THE SILVICULTURE, GROWTH AND YIELD OF NEEM (*Azadirachta indica* A. Juss.) PLANTATIONS IN NORTHERN GHANA

by

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ABSTRACT

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The silviculture and growth and yield of neem (*Azadirachta indica* A. Juss.) grown in individual and community plantations in the Tamale Forest District of Northern Ghana was investigated in 1995. Owing to rising populations and an increasing demand for agricultural land, shortages of wood for poles, rafters and fuel are increasing. Plantations of neem and other exotic species were rapidly expanded from 1989 to minimize the effect of the forthcoming shortage and to guarantee wood products for village communities. The current silviculture for neem in Northern Ghana is adequate for present levels of plantation establishment but will have to improve as the area planted expands. The principal changes will be seed collection from superior phenotypes, improvement in nursery and outplanting practice, closer initial spacing, and thinning. The measurement of 120 temporary sample plots in 30 plantations varying in age from one to nine years in the Tamale Forest District provided the data for the construction of local and standard volume table equations and the development of an empirical yield table. The Yield Table showed that the mean annual increment of Site Class I, II and III neem plantations was 12.9, 8.1 and 4.3 m^3/ha on biologically optimum rotations of 5, 7 and 11 years respectively. The three-parameter Weibull probability density function, the Normal and the Log-normal distributions were used to fit the diameter distributions of the neem plantations. Comparisons of the observed and predicted diameter frequencies indicate that the Log-normal distribution gave the best description of the diameter distributions, though the Weibull function was also found to be suitable.

CONTENTS

TABLES

FIGURES

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D.M.N.

DEDICATION

To

Mary, *for her patience*

Niibsaaban, *so he knows life is not fair*

1.0 INTRODUCTION

In Ghana deforestation is accelerating as a result of rapid population growth, increasing demand for diminishing supplies of fuelwood and building timber, increase in the frequency and extent of annual bush fires, and the extension of shifting cultivation into forested areas.

The World Bank (1988) estimates that the rising consumption and diminishing supply of fuelwood and other forest products in Ghana will result in severe shortages in the near future. New forest resources must now be created to offset greater losses of tree stocks.

In 1989, a Rural Forestry Division was established within the Ghana Forestry Department to encourage the establishment of plantations in order to mitigate the effects of the forthcoming wood shortage. To implement this programme the new Rural Forestry Division was given a mandate to establish and expand existing nurseries, to initiate and expand community and individual plantations, and to provide technical advice to farmers on establishment, management and protection of the trees. In addition, the new Division was to provide extension services and education on rural forestry and agro-forestry.

Before the advent of the Rural Afforestation Programme, the Forestry Department had helped some communities and farmers to establish plantations with exotic species such as neem (*Azadirachta indica* A. Juss.), cassia (*Senna siamia* Lam.)

and teak (*Tectona grandis* L.). With increasing interest in the Afforestation Programme, these plantations have been expanded and new ones established.

Local data is lacking on the survival, and growth and yield of these plantations. Equally lacking is information on the costs of establishment, maintenance and on the economic returns that may be expected from them.

Knowledge of the silvical characteristics and behaviour of the principal exotic species grown in Ghana and of their silviculture, and growth and yield is very important both to farmers and to the Forestry Department to ensure the optimum biological and economic productivity and sustainability of the plantations.

Neem (*Azadirachta indica* A. Juss. [*Meliaceae*]) is one of the most widely planted exotic species on nutrient deficient soils in Northern Ghana. According to Streets (1962), neem was introduced into Ghana *circa.* 1915. It was first planted in small plots scattered throughout the country along roadsides and in amenity belts in towns and villages. Neem has acclimatized well throughout Northern Ghana, and is popular as a source of fuelwood and as poles and rafters for building construction. Neem extracts are also valued for their medicinal properties in treating malaria and as an insecticide for storing grain. As neem is not browsed by animals and grows rapidly, it is easy to grow and maintain even within villages.

The objectives of this study are to:

1] describe and assess the present-day silviculture of neem;

2] assess the growth and yield of neem plantations; and

3] construct volume and empirical yield tables for neem plantations in the Tamale Forest District of Northern Ghana.

