14, 1994 and August 14, 1994. The locations of the survey consisted of three management areas of Perum Perhutani, namely, KPH Bojonegoro, KPH Madiun and KPH Saradan in East Java, Indonesia. The instruments used were comprised of:

Software Instruments

Inventory design

In order to gather data needed from the forest in every stratum and the entire population, this study used the system of the forest inventory that has been implemented by Perum Perhutani. The distance between the centers of two closest sampling locations is systematically determined to be 200 meters or one sampling location for every four hectare (200 m × 200 m) area, in which the first sampling location is selected randomly. Therefore, the ratio between the area in hectares and the number of observations would be approximately 4 : 1. In this way, the number of observations for every stratum (n_h) can be ascertained and the number of observations of the population is automatically determined by adding the number of obeservations of all strata.

Data of each stratum and population

Each sampling method was performed in each stratum and the data from sampling were processed to obtain the estimated mean (the volume per hectare and density of trees per hectare) of the population or each stratum.

Random number table

This table is used to select the first center (the first central point) of sampling location. After the first central point of sampling location was selected randomly through this table, the following centers of the sampling site were determined systematically so that the distance between a central point and the closest centers of sampling locations was 200 meters.

Tariff or local volume table

The tariff or local volume table used by Perum Perhutani in Java relates individual tree circumference or diameter to the individual tree volume of teak forests in a given forest management area. These tables were based on the research since 1940 and every management area/KPH has its own local volume table (tariff). These tables were revised several times in order to check and improve the precision of the estimation for the volume of forest standing stock. Diameter or the basal area can be used to determine the volume of teak trees.

Sample methods and Statistical design

The sample methods applied in this survey were the sample methods described in the literature review (Chapter II). The mean of the population, variance and coefficient of variation of each sample method tested are estimated by the procedures of each method and stratified systematic sampling described on the previous chapter.

Relative efficiency formula

The relative efficiency of each sample method tested will be determined by the formula presented in the literature review (Chapter II). Through this formula, the most efficient sample type (method) among the sample methods can be ascertained.

Hardware Instruments

a. Bitterlich stick (2 units, BAF=1 and BAF=2),
b. Circumference band (2 units),
c. Rolling meters (2 units),

d. Compass (2 units),

e. Stopwatch (1 units),

f. Forest plantation map with scale 1 : 10,000,

g. Tally sheet and writing instruments, and

h. Paint, ropes and miscellaneous supplies.

Data Collection

The data were divided into two categories. The first category was the data that were acquired without direct measurements in the field, namely, the area, bonita, age class, and maps of every stratum and population. These data were used to perform sampling technique (to draw sampling locations) before direct measurements in the forest studied. The second category was the data that were collected by direct measurements in the field, namely, diameters of the trees included in each sample method studied, the distance between the m^{th} tree and the central point of sampling locations for m-tree sampling, the distance between borderline trees (those not clearly 'in' or 'out' in projecting the Bitterlich stick) and the central point of sampling locations for point sampling if required, the time of measurements for each method compared in this study. These data were processed or used to estimate the mean (the volume of the trees per hectare) of the population and every stratum, the average time of the measurements for each sample method researched, and finally to calculate the relative efficiency of each method compared.

The direct measurements for collecting the data required were conducted after sampling locations had been selected systematically with random start in each stratum. The variables measured in each sampling location consisted of the diameter of trees and the time of measurements according to each sample method used. To compile the data, the following procedures were performed:

1. The central points of sampling locations for each sample method tested were located in the survey area on the same points which had been selected systematically designed with a random start.
2. The distance between the central point of a sampling location and the following central point of sampling location (or the closest sampling location) was determined as 200 meters in the forest area or 20 millimeters on the forest map with scale 1:10,000.
3. Starting points for obtaining central points of sampling locations (which had been selected systematically with a random start) in the forest area were chosen by using easily identified locations in the forest (eg. river curves, river merger, triangulation points) having the closest distance to one central point of a sampling location or more. The central point of the sampling location was determined through the azimuth and the distance measurements from the starting points. The remaining central points of the sampling locations were determined through the closest definite points found in the field from those central points or through the measurements of the distance (200 meters) between two closest central points of sampling locations toward north, south, west or east.

4. On each sampling location, the measurements were conducted for each sample method tested as following:

    a) Diameter measurements for all trees which were encompassed by the fixed-radius circular plot with the area 0.1 hectares (radius of 17.84 meters). Results of these measurements were recorded together with the times of the measurements on the tally sheet.

    b) Selections of trees by ocular projection through the Bitterlich stick with BAF=1 and BAF=2 to the trees around the central point of the sampling location were recorded together. Diameters of trees that were selected as tally trees were measured and recorded in addition to the times of the measurements.

    c) Diameter measurements of three trees that were closest from the central point of the sampling location, the distance measurement from the central point of the sampling location to the furthest tree among those three trees from that central point. Results and the times of these measurements were recorded on tally sheet.

    d) Similar procedures to point e were performed for 4, 5, 6, 7, 8, 9 and 10 trees closest to the central point of the sampling location.

Data Processing

Data resulting from the measurement of the trees based on each sample method tested were used to determine the individual volume of every tree accounted in every sample, the area of the sample (for m-tree sampling and plot sampling), basal area of every tree for point sampling, and the density (number) of trees included in the sample.

The individual volume of every tree measured was determined by converting the circumference of the tree to its volume through the tariff or local volume table. These results were used to estimate the volume per hectare and density per hectare for every sample of each sample method tested in accordance with the estimation procedures of these methods as described in the literature review (Chapter II).

The estimated volume and density of trees per hectare from every sample of each method tested were used in further computation which consecutively consisted of:

1. The estimation of the mean (volume/hectare and density/hectare), variance and coefficient of variation for every sample method tested in each stratum.
2. The estimation of the mean (volume/hectare and density/hectare), variance and coefficient of variation of the population for each type of the sample method studied by stratified sampling formulas.
3. The computation of the relative efficiency of each sample method. In each case using the time and coefficient of variation for 0.1 hectares fixed-radius circular plot sampling in the denominator of the relative efficiency formula. This is done because 0.1 hectares fixed-radius circular plot sampling is the technique currently used, and is a logical standard for comparison.

CHAPTER IV

RESULTS AND DISCUSSION

General

On the basis of samples selected from the forest area studied, the study indicates that m-tree sampling (2) (or m-tree sampling using calculation method 2) appears to give biased estimates for mean volume and mean density of the teak forest. Table 8 and Table 14 show that m-tree sampling (2) yields much smaller mean volume and mean density of the trees than m-tree sampling method (1) (m-tree sampling using calculation method 1), circular plot or point sampling in this study. Compared to the other methods, most of the estimated means based on m-tree sampling (2) are also further from the true value of mean volume and mean density of the forest based on the census. The 95% confidence intervals of the mean for most methods of m-tree sampling method (2) tested do not include the true value of the mean volume and mean density of the forest as shown by the census results. There are three reasons for these results. First, management practices in handling trees for every bonita (land fertility class) such as regular intervals of distance in planting trees and systematic thinning causes the teak trees to scatter uniformly resulting in a uniform spatial distribution. Therefore, the tree spatial distribution of the forest studied is different from the Poisson pattern in which m-tree sampling (2) can give unbiased estimates with the correction factor (m - 1)/m as in Jonsson et al. (1992)

in Sweden and Lessard et al. (1994a) in northern Michigan, U.S.A. Second, the estimated density of the trees by using formula $[\{(m - 1)/m\} \times m]/L$ in m-tree sampling (2) is always smaller than the estimate by using formula $(m - 0.5)/L$ on m-tree sampling (1) in which the actual number of trees are included in the samples as shown by Figure 2. The variability of tree diameters within each bonita is small since individual tree volumes within each bonita are very similar in the teak plantations studied. Therefore, the estimated density (the number) of the trees is approximately proportional to the estimated volume of the trees included in the samples. Thus, the smaller estimated density (the number) of trees obtained by using methods of m-tree sampling (2) generally yields a smaller estimated volume of the trees. Third, the mutiplicative correction factor $(m - 1)/m$ of m-tree sampling (2) tends to make numbers proportionally smaller resulting in a smaller standard deviation. As the result, the smaller estimated mean volume or smaller mean density and a smaller standard deviation gives a shorter confidence interval centered at a lower level. This fact can prevent the 95% confidence interval of m-tree sampling (2) from containing the true value of the mean volume and mean density of the forest studied.

Based on Tables 3 to Table 7 and Tables 9 to Table 13, only a few situations of m-tree sampling (2) have confidence intervals which include the true value of mean volume and mean density of the teak trees in strata studied. Generally, these methods consist of m-tree sampling (2) having more than 6 trees included in the samples ($m>6$ trees) in some strata. These results occur for two reasons. First, population standard errors are smaller than stratum standard errors because they are based on more samples. So, in a particular stratum, the 95% confidence interval of the estimated mean is more likely to include the true value of the mean volume and mean density of the strata, since a larger standard error implies a wider confidence interval. However, the standard error associated with population estimates (for all strata combined) is too small to permit a confidence interval wide enough to contain the true value of mean volume and mean density for the entire population researched. These facts can be seen in strata 1, 4 and 5 in which some methods of m-tree sampling (2) include the true value of mean volume and mean density of the forest, but for the whole population, the 95% confidence interval of these methods does not contain the true value of the mean volume and mean density of the forest. Second, although the estimated mean of m-tree sampling (2) is always smaller than that of m-tree sampling (1), the estimates of volume and density for m-tree sampling (2) will be proportionally closer to the estimates of m-tree sampling (1) if larger number of trees are involved in the samples. Therefore for certain strata, confidence intervals from m-tree sampling (2) contained the true mean if the number of trees (m) was large enough. However, even in these cases, the standard errors associated with estimates for the whole population were smaller than for individual strata. Consequently, confidence intervals of m-tree sampling (2) for the whole population including all strata did not include the true population mean for any value of m = 3 to m = 10 (Table 7). Hence, the application of m-tree sampling (2) does not seem to yield reliable estimates of volume and density of the forest studied.

Results in Volume Estimation

Stratum 1.

In the context of volume estimation, all of the methods applied in this study give the smallest estimated mean volume for Stratum 1. These results are in harmony with the result of the census in which the true value of mean volume show the smallest number (50.2842 m^3/hectare) for this stratum. This fact is consistent with classification of land fertility expressed by bonita of the forest area in which the Stratum 1 (bonita 2.0) is classified as the forest area having the lowest class of land fertility among the forest areas researched. For estimation of this true value of mean volume, the methods tested give the results as illustrated by Table 3.

All methods of m-tree sampling (1), circular plot, and point sampling show approximately same value of the estimated mean volume in this stratum (Table 3). These methods together with 8-tree sampling (2), 9-tree sampling (2) and 10-tree sampling (2) yield confidence intervals which include the true value of mean volume of Stratum 1. Among these methods, 5-tree sampling (1) and 7-tree sampling (1) show smaller standard deviation than the rest of these methods. These two methods also comparatively yield shorter confidence intervals and smaller coefficients of variation in which the proportion of the standard deviation is expressed as a percent of the estimated mean volume. This fact indicates that 5-tree sampling (1) and 7-tree sampling (1) give better accuracy and narrower confidence intervals for estimating volume of the trees in the Stratum 1 compared with other methods tested in this study.

Table 3. Results in volume estimation based on 18 samples selected from Stratum 1 (bonita 2.0) of the study area with true value of mean volume 50.2842 m^3/hectare.

Method	Estimated mean vol. (m^3/hectare)	Standard deviation	95 % confidence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	50.8564	11.9868	[44.6379 ; 57.0749]	23.5700	3.3185	1.6858
BAF=2	50.4482	13.1421	[43.6303 ; 57.2661]	26.0508	2.0157	1.2509
M-Tree Sampling (1):						
3-Tree Sampling	50.4901	10.2322	[45.1818 ; 55.7984]	20.2658	2.0870	0.7838
4-Tree Sampling	50.2837	10.9813	[44.5968 ; 55.9806]	21.8388	2.4833	1.0830
5-Tree Sampling	49.4674	8.5437	[45.0356 ; 53.8997]	17.2714	2.9213	0.7968
6-Tree Sampling	50.1047	11.1767	[44.3064 ; 55.9029]	22.3068	3.4704	1.5791
7-Tree Sampling	50.0969	8.4897	[45.6926 ; 54.5012]	16.9467	4.0444	1.0621
8-Tree Sampling	50.4793	10.6227	[46.5131 ; 54.4454]	21.0436	4.8333	1.9572
9-Tree Sampling	50.1039	11.9282	[45.6503 ; 54.5574]	23.8070	5.9204	3.0684
10-Tree Sampling	49.6465	11.7310	[43.5607 ; 55.7323]	23.6290	7.0750	3.6122
M-Tree Sampling (2):						
3-Tree Sampling	39.5540	8.7542	[35.0125 ; 44.0955]	22.1322	2.0870	0.9348
4-Tree Sampling	42.5160	9.1031	[37.7935 ; 47.2385]	21.4110	2.4833	1.0410
5-Tree Sampling	44.5237	8.3204	[40.2072 ; 48.8402]	18.6875	2.9213	0.9329
6-Tree Sampling	45.4285	10.5049	[39.9788 ; 50.0782]	23.1240	3.4704	1.6969
7-Tree Sampling	46.1781	7.8342	[42.1139 ; 50.2423]	16.9652	4.0444	1.0645
8-Tree Sampling	46.8567	10.3210	[43.0032 ; 50.7102]	22.0267	4.8333	2.1443
9-Tree Sampling	47.3390	11.5927	[43.0107 ; 51.6673]	24.4888	5.9204	3.2466
10-Tree Sampling	47.1883	10.9551	[41.5050 ; 52.8716]	23.2156	7.0750	3.4869
Circular Plot:						
(Area 0.1 hectares)	50.5753	10.0906	[45.3405 ; 55.8101]	19.9516	2.7472	1.0000

The real difference between 5-tree sampling (1) and 7-tree sampling (1) is shown by their efficiency ratio. In this case, 5-tree sampling (1) is more efficient than circular plot sampling as the standard comparison, while 7-tree sampling (1) is less efficient than circular plot sampling. Moreover, in terms of efficiency, 5-tree sampling (1) appears as the best method with efficiency ratio of 0.7968. Hence, among the methods studied, 5-tree sampling (1) is the most efficient method in estimating volume of this stratum. The increased efficiency of 5-tree sampling (1) as compared to 7-tree sampling (1) is due to the fact that less-time is required for 5-tree sampling (1) (Table 3).

Stratum 2.

Compared with Stratum 1, Stratum 2 (bonita 2.5) has higher yields with the true value of mean volume of 90.7362 m^3/hectare. This result is in accordance with bonita classification in which a higher bonita is expected to produce more yield in terms of the volume/hectare (Table 4).

Variations of the estimated mean volumes provided by the methods studied are shown in Table 4. However, these results can be generally divided into two categories: the estimated mean confidence interval which includes the true value of mean volume of the forest, and the estimated mean having confidence interval which does not include the true value of the mean volume of the forest.

Among the methods having confidence interval of the mean volume that includes true mean volume, 5-tree sampling (1) yields the closest estimated mean to the true value of mean volume of this stratum. The smallest coefficient variation and the shortest confidence interval with smaller standard deviation are also associated with this method.

Table 4. Results in volume estimation based on 30 samples selected from Stratum 2 (bonita 2.5) of the study area with true value of mean volume 90.7362 m^3/hectare.

Method	Estimated mean vol. (m^3/hectare)	Standard deviation	95 % confidence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	89.1676	9.3616	[85.6723 ; 92.6629]	10.4989	6.8333	1.7733
BAF=2	91.0802	10.4551	[87.1766 ; 94.9838]	11.4790	2.9444	0.9134
M-Tree Sampling (1):						
3-Tree Sampling	86.6211	14.5640	[81.1834 ; 92.0588]	16.8134	1.9439	1.2937
4-Tree Sampling	86.6598	13.6554	[81.5614 ; 91.7582]	15.7574	2.3261	1.3597
5-Tree Sampling	90.7056	7.9895	[87.7226 ; 93.6886]	8.8081	2.7227	0.4973
6-Tree Sampling	91.7097	10.6023	[87.7512 ; 95.6682]	11.5607	3.3311	1.0481
7-Tree Sampling	89.5028	10.9967	[85.3970 ; 93.6086]	12.2864	3.9389	1.3998
8-Tree Sampling	89.8784	12.4926	[85.2141 ; 94.5427]	13.8995	4.8650	2.2128
9-Tree Sampling	87.2142	10.4890	[83.2980 ; 91.6304]	12.0267	6.0006	2.0433
10-Tree Sampling	89.2635	10.5721	[85.3163 ; 93.2107]	11.8437	7.2344	2.3891
M-Tree Sampling (2):						
3-Tree Sampling	68.9707	11.1019	[64.8256 ; 73.1157]	16.0965	1.9439	1.1857
4-Tree Sampling	76.1606	11.9071	[71.7149 ; 80.6063]	15.6342	2.3261	1.3385
5-Tree Sampling	80.2720	7.3969	[77.5103 ; 83.0337]	9.2147	2.7227	0.5443
6-Tree Sampling	82.5639	9.6697	[78.9536 ; 86.1742]	11.7117	3.3311	1.0757
7-Tree Sampling	82.6782	10.5675	[78.7327 ; 86.6237]	12.7814	3.9389	1.5149
8-Tree Sampling	83.5720	12.1449	[79.0375 ; 88.1065]	14.5322	4.8650	2.4188
9-Tree Sampling	82.4354	9.4701	[78.8996 ; 85.9712]	11.4879	6.0006	1.8644
10-Tree Sampling	84.3604	9.7464	[80.7214 ; 87.9994]	11.5533	7.2344	2.2734
Circular Plot:						
(Area 0.1 hectares)	91.4053	9.6099	[87.8173 ; 94.9933]	10.5135	3.8428	1.0000

These facts suggests that 5-tree sampling (1) yields the best accuracy for estimating volume of the forest studied in this stratum.

In view of efficiency, 5-tree sampling (1) also yields the best result for this stratum. To estimate the volume of the trees in the Stratum 2, this method shows an efficiency ratio of 0.4973 which is the best ratio for any method tested. Hence, among the methods applied in this study, 5-tree sampling (1) is the most efficient method for estimating volume of the Stratum 2.

Stratum 3.