This work will provide the first account of the silviculture of and preliminary volume and yield tables for neem in the Tamale Forest District. It is hoped that the results of this study may be used to recommend changes in the silviculture of neem plantations in order to improve its growth and yield.

2.0 LITERATURE REVIEW

2.1 CRITICAL SILVICS OF NEEM

2.1.1 General Description

Neem or nim (*Azadirachta indica* A. Juss.) which is synonymous with *Melia indica* (A. Juss.) Brand., and *Melia azadirachta* L. belongs to the family Meliaceae. It is a deep-rooted, small to medium sized tree, broad-leaved and evergreen, except in periods of extreme drought (National Academy of Sciences, 1980). Mature trees attain heights of 7 - 20 m with a spread of 5 - 10 m and may live for more than 200 years (Ketkar, 1976). With its widely extended branches, the tree forms an ovate to round crown on a straight stem (von Maydell, 1990). The bark is brown-gray, of medium thickness and longitudinally and obliquely fissured; the slash is reddish brown (von Maydell, 1990). The heartwood is hard and durable with a specific gravity varying from 0.56-0.85 with an average of 0.68. The wood is resistant to termites and other wood-destroying insects even in exposed areas (von Maydell, 1990).

The leaves are imparinpinate, alternate, 20-40 cm long and 1 - 3 cm wide on slim petioles; 6- 10 cm long. The flowers are white, yellowish or cream-coloured, small, numerous and honey-scented (von Maydell, 1990). The fruit is an ellipsoidal drupe, with one, rarely two, seeds, 1.2-1.8 cm long, green-yellow when ripe, with a thin cuticle and juicy fruit pulp (National Academy of Sciences, 1980).

2.1.2 Distribution

In its native Indo-Pakistan subcontinent, neem is found in a large belt extending southwards from Delhi and Lahore to Cape Comorin. In South Asia, it is also found in Bangladesh, upper Burma, and in the drier parts of Sri Lanka. In Southeast Asia it occurs scattered in Thailand, southern Malaysia, and in the drier Indonesian islands east of Java (Ahmed and Grainge, 1986). In Africa, it is particularly widespread in Nigeria and Sudan; it is also found along the East African coastal plains stretching from Ethiopia across Somalia, Kenya and Tanzania to Mozambique and in West Africa in the sub-Sahelian region of Mauritania, Togo, Ivory Coast and Ghana.

2.1.3 Site Requirements

Neem is very drought resistant and grows with as little as 150 mm of annual rainfall. The optimum annual rainfall however, is 450 - 750 mm (von Maydell, 1990). The tree has been successfully grown in regions with up to 2,000 mm annual rainfall and temperatures of between 0°C and 44°C though the tree is frost tender in the seedling and sapling stages (National Academy of Sciences, 1980; Radwanski and Wickens, 1981). Neem also grows better on dry, stony, shallow and nutrient-deficient soils than other species. Neem is salt-tolerant and can be grown on marginal soils with low fertility (Ahmed and Grainge, 1986).The tree requires neutral to alkaline soils and will not grow well where the pH is less than 6 (Laurie, 1974). It tolerates altitudes of 50 - 1,500 m above sea level. Generally, lateral roots may extend radially to 15 m. The tree however is intolerant to frequent inundation and lateritic outcrops (von Maydell, 1990). Poor soil drainage may retard the growth of neem.

2.1.4 Propagation and Management

Propagation is generally by seeds which should be sown immediately after maturity, i.e. December to the end of February (von Maydell, 1990). This is because the seeds are short lived and do not retain their viability for long periods (Troup, 1921). The seeds begin to germinate as soon as they fall from the trees (Evans, 1992). Loss of viability appears to be due to and is accompanied by the fermentation of the unopened cotyledons inside the inner seed case. If the cotyledons are green, the seeds are good and will germinate, but if the cotyledons have turned brown or yellowish, they are not likely to germinate (Smith, 1939). Nagaveni *et al.* (1987) recommend collection of neem fruits when they are greenish-yellow and still on the tree, as opposed to the usual practice of collecting fallen fruit. If this is followed by depulping or drying, immediate germination will be delayed and therefore permit longer storage (Evans, 1992). It is advisable to use only swollen seeds, and to transplant when seedlings are 30 - 50 cm high. Neem trees start bearing fruits from the fifth year onwards and a mature tree produces more than 20 kg of fruit, corresponding to 10 - 15 kg of seeds per year. There are about 4,000 - 6,500 seeds/kg (Evans, 1992). The bare-root method has been the traditional way of raising planting stock in the Sahel-Sudan zone of Africa though in dry years survival is often poor (Evans, 1992).