Stratum 3 obviously shows higher yield than previous strata with the true value of mean volume is 149.2495 m^3/hectare. As for Stratum 1 and Stratum 2, this result is in agreement with bonita classification, since the bonita (land fertility class) of this stratum is higher than for the former strata. Estimates of the true value of mean volume, for each of the methods tested are given by Table 5.

The best estimate of mean volume for this stratum is given by 5-tree sampling (1) (Table 5). This method gives an estimated mean volume which is approximately equal to the true value of mean volume for this stratum. Although 5-tree sampling (2) shows smaller value of standard deviation, coefficient variation and narrower 95% confidence interval, 5-tree sampling (1) has a confidence interval that contains the true mean volume of the stratum. For 5-tree sampling (2), however, the 95% confidence interval does not include the true value of the mean volume above. Therefore, among the methods researched, 5-tree sampling (1) performs best in terms of accuracy for estimating mean volume of the Stratum 3.

Table 5. Results in volume estimation based on 24 samples selected from Stratum 3 (bonita 3.0) of the study area with true value of mean volume 149.2495 m^3/hectare.

Method	Estimated mean vol. (m^3/hectare)	Standard deviation	95 % confidence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	145.5520	15.8047	[138.8772 ; 152.2268]	10.8584	9.1062	1.9701
BAF=2	144.6108	19.8573	[136.2244 ; 152.9972]	13.7315	4.3014	1.4882
M-Tree Sampling (1):						
3-Tree Sampling	148.7704	17.7757	[141.2631 ; 156.2777]	11.9484	1.6972	0.4446
4-Tree Sampling	145.2067	16.3607	[138.2970 ; 152.1164]	11.2672	2.2188	0.5168
5-Tree Sampling	149.0866	12.9300	[143.6258 ; 154.5474]	8.6728	2.7354	0.3775
6-Tree Sampling	146.4624	17.0026	[139.2816 ; 153.6432]	11.6089	3.3910	0.8385
7-Tree Sampling	147.9537	13.2378	[142.3629 ; 153.5445]	8.9473	4.0257	0.5913
8-Tree Sampling	147.6517	15.7102	[141.0168 ; 154.2866]	10.6400	4.7979	0.9967
9-Tree Sampling	144.3681	16.9912	[137.1922 ; 151.5440]	11.7694	5.7688	1.4663
10-Tree Sampling	149.2186	16.8429	[142.1053 ; 156.3319]	11.2874	6.8646	1.6048
M-Tree Sampling (2):						
3-Tree Sampling	119.0054	14.9677	[112.6841 ; 125.3267]	12.5774	1.6972	0.4926
4-Tree Sampling	123.6707	13.9638	[117.7733 ; 129.5681]	11.2911	2.2188	0.5190
5-Tree Sampling	131.6397	11.0855	[126.9579 ; 136.3215]	8.4211	2.7354	0.3559
6-Tree Sampling	132.5702	14.1585	[126.5906 ; 138.5498]	10.6800	3.3910	0.7097
7-Tree Sampling	136.8822	12.6730	[131.5300 ; 142.2344]	9.2584	4.0257	0.6332
8-Tree Sampling	136.8116	15.0322	[130.4630 ; 143.1602]	10.9875	4.7979	1.0628
9-Tree Sampling	136.1022	16.2363	[129.2451 ; 142.9593]	11.9295	5.7688	1.5064
10-Tree Sampling	140.7768	16.4746	[133.8190 ; 147.7346]	11.7026	6.8646	1.7250
Circular Plot:						
(Area 0.1 hectares)	154.4820	17.8971	[146.9235 ; 162.0405]	11.5852	4.0604	1.0000

Most methods of m-tree sampling show better efficiency ratios than point or plot sampling (Table 5). Of methods that have confidence intervals containing the true mean volume, 5-tree sampling (1) has the best value of the efficiency ratio (0.3775). On the basis of these facts, 5-tree sampling (1) seems to be the best method to estimate volume of the trees of the Stratum 3 due to its accuracy and its efficiency ratio.

Stratum 4.

For Stratum 4, the true value of mean volume is 181.3113 m^3/hectare. This is significantly larger than volumes for the previous strata and suggests the response of a forest area having a higher productive potential as indicated by a higher bonita. The estimates of this mean volume for the methods studied are given in Table 6.

On the basis of the Table 6, 9-tree sampling (2), 10-tree sampling (2), all methods of m-tree sampling (1), circular plot and point sampling have 95% confidence intervals that contain true mean volume.

The best result in estimating mean volume of Stratum 4 is shown by 5-tree sampling (1). Among the methods having confidence intervals which include the true value of mean volume, 5-tree sampling (1) yields the best confidence interval, standard deviation and the best coefficient variation. Also, 5-tree sampling (1) is the method having the best efficiency ratio among the methods tested whose confidence intervals also include the true mean volume.

Table 6. Results in volume estimation based on 12 samples selected from Stratum 4 (bonita 3.5) of the study area with true value of mean volume 181.3113 m^3/hectare.

Method	Estimated mean vol. (m^3/hectare)	Standard deviation	95 % confidence interval	Coefficient of variation (%)	Mean Time (min)	Efficiency ratio
Point Sampling:						
BAF=1	170.5495	17.7286	[159.2852 ; 181.8138]	10.3950	11.0653	1.9723
BAF=2	175.6610	15.7194	[165.6733 ; 185.6487]	8.9487	5.6555	0.7470
M-Tree Sampling (1):						
3-Tree Sampling	175.6988	13.3074	[167.2436 ; 184.1540]	7.5740	1.7069	0.1615
4-Tree Sampling	177.2050	15.9240	[167.0873 ; 187.3227]	8.9862	2.1667	0.2886
5-Tree Sampling	177.7993	9.1475	[171.9872 ; 183.6114]	5.1448	2.7014	0.1179
6-Tree Sampling	180.1320	11.0622	[173.1034 ; 187.1606]	6.1411	3.3250	0.2068
7-Tree Sampling	183.4201	12.7124	[175.3430 ; 191.4972]	6.9308	3.9361	0.3119
8-Tree Sampling	178.7386	14.1815	[169.7280 ; 187.7492]	7.9342	4.9389	0.5128
9-Tree Sampling	180.7903	17.7458	[169.5151 ; 190.0655]	9.8157	5.9764	0.9498
10-Tree Sampling	184.0428	23.2876	[169.2465 ; 198.8391]	12.6533	7.2472	1.9140
M-Tree Sampling (2):						
3-Tree Sampling	137.5833	10.2717	[131.0569 ; 144.1097]	7.4658	1.7069	0.1569
4-Tree Sampling	151.9444	15.8091	[141.8997 ; 161.9891]	10.4045	2.1667	0.3869
5-Tree Sampling	157.2961	6.5691	[153.1223 ; 161.4699]	4.1763	2.7014	0.0777
6-Tree Sampling	165.1149	10.9907	[158.1317 ; 172.0981]	6.6564	3.3250	0.2430
7-Tree Sampling	170.2490	13.3702	[161.7539 ; 178.7441]	7.8533	3.9361	0.4004
8-Tree Sampling	164.4076	12.2137	[156.6473 ; 172.1679]	7.4289	4.9389	0.4496
9-Tree Sampling	171.4739	18.5748	[159.6720 ; 183.2758]	10.8325	5.9764	1.1568
10-Tree Sampling	175.3898	21.9612	[161.4362 ; 189.3434]	12.5214	7.2472	1.8742
Circular Plot:						
(Area 0.1 hectares)	172.6055	19.8904	[159.9677 ; 185.2433]	11.5236	4.5653	1.0000

Stratum 5.

Stratum 5 has a greater yield than any other stratum since the true value of mean volume is 205.2242 m^3/hectare. This result is expected since this stratum has the highest bonita among the strata studied. In terms of the 95% confidence interval, this stratum shows similar results to Strata 1 and 4. All methods of m-tree sampling (1), circular plot and point sampling, and some methods of m-tree sampling (2) show confidence intervals which include the true value of the mean volume of this stratum. But, in this case, 7-tree sampling (2) appears as the best method in terms of standard deviation, confidence interval and coefficient variation. Although 5-tree sampling (1) and point sampling with BAF = 1 show estimated means closer to the true value of the mean volume, 7-tree sampling (2) yields the smallest standard deviation and coefficient variation besides having the shortest confidence interval. Hence, 7-tree sampling (2) yields the best precision in estimating volume of the Stratum 5.

All methods of point sampling and most methods of m-tree sampling give better efficiency ratios than circular plot sampling. This fact indicates that these methods are more efficient than circular plot sampling. Among these methods, 7-tree sampling (2) shows the best result with an efficiency ratio of 0.1064. Therefore, 7-tree sampling (2) appears to be the most efficient method in estimating volume of this stratum.

Population.

The entire population of the forest consisting of all strata combined has a true value of mean volume of 121.7469 m^3/hectare. Results from the use of the methods studied to estimate this mean volume are shown by Table 8.

Table 7. Results in volume estimation based on 9 samples selected from Stratum 5 (bonita 4.0) of the study area with true value of mean volume 205.2242 m3/hectare.

Method	Estimated mean vol. (m^3/hectare)	Standard deviation	95 % confi- dence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	204.0793	21.4830	[187.5660 ; 220.5926]	10.5268	12.0481	0.7838
BAF=2	191.8926	22.1707	[174.8507 ; 208.9345]	11.5537	6.5889	0.5163
M-Tree Sampling (1):						
3-Tree Sampling	174.3759	46.6237	[138.5378 ; 210.2140]	26.7375	1.5648	0.6567
4-Tree Sampling	177.0006	30.3760	[153.6515 ; 208.3496]	17.1615	2.2056	0.3813
5-Tree Sampling	202.7714	25.4437	[183.2137 ; 222.3291]	12.5480	2.7704	0.2561
6-Tree Sampling	197.6262	26.4090	[177.3265 ; 217.9259]	13.3631	3.3981	0.3562
7-Tree Sampling	212.2221	15.6311	[200.2070 ; 224.2372]	7.3654	4.0426	0.1287
8-Tree Sampling	220.6802	28.5126	[198.7635 ; 242.5969]	12.9203	4.8518	0.4755
9-Tree Sampling	200.8115	36.7485	[172.5641 ; 229.0588]	18.3000	5.6741	1.1155
10-Tree Sampling	192.0476	33.9462	[165.9543 ; 218.7409]	17.6760	6.6611	1.2218
M-Tree Sampling (2):						
3-Tree Sampling	138.2082	36.9420	[109.8121 ; 166.6043]	26.7292	1.5648	0.6563
4-Tree Sampling	153.0283	24.2447	[134.3922 ; 171.6644]	15.8433	2.2056	0.3250
5-Tree Sampling	177.0287	19.6047	[161.9592 ; 192.0982]	11.0743	2.7704	0.1995
6-Tree Sampling	180.3415	22.5532	[163.0056 ; 197.6774]	12.5059	3.3981	0.3120
7-Tree Sampling	198.6244	13.2966	[188.4037 ; 208.8450]	6.6944	4.0426	0.1064
8-Tree Sampling	205.6179	26.6239	[185.1530 ; 226.0828]	12.9482	4.8518	0.4775
9-Tree Sampling	188.3053	35.3171	[161.1582 ; 215.4524]	18.7552	5.6741	1.1717
10-Tree Sampling	181.8698	31.7816	[157.4403 ; 206.2993]	17.4749	6.6611	1.1941
Circular Plot:						
(Area 0.1 hectares)	217.2647	38.6473	[187.5578 ; 246.9716]	17.7881	5.3833	1.0000

Table 8. Results in volume estimation based on 93 samples selected from the entire population of the study area with true value of mean volume 121.7469 m^3/hectare.

Method	Estimated mean vol. (m^3/hectare)	Standard error	95 % confidence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	118.9702	1.4905	[116.0489 ; 121.8915]	1.5144	7.8714	1.3642
BAF=2	118.8595	1.6349	[115.6551 ; 122.0639]	1.3755	3.8474	0.8038
M-Tree Sampling (1):						
3-Tree Sampling	116.8248	2.0591	[112.7891 ; 120.8605]	1.7625	1.8373	0.6302
4-Tree Sampling	116.3376	1.7159	[112.9744 ; 119.7008]	1.4750	2.2929	0.5508
5-Tree Sampling	121.0305	1.2612	[118.5585 ; 123.5025]	1.0421	2.7628	0.3313
6-Tree Sampling	120.6432	1.5194	[117.6651 ; 123.6213]	1.2594	3.3767	0.5914
7-Tree Sampling	122.1180	1.2465	[119.6748 ; 124.5614]	1.0208	3.9893	0.4590
8-Tree Sampling	122.3735	1.6031	[119.2313 ; 125.5157]	1.3094	4.8511	0.9193
9-Tree Sampling	119.0015	1.8099	[115.4541 ; 122.5489]	1.5209	5.8926	1.5051
10-Tree Sampling	120.4822	1.8530	[116.8503 ; 124.1141]	1.5380	7.0589	1.8438
M-Tree Sampling (2):						
3-Tree Sampling	92.6649	1.6451	[89.4405 ; 95.8893]	1.7753	1.8373	0.6394
4-Tree Sampling	100.1645	1.4768	[97.2700 ; 103.0590]	1.4744	2.2929	0.5504
5-Tree Sampling	106.9310	1.0519	[104.8694 ; 108.9926]	0.9837	2.7628	0.2952
6-Tree Sampling	109.4897	1.3349	[106.8733 ; 112.1061]	1.2192	3.3767	0.5542
7-Tree Sampling	113.1983	1.1927	[110.8606 ; 115.5360]	1.0536	3.9893	0.4890
8-Tree Sampling	113.4396	1.5115	[110.4770 ; 116.4022]	1.3324	4.8511	0.9510
9-Tree Sampling	112.3272	1.7510	[108.8953 ; 115.7591]	1.5588	5.8926	1.5811
10-Tree Sampling	114.0861	1.7527	[110.6508 ; 117.5214]	1.5363	7.0589	1.8394
Circular Plot:						
(Area 0.1 hectares)	123.4849	1.8700	[119.8197 ; 127.1501]	1.5144	3.9489	1.0000

The estimated mean volume shows some variation among the methods studied. An underestimate in mean volume is shown by all methods of m-tree sampling (2) as consequences of some factors discussed in the general discussion above. Among the other methods, 3-tree sampling (1) and 4-tree sampling (1) also underestimate mean volume. Although the variability for tree diameter is small in teak plantations, the results in Table 8 suggest that when only 3 trees or 4 trees are included in the samples they are not enough to represent the variability in tree diameters at the sample locations. A larger sample of trees at each sample location may also tend to reduce biases associated with m-tree sampling. All methods other than m-tree sampling (2), 3-tree sampling (1) and 4-tree sampling (1) have confidence intervals that include the true value of the mean volume of the population.

The best estimates of the mean volume are shown by 5-tree sampling (1) and 7-tree sampling (1). Among the methods having a confidence interval that contains the true value of the mean volume, 5-tree sampling (1) and 7-tree sampling (1) yield the smallest standard deviation, the shortest confidence interval and the smallest coefficient of variation. These methods exhibit approximately same value of standard deviation and coefficient of variation. However, the estimated mean volume of 5-tree sampling (1) is approximately equal to the true value of the mean volume of the population (121.0305 m^3/hectare), while the estimated mean volume of 7-tree sampling (1) shows a slight overestimate (122.1180 m^3/hectare).

Except point sampling with BAF = 1, 9-tree sampling and 10-tree sampling, the methods studied show smaller efficiency ratios than circular plot sampling. But no methods of m-tree sampling (2), 3-tree sampling (1) or 4-tree sampling (1) can be categorized as unbiased methods in estimating volume of the population since these methods do not have confidence intervals that contain true mean volume. The 95% confidence interval of the methods studied is one of the important considerations used to compare the methods studied since an inventory method cannot be applied in practice if it is significantly biased. Therefore, in order to select an appropriate method to be applied in forest inventory, the efficiency ratio needs to be supported by an evaluation of accuracy for the estimate which is expressed by the estimated mean and the confidence interval.

On the basis of the considerations mentioned above, there are five methods that have a good efficiency ratio and do not show significant bias. These methods consist of point sampling with BAF = 2, 5-tree sampling (1), 6-tree sampling (1), 7-tree sampling (1) and 8-tree sampling (1). Of these methods, 5-tree sampling (1) shows the best performance with efficiency ratio of 0.3313. Hence, 5-tree sampling (1) is considered the most efficient method of those not significantly biased in estimating volume of the population studied.

Results in Density Estimation

Stratum 1.

This stratum yields mean density of 45.0383 trees/hectare. This result is generally close to the estimated mean density given by the methods studied except for 3-tree sampling (2), 4-tree sampling (2) and 5-tree sampling (2). The responses of all the methods studied in estimating this mean density are given by Table 9.

Table 9. Results in density estimation based on 18 samples selected from Stratum 1 (bonita 2.0) of the study area with true value of mean density 45.0383 trees/hectare.

Method	Estimated mean density. (trees/hectare)	Standard deviation	95 % confi- dence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	43.5886	16.0516	[35.2613 ; 51.9159]	36.8252	3.3185	1.7351
BAF=2	41.9377	17.8682	[32.6680 ; 51.2074]	42.6066	2.0157	1.4109
M-Tree Sampling (1):						
3-Tree Sampling	44.2531	13.5665	[37.2151 ; 51.2911]	30.6565	2.0870	0.7563
4-Tree Sampling	45.5162	13.1623	[38.6878 ; 52.3445]	28.9178	2.4833	0.8007
5-Tree Sampling	44.4482	11.3841	[38.5423 ; 50.3541]	25.6121	2.9213	0.7388
6-Tree Sampling	44.8199	13.3217	[37.9089 ; 51.7309]	29.7226	3.4704	1.1821
7-Tree Sampling	45.1305	12.4705	[38.6610 ; 51.5999]	27.6321	4.0444	1.1906
8-Tree Sampling	45.5127	12.8147	[38.8647 ; 52.1607]	28.1562	4.8333	1.4774
9-Tree Sampling	45.6415	13.7989	[38.4829 ; 52.8001]	30.2332	5.9204	2.0865
10-Tree Sampling	45.1747	14.4659	[37.6701 ; 52.6793]	32.0221	7.0750	2.7972
M-Tree Sampling (2):						
3-Tree Sampling	35.4025	10.8532	[29.7721 ; 41.0329]	30.6565	2.0870	0.7563
4-Tree Sampling	39.0139	11.2820	[33.1610 ; 44.8668]	28.9178	2.4833	0.8007
5-Tree Sampling	39.5095	10.1192	[34.2599 ; 44.7591]	25.6121	2.9213	0.7388
6-Tree Sampling	40.7454	12.1106	[34.4626 ; 47.0281]	29.7226	3.4704	1.1821
7-Tree Sampling	41.6589	11.5112	[35.6871 ; 47.6307]	27.6321	4.0444	1.1906
8-Tree Sampling	42.4786	11.9604	[36.2738 ; 48.6834]	28.1562	4.8333	1.4774
9-Tree Sampling	42.9567	12.9872	[36.2192 ; 49.6942]	30.2332	5.9204	2.0865
10-Tree Sampling	42.7971	13.7045	[35.6875 ; 49.9067]	32.0221	7.0750	2.7972
Circular Plot:						
(Area 0.1 hectares)	45.0000	13.8267	[37.8270 ; 52.1730]	30.7259	2.7472	1.0000

Table 9 shows that the estimated mean densities of 3-tree sampling (2), 4-tree sampling (2), and 5-tree sampling (2) are comparatively much smaller than the true value of the mean density mentioned above. Unlike other methods tested, the 95% confidence intervals of these three methods do not include the true value of the mean density, so that these methods show significant bias in estimating density of this stratum.