In a study by Oboho and Ali (1985) in northern Nigeria, germination time did not vary with seed weight, but seedling height at time of appearance of leaflets did, being tallest for the high weight and lowest for the low weight class. The number of leaflets, biomass production and growth rate varied with seed weight. It was realized in this study that the biomass production of the high weight class was three times that of the medium weight class, due to the appearance of twin seedlings from the high weight class.

Weeds do not seriously affect growth and neem is very resistant to competition and may become a noxious weed under favourable site conditions since the seeds are widely distributed by birds (von Maydell, 1990). However, in Nigeria, a study revealed that freeing young plants of grass had a striking effect on planted seedlings. The study showed that strips that had been hoed to rid them of grass, with little breaking of the soil, showed a spectacular difference in health and survival. The results appeared to be due entirely to the eradication of grass and not to disturbance of soil, for cultivation round plants had no better effect than light surface hoeing (Anon., 1952). The tree coppices freely and early growth from coppice is faster than growth from seedlings (von Maydell, 1990).

2.1.5 Growth and Yield

Neem is a fast growing tree: two-thirds of the final height may be reached after three to five years (von Maydell, 1990). The rate of development of young neem plants after the first season is fairly rapid. As a rule, the trees put on an average annual girth increment of 2.3 - 3.0 cm (0.73 - 0.96 cm in diameter), though more rapid growth is easily attained (National Academy of Sciences, 1980). In four different test plots in West Africa, the height of neem trees varied from 4 to 7 m after the first three years and from 5 to 11 m in 8-year-old stands. According to the National Academy of Sciences (1980), in West Africa, cropping is usually done on an 8-year rotation, with original spacing between the plantation trees most commonly 2.4 x 2.4 m. In Ghana, first rotation yield (at 8 years) was 108 - 137 m^3 of fuelwood/ha and in Samaru (northern Nigeria), the yield at the same rotation was 19-169 m^3/ha (National Academy of Sciences, 1980; von Maydell, 1990). Streets (1962) reported mean heights for Northern Ghana as 3.6 and 7.5 m after two and five years respectively. In Cuba, a small stand of neem trees planted on a fertile soil reached a mean height of 14.2 m and mean dbh of 27 cm eight years after planting (Betancourt, 1972). Mean tree diameter after four years of growth in Nigeria was reported as 5.14 cm and survival was more than 75% (Verinumbe, 1991). In the semi-arid Sahel of Africa, neem typically achieves 5 m^3/ha/a (Evans, 1992). Under favourable Sahel conditions, the annual leaf biomass production may reach more than 10 tons/ha (von Maydell, 1990).

2.2 USES OF NEEM

2.2.1 Energy and Fuelwood

Neem seeds contain up to 40% oil, which is used as fuel in lamps and as a lubricant for machinery (National Academy of Sciences, 1980; von Maydell, 1990).

Neem has long been used as fuel in India and Africa. It has become the most important plantation species in northern Nigeria and is planted for fuelwood and poles around the large towns (National Academy of Sciences, 1980). The high wood production capacity of neem, coupled with its high calorific value of 51.1 MJ/tree and fuelwood value index (FVI) of 3.9 at 56 months after planting, make the species an ideal choice for this purpose (Lamers *et al.*, 1994).

2.2.2 Construction

The natural durability of neem makes it a good choice for use in building construction and for making furniture in rural areas. The wood is tougher than teak and very similar in characteristics to mahogany (National Academy of Sciences, 1980). In rural areas, supply of poles for building is frequently the most pressing need and for many purposes, pole diameters at breast height of 10 cm are required along with a smooth surface, freedom from snags and resins and good natural durability (Evans, 1992). Neem possesses most of these qualities.

2.2.3 Shade and Windbreak

Neem has been used successfully as a windbreak and as a source of shade for humans and cattle. It is a splendid street tree for the arid tropics. In Niger, shelter belts of neem interplanted with other species reduce windspeeds by up to 65% (National Academy of Sciences, 1980).