In general, all methods of m-tree sampling (1) and circular plot sampling estimate the true value of the mean density more closely and their 95% confidence intervals contain the true mean density. These methods generally exhibit shorter confidence intervals and smaller coefficients of variation. Of these methods, the three most efficient methods are 3-tree sampling (1), 4-tree sampling (1) and 5-tree sampling (1) according to efficiency ratios in Table 9. Among these methods, 5-tree sampling (1) gives the best result with an efficiency ratio of 0.7388.

Of all methods, 5-tree sampling (1) exhibits the best result for estimating the density of this stratum. Of all the methods whose confidence intervals contain the true mean density, 5-tree sampling (1) has the smallest standard deviation, coefficient of variation, and efficiency ratio.

Stratum 2.

The true value of mean density for this stratum is 66.2765 trees/hectare. This mean density is generally close to the estimated mean density given by methods of point sampling, circular plot and m-tree sampling (1). The estimates of this mean density given by the methods studied is presented in Table 10.

Table 10. Results in density estimation based on 30 samples selected from Stratum 2 (bonita 2.5) of the study area with true value of mean density 66.2765 trees/hectare.

Method	Estimated mean density (trees/hectare)	Standard deviation	95 % confidence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	62.2536	14.1657	[56.9646 ; 67.5426]	22.7548	6.8333	2.1374
BAF=2	61.3022	16.1498	[55.2724 ; 67.3319]	26.3446	2.9444	1.2345
M-Tree Sampling (1):						
3-Tree Sampling	64.9696	15.4901	[59.1861 ; 70.7530]	23.8421	1.9439	0.6675
4-Tree Sampling	62.8710	16.1773	[56.8310 ; 68.9110]	25.7309	2.3261	0.9304
5-Tree Sampling	64.3126	13.3562	[59.3259 ; 69.2993]	20.7676	2.7227	0.7094
6-Tree Sampling	65.7864	13.3463	[60.8034 ; 70.7694]	20.2874	3.3311	0.8282
7-Tree Sampling	64.5962	12.8924	[59.7826 ; 69.4098]	19.9585	3.9389	0.9479
8-Tree Sampling	65.0756	13.3700	[60.0837 ; 70.0675]	20.5453	4.8650	1.2406
9-Tree Sampling	63.1107	12.5963	[58.4077 ; 67.8137]	19.9590	6.0006	1.4441
10-Tree Sampling	64.3183	12.1314	[59.7889 ; 68.8477]	18.8614	7.2344	1.5548
M-Tree Sampling (2):						
3-Tree Sampling	51.9757	12.3962	[47.3474 ; 56.6040]	23.8421	1.9439	0.6675
4-Tree Sampling	53.8894	13.8662	[48.7123 ; 59.0665]	25.7309	2.3261	0.9304
5-Tree Sampling	57.1668	11.8721	[52.7342 ; 61.5994]	20.7676	2.7227	0.7094
6-Tree Sampling	59.8058	12.1330	[55.2758 ; 64.3358]	20.2874	3.3311	0.8282
7-Tree Sampling	59.6272	11.9007	[55.1839 ; 64.0705]	19.9585	3.9389	0.9479
8-Tree Sampling	60.7372	12.4787	[56.0781 ; 65.3963]	20.5453	4.8650	1.2406
9-Tree Sampling	59.3983	11.8553	[54.9719 ; 63.8246]	19.9590	6.0006	1.4441
10-Tree Sampling	60.9331	11.4929	[56.6421 ; 65.2241]	18.8614	7.2344	1.5548
Circular Plot:						
(Area 0.1 hectares)	66.3333	13.7674	[61.1930 ; 71.4735]	20.7548	3.8428	1.0000

Unlike other methods in this study, all methods of m-tree sampling (2) exhibit a significantly biased estimate of the true mean density mentioned above since the 95% confidence intervals of these methods do not include the true value of the mean density of this stratum. These methods also yield smaller estimated mean densities than the rest of the methods for the reasons discussed in general view mentioned above. Therefore, for this stratum, no methods of m-tree sampling (2) can be recommended because of their biases in the estimate of the mean density.

On the basis of standard deviation, coefficient of variation and the 95% confidence interval, 10-tree sampling (1) yields the best result, though the values of this method approximate closely those of 5-tree sampling (1), 6-tree sampling (1), 7-tree sampling (1), 8-tree sampling (1), 9-tree sampling (1) and plot sampling. This method also shows a shorter confidence interval than those methods. Hence, 10-tree sampling (1) is considered the method having the best accuracy in estimating density of the Stratum 2.

The efficiency of the methods studied exhibits a different rank from the criteria discussed above. Although 5-tree sampling (1) and 6-tree sampling (1) show better precision than 3-tree sampling (1), 3-tree sampling (1) gives the smallest efficiency ratio of 0.6675. So, among the methods whose confidence interval contain the true mean density, 3-tree sampling (1) is considered the most efficient method in estimating density of this stratum.

Stratum 3.

Stratum 3 yields the true value of mean density of 65.9240 trees/ hectare. If this value is compared to the estimates of the mean density based on the methods tested, only four methods do not give reliable estimates of this value in the sense that their confidence intervals do not contain the true mean density. These methods are 3-tree sampling (2), 4-tree sampling (2), 5-tree sampling (2) and 6-tree sampling (2). Also, the estimates of mean density of these methods are comparatively further from the true value of the mean density of this stratum. These facts suggest that these four methods may provide biased estimates for forest inventory of the area studied.

Table 11 presents detailed results of density estimation for Stratum 3 which reflects responses of the methods tested in estimating density of this area. This table suggests that point sampling with BAF = 1 shows the best results in terms of the 95% confidence interval, standard deviation and the coefficient of variation in estimating density of this stratum. Point sampling with BAF = 1 yields the smallest standard deviation and the shortest confidence interval. This method also shows the smallest coefficient of variation beside having a confidence interval which includes the true value of the mean density of the Stratum 3. Based on these results, the point sampling with BAF = 1 is to be regarded as the method having the best accuracy in estimating density of this stratum.

According to Table 11, a group of four methods has the best efficiency ratios among methods whose confidence intervals contain the estimate of the mean density of this stratum. These methods are 3-tree sampling (1), 4-tree sampling (1), 5-tree sampling (1) and 6-tree sampling (1). Of these methods, 3-tree sampling (1) shows the best ratio though 5-tree sampling (1) and 6-tree sampling (1) have a more precise estimate of the mean density. The 3-tree sampling (1) method yields the smallest efficiency ratio (0.5335) and hence this method is regarded the most efficient method in estimating density of the Stratum 3.

Table 11. Results in density estimation based on 24 samples selected from Stratum 3 (bonita 3.0) of the study area with true value of mean density 65.9240 trees/hectare.

Method	Estimated mean density. (trees/hectare)	Standard deviation	95 % confi- dence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	62.3787	14.8723	[56.0976 ; 68.6598]	23.8419	9.1062	1.8287
BAF=2	63.3170	17.6959	[55.8434 ; 70.7906]	27.9481	4.3014	1.1870
M-Tree Sampling (1):						
3-Tree Sampling	63.5189	18.9470	[55.5170 ; 71.5208]	29.8290	1.6972	0.5335
4-Tree Sampling	62.6272	19.0545	[54.5799 ; 70.6745]	30.4253	2.2188	0.7256
5-Tree Sampling	64.9866	17.8062	[57.4665 ; 72.5067]	27.3998	2.7354	0.7255
6-Tree Sampling	64.3438	17.6829	[56.8757 ; 71.8119]	27.4820	3.3910	0.9048
7-Tree Sampling	65.0912	17.3582	[57.7603 ; 72.4221]	26.6675	4.0257	1.0114
8-Tree Sampling	65.3495	18.2907	[57.6247 ; 73.0743]	27.9890	4.7979	1.3279
9-Tree Sampling	64.4000	18.8124	[56.4549 ; 72.3451]	29.2118	5.7688	1.7391
10-Tree Sampling	66.4914	17.7856	[58.9799 ; 74.0028]	26.7488	6.8646	1.7352
M-Tree Sampling (2):						
3-Tree Sampling	50.8151	15.1576	[44.4135 ; 57.2167]	29.8290	1.6972	0.5335
4-Tree Sampling	53.6805	16.3324	[46.7828 ; 60.5782]	30.4253	2.2188	0.7256
5-Tree Sampling	57.7659	15.8278	[51.0813 ; 64.4505]	27.3998	2.7354	0.7255
6-Tree Sampling	58.4943	16.0754	[51.7051 ; 65.2835]	27.4820	3.3910	0.9048
7-Tree Sampling	60.0842	16.0230	[53.3172 ; 66.8512]	26.6675	4.0257	1.0114
8-Tree Sampling	60.9929	17.0713	[53.7831 ; 68.2027]	27.9890	4.7979	1.3279
9-Tree Sampling	60.6117	17.7058	[53.1340 ; 68.0894]	29.2118	5.7688	1.7391
10-Tree Sampling	62.9918	16.8495	[55.8757 ; 70.1079]	26.7488	6.8646	1.7352
Circular Plot:						
(Area 0.1 hectares)	67.9167	17.9320	[60.3434 ; 75.4900]	26.4030	4.0604	1.0000

Stratum 4.

The true value of mean density in Stratum 4 is 76.6340 trees/hectare, while the estimate of this mean density given by each method tested is shown by Table 12. The 95% confidence interval of all methods except for 3-tree sampling (2), 4-tree sampling 2), and 5-tree sampling (2) contain the true value of mean density. Therefore, the methods other than 3-tree sampling (2), 4-tree sampling (2), and 5-tree sampling (2) can be used in comparison of efficiency since they have not shown significant bias in estimating density of this stratum.

Among the methods applied in this study, point sampling with BAF = 2 shows the most precise estimate of the mean density of this stratum. Besides containing the true mean density in its 95% confidence interval, this method shows the smallest standard deviation and smallest coefficient of variation. This method also yields the shortest confidence interval among the methods studied. Hence, point sampling with BAF = 2 exhibits the best accuracy in estimating the density of the Stratum 4.

An interesting result in this stratum is presented by the efficiency of the methods studied. Except for point sampling with BAF = 1 and the methods having bias in the estimate of the mean density above (since these methods are not considered), the methods studied yield efficiency ratios smaller than one. This fact indicates that these methods are more efficient than circular plot sampling in estimating density of this stratum.

The best (smallest) efficiency ratio is associated with 3-tree sampling (1) which has an efficiency ratio of 0.3154. So, 3-tree sampling (1) is to be regarded as the most efficient method in estimating density in Stratum 4.

Table 12. Results in density estimation based on 12 samples selected from Stratum 4 (bonita 3.5) of the study area with true value of mean density 76.6340 trees/hectare.

Method	Estimated mean density. (trees/hectare)	Standard deviation	95 % confi- dence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	71.3126	18.8002	[59.3674 ; 83.2578]	26.3631	11.0653	2.4504
BAF=2	71.3914	12.5981	[63.3869 ; 79.3959]	17.6465	5.6555	0.5612
M-Tree Sampling (1):						
3-Tree Sampling	71.5798	17.2365	[60.6282 ; 82.5314]	24.0802	1.7094	0.3154
4-Tree Sampling	73.4206	16.8631	[62.7062 ; 84.1350]	22.9677	2.1667	0.3642
5-Tree Sampling	74.1121	16.3708	[63.7105 ; 84.5137]	22.0892	2.7014	0.4200
6-Tree Sampling	74.6172	16.5983	[64.0711 ; 85.1633]	22.2446	3.3250	0.5242
7-Tree Sampling	74.5720	15.0882	[64.9853 ; 84.1586]	20.2331	3.9361	0.5134
8-Tree Sampling	73.4411	15.3840	[63.6665 ; 83.2157]	20.9474	4.9389	0.6905
9-Tree Sampling	74.6142	15.5562 1	[64.7302 ; 84.4982]	20.8448	5.9764	0.8277
10-Tree Sampling	74.6898	15.3008	[64.9681 ; 84.4115]	20.4859	7.2472	0.9691
M-Tree Sampling (2):						
3-Tree Sampling	57.2639	13.7892	[48.5026 ; 66.0252]	24.0802	1.7094	0.3154
4-Tree Sampling	62.9319	14.4540	[53.7482 ; 72.1156]	22.9677	2.1667	0.3642
5-Tree Sampling	65.8774	14.5518	[56.6316 ; 75.1232]	22.0892	2.7014	0.4200
6-Tree Sampling	67.8338	15.0893	[58.2464 ; 77.4211]	22.2446	3.3250	0.5242
7-Tree Sampling	68.8357	13.9276	[59.9865 ; 77.6849]	20.1331	3.9361	0.5134
8-Tree Sampling	68.5450	14.3584	[59.4220 ; 77.6680]	20.9474	4.9389	0.6905
9-Tree Sampling	70.2251	14.6411	[60.9225 ; 79.5277]	20.8488	5.9764	0.8277
10-Tree Sampling	70.7587	14.4955	[61.5486 ; 79.9688]	20.4859	7.2472	0.9691
Circular Plot:						
(Area 0.1 hectares)	73.3333	19.2275	[61.1166 ; 85.5500]	26.2193	4.5653	1.0000

Stratum 5.

This stratum yields true value of mean density of 83.3430 trees/ hectare. In general, this true value of mean density is included in the 95% confidence interval of the methods researched, except for 3-tree sampling (2) and 4-tree sampling (2). The methods tested yield the estimates of the mean density as described by Table 13.

Table 13 shows that 7-tree sampling (2) yields the best result in terms of standard deviation, confidence interval and coefficient of variation. This method exhibits the smallest standard deviation and smallest coefficient of variation among the methods studied. This method also yields the shortest confidence interval which includes the true value of the mean density in Stratum 5. Based on these facts, 7-tree sampling (2) is ranked as the method having the best precision in estimating density of this stratum.

In terms of efficiency, only 6 of the methods that are not significantly biased show efficiency ratios smaller than one in this stratum. These methods are 3-tree sampling (1), 4-tree sampling (1), 5-tree sampling (1), 7-tree sampling (1), 5-tree sampling (2) and 7-tree sampling (2). Of these methods, 3-tree sampling (1) gives the best result with efficiency ratio of 0.4700. Therefore, 3-tree sampling (1) is the most efficient method for estimating density of the Stratum 5.

Population.

On the basis of results given by all strata in this study, the population studied has the true value of mean density 65.7812 trees/hectare. In general, this mean density is included in the 95% confidence interval of all methods of m-tree sampling (1), circular

Table 13. Results in density estimation based on 9 samples selected from Stratum 5 (bonita 4.0) of the study area with true value of mean density 83.3430 trees/hectare.

Method	Estimated mean density. (trees/hectare)	Standard deviation	95 % confi- dence interval	Coefficient of variation (%)	Mean time	Efficiency ratio
Point Sampling:						
BAF=1	85.0684	28.0937	[63.4737 ; 106.6631]	33.0248	12.0481	3.4543
BAF=2	79.5345	21.8683	[62.7251 ; 96.3439]	27.4954	6.5889	1.3095
M-Tree Sampling (1):						
3-Tree Sampling	70.6862	23.8934	[52.3201 ; 89.0523]	33.8021	1.5648	0.4700
4-Tree Sampling	72.2222	21.9311	[55.3645 ; 89.0799]	30.3662	2.2056	0.5346
5-Tree Sampling	83.6373	23.0883	[65.8901 ; 101.3845]	27.6053	2.7704	0.5550
6-Tree Sampling	83.7142	28.8900	[61.5074 ; 105.9210]	34.5102	3.3981	1.0639
7-Tree Sampling	86.1392	20.4009	[70.4577 ; 101.8207]	23.6836	4.0426	0.5961
8-Tree Sampling	89.2587	25.6591	[69.5354 ; 108.9820]	28.7469	4.8518	1.0540
9-Tree Sampling	80.6063	21.2074	[64.3049 ; 96.9077]	26.3098	5.6741	1.0325
10-Tree Sampling	77.9420	22.4981	[60.6485 ; 95.2355]	28.8652	6.6611	1.4590
M-Tree Sampling (2):						
3-Tree Sampling	56.5489	19.1147	[41.8561 ; 71.2417]	33.8021	1.5648	0.4700
4-Tree Sampling	61.9047	18.7981	[47.4552 ; 76.3542]	30.3662	2.2056	0.5346
5-Tree Sampling	74.3443	20.5229	[58.5690 ; 90.1196]	27.6053	2.7704	0.5550
6-Tree Sampling	76.1038	26.2636	[55.9158 ; 96.2917]	34.5102	3.3981	1.0639
7-Tree Sampling	79.5131	18.8316	[65.0379 ; 93.9883]	23.6836	4.0426	0.5961
8-Tree Sampling	83.3081	23.9485	[64.8997 ; 101.7165]	28.7469	4.8518	1.0540
9-Tree Sampling	75.8647	19.9599	[60.5222 ; 91.2072]	26.3098	5.6741	1.0325
10-Tree Sampling	73.8398	21.3140	[57.4564 ; 90.2232]	28.8652	6.6611	1.4590
Circular Plot:						
(Area 0.1 hectares)	87.7778	23.3333	[69.8422 ; 105.7133]	26.5823	5.3833	1.0000

plot and point sampling. In estimating this mean density, each method studied gives results as shown by Table 14.