2.2.4 Pest Control

A pool of biologically active constituents, including the triterpenoids, azadirachtin, margosan-o, salanin, and meliantroil, are found in neem leaf, fruit, bark, and seed (Evans, 1992; Schmutterer, 1982; Warthen, 1979). These compounds reportedly control more than 100 species of insects, mites, and nematodes - including such economically important pests as the desert and migratory locusts, rice and maize borers, pulse beetle and rice weevil, rootknot and reniform nematodes and citrus red mice (Grainge *et al.*, 1985; Warthen, 1979; Jacobson, 1958, 1975). Modes of control include antifeedant, growth regulatory, repellent, hormonal, or pesticidal action in larval and/or adult stages of these pests.

Traditionally, Indo-Pakistani farmers simply mixed 2 - 5 kg of dried neem leaves/100 kg of grain in order to control stored-grain pests (Ahmed and Koppel, 1985). Alternatively, empty sacks were soaked overnight in water containing 2 - 10 kg of neem leaves/100 l water and then dried these sacks before filling them with grain (Ahmed, 1984). Evans (1992) indicated that mulches of neem foliage inhibit termite attack of newly planted trees. It is reported that the insecticidal effect of azadirachtin is as good as DDT, and is not toxic to man (von Maydell, 1990).

2.2.5 Soil Improvement

The oil cake of neem is a good fertilizer and is effective in reducing attack of agricultural crops by termites and diverse insects after fertilization (de Datta, 1978). In northwest Nigeria, neem is used on degraded agricultural lands for soil amelioration in order to improve the pH value and to make available soil nutrients for commercial crops (von Maydell, 1990). Neem seeds also contain fatty acids which are capable of inhibiting the nitrifying bacteria that are largely responsible for decreasing the efficiency of applied nitrogen fertilizers in the tropics, thus increasing the efficiency of these fertilizers (Ketkar, 1984).

In order to evaluate the effects neem plantations have on the yield of food crops, surface soil under 12-year-old plantations of neem was used to grow food crops. The results indicated that two months after planting, the crops produced five times higher biomass on the soil from the neem plantation than on the control. The trees had favourable effects on soil fertility and therefore improved crop yield (Verinumbe, 1991).

The extensive root system of neem can extract nutrients from deep subsoils and enrich surface soils through litter. Thus, in northwest Nigeria, significantly higher total cations, cation exchange capacity, base saturation and pH were observed in soils under neem than on similar soils under fallow (Radwanski and Wickens, 1981). Mulching sorghum (*Sorghum bicolor*) with neem leaves in Burkina Faso improved sorghum yields by up to 422% of the unmulched control (Tilander, 1993).

2.2.6 Medicinal Values

Many medicinal uses have been reported for neem. The bark, leaves, fruit, oil and sap reportedly cure various skin diseases, venereal diseases (syphilis) and tuberculosis (von Maydell, 1990). Ahmed and Grainge (1985) and Hepburn (1989) also report that neem oil has contraceptive qualities. Undiluted neem oil showed strong spermicidal action and was 100% effective in preventing pregnancies in rhesus monkeys and human subjects (Sinha *et al.*, 1984).

2.3 TREE-VOLUME ESTIMATION

According to Spurr (1952), few subjects in the entire field of forestry have received as much attention as the estimation of tree volume. The large number of approaches to the problem of volume estimation may be taken as an indication that no one approach has received more than partial recognition. To assess the volume of a complex and highly variable geometric solid like a tree in terms of very few measurements and by simple algebraic techniques is by its very nature difficult if not impossible (Spurr, 1952).

There are two general approaches to the estimation of stand volume in use. In practically all inventory and management work, volume tables are used. To use a volume table for volume estimation, a large sample of trees is measured, but only from one to three measurements are taken on each tree (Spurr, 1952). If only one measurement is taken, it is usually the dbh; if two, height is also measured; if three measurements; a measure of form is also included. From these few variables, volume is estimated by reference to volume tables (Spurr, 1952; Husch *et al.*, 1982). Volume tables give the mean regression of volume on dbh, height and form (in form-class tables only) for a series of carefully measured sample trees.