As consequences of factors mentioned in general discussion above, all methods of m-tree sampling (2) show bias in their confidence intervals. The 95% confidence interval of these methods do not contain the true value of the mean density. The estimated mean density of these methods also is comparatively further from the true value of the mean density than the other methods. Therefore, none of the methods of m-tree sampling (2) can be considered for comparison of accuracy and efficiency due to their bias in estimation of the mean density.

Among methods whose confidence intervals contain the true mean density above, 5-tree sampling (1), 7-tree sampling (1) and 10-tree sampling (1) exhibit the best estimates of the mean density. These methods show smaller standard deviations and smaller coefficients of variation than the others. These methods also yield shorter confidence intervals than other methods. In this case, 10-tree sampling (1) gives the smallest standard deviation, shortest confidence interval and the smallest coefficient of variation. So, 10-tree sampling (1) is considered the most accurate method in estimating density of the population studied.

A different pattern of results in density estimation is shown by the efficiency of the methods studied. The ranking of the precision is generally contrary to the ranking of efficiency ratio, except 5-tree sampling (1) which shows much better efficiency than most of the methods. In this case, 3-tree sampling (1) exhibits the best efficiency ratio (0.5515) although this method yields a larger standard deviation, larger coefficient variation and a

Table 14. Results in density estimation based on 93 samples selected from the entire population of the study area with true value of mean density 65.7812 trees/hectare.

Method	Estimated mean density (trees/hectare)	Standard error	95 % confidence interval	Coefficient of variation (%)	Mean time (min)	Efficiency ratio
Point Sampling:						
BAF=1	62.3646	1.7718	[58.8918 ; 65.9374]	2.8411	7.8714	2.2950
BAF=2	61.4902	1.7624	[58.0360 ; 65.8444]	2.8661	3.8474	1.1416
M-Tree Sampling (1):						
3-Tree Sampling	62.3682	1.7979	[58.8444 ; 65.8920]	2.8827	1.8373	0.5515
4-Tree Sampling	62.0664	1.7878	[58.5622 ; 85.8106]	2.8805	2.2929	0.6872
5-Tree Sampling	64.1281	1.6465	[60.9009 ; 67.3553]	2.5676	2.7628	0.6579
6-Tree Sampling	64.5949	1.7572	[61.1508 ; 68.0390]	2.7204	3.3767	0.9026
7-Tree Sampling	64.6686	1.5778	[61.5762 ; 67.7610]	2.4398	3.9893	0.8578
8-Tree Sampling	65.1094	1.7011	[61.7752 ; 68.4436]	2.6127	4.8511	1.1962
9-Tree Sampling	63.5621	1.6497	[60.3286 ; 66.7956]	2.5955	5.8926	1.4338
10-Tree Sampling	64.1940	1.6289	[61.0013 ; 67.3867]	2.5375	7.0589	1.6418
M-Tree Sampling (2):						
3-Tree Sampling	49.8846	1.4383	[47.0656 ; 52.7036]	2.8827	1.8373	0.5515
4-Tree Sampling	53.1998	1.5324	[50.1962 ; 56.2034]	2.8805	2.2929	0.6872
5-Tree Sampling	57.0027	1.4636	[54.1341 ; 59.8713]	2.5676	2.7628	0.6579
6-Tree Sampling	58.7226	1.5975	[55.5916 ; 61.8536]	2.7204	3.3767	0.9026
7-Tree Sampling	59.6941	1.4564	[56.8396 ; 62.5486]	2.4398	3.9893	0.8578
8-Tree Sampling	60.7688	1.5877	[57.6569 ; 63.8807]	2.6127	4.8511	1.1962
9-Tree Sampling	59.8232	1.5527	[56.7799 ; 62.8665]	2.5955	5.8926	1.4338
10-Tree Sampling	60.8154	1.5432	[57.7907 ; 63.8401]	2.5375	7.0589	1.6418
Circular Plot:						
(Area 0.1 hectares)	65.9312	1.7457	[62.5096 ; 69.3528]	2.6478	3.9489	1.0000

wider confidence interval. This occured because the average time required for 3-tree sampling (1) was less than the time required for any other method. The 3-tree sampling (1) method is considered the most efficient method in estimating density of the population studied.

Closing View

On the basis of the discussions described above, this study achieves two major results. First, among the methods that did not show significant bias in this study, 5-tree sampling (1) is considered the most precise, accurate and most efficient method in estimating volume of the study area. Second, in density estimation of the study area, 3-tree sampling (1) is regarded the most efficient method if compared with other methods applied in this study. To decide which method will be used in forest inventory of the study area will depend upon the needs of forest managers in the field.

In general, for the timber management performed for teak plantations, both volume and density of mature forests are essential to furnish information for production planning. Since the study area is a part of the population of mature teak forests, the application of a method needs to yield not only reliable estimates of density but also reliable estimates of volume for the forest. One of the major considerations for application of an inventory method is the need to obtain accurate information of the forest as efficiently as possible. In this case, 3-tree sampling (1) should not be applied alone since risks in terms of bias in volume estimation of the forest are likely to occur (Table 8). Although this method can efficiently yield reliable estimates of the density of the forest, it does not satisfy the need to have reliable estimates of the volume of the forest. If this method is used together with another method that gives reliable estimates of the volume of the forest, additional time will be needed. Since large numbers of samples are taken from the mature teak forest for management planning every year, this procedure will increase the time need for measurements and consequently increase the cost of the forest inventory. Moreover, although 3-tree sampling (1) is regarded as the most efficient method in density estimation of the forest, the precision of this method is generally less than other methods which also have reliable estimates and efficiency ratios less than one. Hence, the application of 3-tree sampling (1) for estimating density and volume of the teak forests will probably not be practical in actual forest management.

The application of 5-tree sampling (1) seems to be preferable in estimating volume and density of the mature teak forests. Based on volume estimation, 5-tree sampling (1) is the most efficient method in estimating volume of the teak forest studied. This method also shows the best accuracy in estimating this parameter. For density estimation, 5-tree sampling (1) yields much better precision than 3-tree sampling (1) although 5-tree sampling (1) is ranked as the second most efficient method in estimating density. Moreover, for density estimation of the study area, this method also yields better accuracy than most methods applied in this study. Thus, 5-tree sampling (1) may be the most suitable of the methods studied for forest inventory of the teak forest.

It is interesting to note that 5-tree sampling (1) has never been applied for inventories of teak plantations in the research area, or anywhere else in Java. The only method previously used to inventory this mature forest in this region is the circular plot sampling (0.1 hectares). Hence, successful application of 5-tree sampling (1) in this study may lead to a more efficient way of estimating volume and density of the teak plantations in this area.

An inspection of the results of similar studies frequently shows the potential utility of m-tree sampling for forest inventories. Prodan (1968) found that 6-tree sampling (1) was the most efficient method among methods tested for inventory of mixed-forests in Southern West Germany. Rusydi (1982) concluded that 8-tree sampling (1) was the best method of the methods studied for estimating volume and density of growing teak plantations (age class 3 - 4) in Bojonegoro, East Java, Indonesia. Other results were obtained by simulation research conducted by Jonsson et al. (1992). The researcher concluded that 6-tree sampling (2) to 12 tree sampling (2) were generally quick and objective besides producing insignificant bias for inventory of mixed-forests having Poisson spatial patterns in Lapland and Vastergotland, Sweden. Lessard et al. (1994) showed that the error, cost efficiency index and time for 3-tree sampling (2) were generally competitive with the other methods tested in estimating cord volume, basal area and density of randomly patterned red pine and clumped hardwoods in northern Michigan, U.S.A. In the study of Lessard et al. (1994a) 3-tree sampling method was more efficient than point or fixed-radius circular plot sampling for density and volume estimation in the red pine plantation and in clumped hardwoods, while point and fixed-radius circular plot sampling were more efficient than m-tree sampling for estimation of board-foot volume in the northern hardwoods type. In another comparison of m-tree sampling, point sampling and fixed-radius circular plot sampling conducted by computer simulation of mapped forest stands, Lessard et al. (1994b) found that 3-tree sampling and point sampling were the most efficient methods for the northern hardwoods data, while in the red pine plantation, the time required by each of the three techniques to obtain 20% error in estimation at the 95% probability level was very similar for all three methods.

In general, the variation in the results of these studies seemed to be caused by a variety of tree spatial distributions and physical situations of the research areas. A variety of forest types, including plantations and naturally occurring stands, were represented by various studies. A variety of species were represented as well as differing management regimes. As a result, the spatial distributions and intervals of distance among trees are different in each area studied. Consequently, there was variation concerning the best number of trees (m) for m-tree sampling in different studies.

A significant feature of these studies was that various methods of m-tree sampling frequently showed the best performance in estimating volume and density of the forest. These facts indicate that the m-tree methods have significant potential for application. Therefore, the results of these studies are supposed to be an input for evaluating forest inventory in this region in the future.

Also there was variation concerning the best method of bias correction for use in m-tree sampling. Some studies, such as that of Lessard et al. (1994a) obtained satisfactory results with the factor (m-1)/m for bias correction. In other studies, such as the one presented here, alternate methods performed better.

An advantage of fixed-radius circular plot sampling and point sampling over m-tree sampling is that both fixed-radius circular plot and point sampling can be proven mathematically to be unbiased for any tree spatial distribution (Palley and Horwitz 1961). When the bias correction factor (m-1)/m is used, m-tree sampling has been proven to be mathematically unbiased in forests having a Poisson spatial distribution (random spatial distribution) and a negative binomial spatial distribution (clumped spatial distribution) (Eberhart 1967, Moore 1954, Jonsson et al. 1992). However, there are no mathematical proofs of unbiasedness for m-tree sampling in forests having other spatial distributions such as uniform (plantations). For forests that do not have either negative binomial or Poisson spatial distributions one must currently rely on results from empirical studies and computer simulations.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

Successful applications of point sampling and m-tree sampling in several forest types suggested the potential utility of these methods for inventories of teak plantations in Java, in which fixed-radius circular plot sampling is still used exclusively. In order to obtain the best inventory method for these forests, efficiency of those methods need to be evaluated. Therefore, the objective of this study is to compare the relative efficiency of point sampling, fixed-radius circular plot, and m-tree sampling, using fixed-radius circular plot sampling as the standard of the comparison for estimating volume and density of teak plantations at three forest management areas of Perum Perhutani in East Java, Indonesia.

To perform this study, mature teak plantations having age class 8 (71-80 years) at KPH Madiun, KPH Bojonegoro and KPH Saradan were used as the population of the study. This population was divided into five strata according to bonita (forest land fertility class): Stratum 1 (bonita 2.0), Stratum 2 (bonita 2.5), Stratum 3 (bonita 3.0), Stratum 4 (bonita 3.5) and Stratum 5 (bonita 4.0).

To estimate the mean volume and mean density of every stratum and the entire population, nineteen inventory methods were applied in the study area. These methods consisted of two methods of point sampling (each with a different BAF), sixteen methods of m-tree sampling and 0.1 hectare fixed-radius circular plot sampling.

In applying these methods, ninety three samples for each method were selected systematically with random start from the whole strata in which the same sampling locations were used for every method. Measurements and data processing were performed in accordance with procedures of each method. These results were utilized to estimate the mean (volume and density), and variability of each method by using the procedures of stratified systematic sampling.

The true value of the mean (volume and density) from the census of the forest was used to evaluate the reliability of each method in estimating volume and density of the forest studied. The methods having bias for volume or density estimation did not qualify for further comparison of efficiency. The efficiency of each method was compared by using the relative efficiency formula.

The results of the study indicate that the application of methods of m-tree sampling (2) yields biased estimates of volume and density of the study area since the 95% confidence intervals of these methods generally shows departures from the true value of the mean volume and mean density of the population. This fact is probably due to the uniform spatial distribution of teak plantations in which the correction factor (m - 1)/m is presumably not suitable to be applied.

In estimating volume of the population, 3-tree sampling (1) and 4-tree sampling (1) give biased estimates of the mean volume of the population. This indicates more trees need to be sampled at each field location to reduce bias.

The method of 5-tree sampling (1) shows the best accuracy and the best efficiency ratio for estimating volume of Strata 1, 2, 3, and 4. For Stratum 5, this method is considered as the second ranking in terms of efficiency since 7-tree sampling (2) appears with the best accuracy and the best efficiency ratio for estimating volume of this stratum. In general, 5-tree sampling (1) yields the best accuracy and the best efficiency ratio (0.3313) for estimating volume of the population studied.

The method of 5-tree sampling (1) is found as the best method for estimating density of Stratum 1 since this method shows the best accuracy and smallest efficiency ratio (0.7388). However, this method only remains as the second ranking in efficiency ratio for Strata 2, 3 and the entire population since 3-tree sampling (1) has the best efficiency ratio for estimating density of Strata 2, 3, 4 and 5. In general, 3-tree sampling (1) yields the smallest efficiency ratio (0.5515) for estimating density of the population studied.

To decide which method will be used in forest inventory of the forest studied will depend upon the need of management practice in the field. In general, for the timber management performed for teak plantations, both volume and density of mature forests are essential to furnish information for production planning.

The results of similar studies showed the potential utility of individual methods of m-tree sampling for forest inventory. Various individual methods of m-tree sampling frequently showed good performance in estimating volume and density of the forests studied.

Conclusions

Among the methods applied in this study, 5-tree sampling (1) is generally considered the most accurate and most efficient method for estimating volume of the mature teak plantations studied. For density estimation, 3-tree sampling (1) generally appears as the most efficient method for estimating the number of trees of the study area.

The application of 3-tree sampling (1) does not seem to be beneficial for inventory of the population studied due to its bias for volume estimation, its relative lack of precision for density estimation, and time of measurement in using this method together with another method having reliable estimate for volume estimation. In order to fulfill the need of providing basic data concerning both volume and density of the mature teak forest, 5-tree sampling (1) is favorable to be employed for inventory of mature teak plantations studied since this method generally gives better accuracy and efficiency for estimating both volume and density of the study area.

The results of this study and similar studies indicate that various methods of m-tree sampling can perform as effectively as more conventional methods such as fixed-radius circular plot and point sampling. For the mature teak forests studied here, m-tree sampling was more efficient than fixed-radius circular plot and point sampling. The results of these studies should be useful for evaluating forest inventory alternatives in the future, especially for mature teak plantations in Java, Indonesia.

LITERATURE CITED

Afanasiev, M. 1958. Some results of the use of the Bitterlich method of cruising in an even-aged stand of longleaf pine. Journal of Forestry, 58: 341-343.

Avery, T.E., and Burkhart, H.E. 1994. Forest measurements. New York: McGraw-Hill. 408 p.

Bitterlich, W. 1947. Die winkelzahlmessung. Allg. Forst-u Holzwirts Zeitung, 58: 94-96.

Cochran, W.G. 1977. Sampling techniques. New York: John Wiley & Sons Inc. 428 p.

Eberhardt, L.L. 1967. Some developments in distance sampling. Biometrics 23: 207-216.

Grosenbaugh, L.R. and Stover, W.S. 1957. Point-sampling compared with plot sampling in Southeast Texas. Forest Science, 3: 2-14.

Holgate, P. 1967. The angle-count method. Biometrika, 54: 615-623.

Husch, B., Miller, C.I., and Beers, T.W. 1982. Forest mensuration. New York: John Willey & Sons Inc. 410 p.

Jonsson, B., Holm, S., and Kallur, H. 1992. A forest inventory method based on density-adapted circular plot size. Scandinavian Journal of Forest Resources, 7: 405-421.

Lessard, V.C., Reed, D.D., Monkevich, N. 1994a. Comparing n-tree distance sampling with point and plot sampling in northern Michigan forest types. Northern Journal of Applied Forestry 11(1): 12-16.

Lessard, V.C., Reed, D.D., and Drummer, T.D. 1994b. N-tree distance sampling compared to fixed-radius plot and variable radius point sampling in forest inventory estimation of basal area per acre. In: Proceedings of the Mone Verita conference on forest survey design, Ascona, Switzerland, May 2-7, 1994: 81-90.

Loetsch, F., Zohrer, F. and Haller, K.E. 1978. Forest inventory. Volume 2. Munchen: Blv Verlagsgesselschaft, Bassel, Wien. 469 p.

Matérn, B. 1972. The Precision of Basal Area Estimates. Forest Science, 18: 123-125.

Moore, P.G. 1954. Spacing in plant populations. Ecology 35: 222-227.

Munawardi. 1960. Tingkah laku manusia dan organisasi. Majalah Administrasi Negara, II (3): 4-5.

Nasution, A.H., and Barizi, B. 1976. Metoda Statistika. Jakarta: PT. Gramedia. 365 p.

Oderwald, R.G. 1981. Comparison of point sampling and plot sampling basal area estimators. Forest Science, 27: 42-48.

Palley, M.N., and Horwitz, L.G. 1961. Properties of some random and systematic point sampling estimators. Forest Science 7: 52-65.

Payandeh, B., and A.R. Ek. 1986. Distance methods and density estimators. Canadian Journal of Forestry Research 16: 918-924.

Perum Perhutani. 1979. Petunjuk pelaksanaan menghitung volume dan jumlah batang kayu perkakas jati. Jakarta: Direktur Jenderal Kehutanan, Indonesia. 106 p.

Prodan, M. 1968. Punkstichprobe für die Forsteinrichtung. Forst und Holzwirt, 23 (11): 225-226.

Riyadi, R. 1975. Efisiensi dan informasi. Majalah Manajemen (II): 8-10.

Rusydi. 1982. Studi perbandingan bermacam petak coba dalam pendugaan potensi tegakan jati (Tectona grandis) di KPH Bojonegoro Perum Perhutani Unit II Jawa Timur. Thesis in the Departement of Management, Faculty of Forestry. Bogor: Bogor Agricultural University.

Soekiman, S. 1954. Memperkenalkan alat Bitterlich pengukur bidang dasar tiap hektar. Rimba Indonesia III (8-9-10): 352-357.

Spurr, S.H. 1952. Forest inventory. New York: The Ronald Press Company. 476 p.

Sukhatme, P.V., 1963. Sampling theory of surveys with applications. New Delhi: The Indian Society of Agricultural Statistics. 491 p.

Sukwong, S., Frayer, W.E. and Mogren, E.W. 1971. Generalized comparisons of the precision of fixed-radius and variable radius plots for basal-area estimates. Forest Science, 17: 263-271.

Sutarahardja, S. 1976. Metode 6-baum stichprobe. Sebetan, IX (63): 25-31.

Thompson, H.R. 1956. Distribution of distance to nth neighbor in a population of randomly distributed individuals. Ecology 37: 391-394.

VITA 2

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