The second general approach has been termed the mean tree approach. The underlying theory of this method is that, if the tree of mean volume can be isolated, then the volume obtained by careful measurement of this tree can be multiplied by the number of trees in the stand to give the volume of the stand (Spurr, 1952). One method of determining the tree of mean volume is to use the mean sample tree, which is based upon the assumption that the tree of mean basal area is also the tree of mean volume (Spurr, 1952; Crow, 1971). Although fairly good results have been obtained by this method, the fallacy of the basic assumption has long been recognized (Spurr, 1952). Crow (1971), agreed that the mean tree method can be used for expedient estimates of tree biomass in plantations or uniform, natural stands or even-aged species. Especially promising are techniques based on individuals at one standard deviation from a mean stand dimension.

2.4 VOLUME TABLES

Credit for the first modern volume table is generally given to Heinrich Cotta, who published one for beech in 1804 and in 1817, developed a set of standard volume tables. Three types of volume tables are recognized: local, standard and form-class volume tables (Husch *et al.,* 1982).

Local volume tables give tree volume in terms of dbh only. The term local is used because such tables are generally restricted to the local area for which the height-diameter relationship hidden in the table is relevant (Husch *et al*., 1982). Local volume tables are usually derived from standard volume tables though they can be prepared from raw data - that is from volume and diameter measurements for a sample of trees.

Standard volume tables give volume in terms of dbh and merchantable or total height. Tables of this type may be prepared for individual species, or groups of species, and specific localities (Husch *et al.*, 1982).

Form class volume tables give volumes in terms of dbh, merchantable or total height, and some measure of form, such as Girard form class or absolute form quotient (Spurr 1952; Husch *et al.*, 1982).

2.5 VOLUME TABLE CONSTRUCTION

The problem of constructing volume tables is a statistical one. The construction of volume tables involves directly relating volume to height and diameter by means of graphs, alignment charts or equations (Spurr, 1952). The possibility exist however, of relating tree diameter and height to an indirect measure of volume such as a form factor or taper, and then constructing the volume table as a separate step from the form-factor table or taper curves (Spurr, 1952).

Spurr (1952) describes the three methods that have been used for volume table construction and their merits and demerits.

2.5.1 Graphic Techniques

Of the three general approaches to volume table construction, the graphic method is the oldest and requires less mathematical skill than the least-squares or alignment chart techniques (Spurr, 1952).

Basically, the harmonized-curve method involves the sorting of data into groups according to diameter and height classes, and the preparation of a series of curves which give volume for any combination of height and diameter. Another advantage of the graphic technique is that the curves are fitted to the actual data rather than being forced to conform to any set pattern (Spurr, 1952). Spurr (1952) however, notes that the method is not only subjective, but considerable experience is necessary especially for a small sample, and a large number of tree measurements are needed to provide good trends for each of the diameter and height classes.

2.5.2 Alignment-Chart Techniques

Alignment charts provide an efficient means of expressing an equation (Spurr, 1952). They were introduced as tools to correct for curvillinearity in multiple regression equations by Bruce and Reineke (1931). Spurr, 1952 indicates that this method has been generally accepted as a method of constructing volume tables. It requires little mensurational training and generally gives satisfactory results. Spurr (1952) discussed several disadvantages of this method. Firstly, prepared base charts are needed which are not always available. Furthermore, the charts cannot be read too accurately and are quite subject to error because of dimensional changes in the paper.

2.5.3 Least-Squares Techniques

Husch *et al.* (1982) note that the graphic and alignment-chart techniques have been generally discarded in favour of mathematical functions and models. Standard regression techniques that are based on the method of least squares have gained wide acceptance for the construction of volume tables (Unnikrihnan and Singh, 1984). This is because the method is free from the subjective bias of fitting curves by hand (Spurr, 1952). A large number of different equations have been proposed for volume table construction and considerable difficulty may arise in attempting to decide which equation is the most appropriate for a particular set of data (Furnival, 1961). Considerable difference of opinion also persists regarding not only the function to be used but the proper criterion of comparison (Spurr, 1952).

Classical least squares estimation is based on the assumptions of independently and normally distributed errors and the property of homoscedasticity, i.e. the variance of the dependent variable is constant for all values of the independent variables. The fourth assumption is that the sample is a simple random sample (Cunia, 1964). In practice, however, most, if not all of these assumptions are not satisfied. Cunia (1964), found that tree volume for a given dbh is not normally distributed and highly skewed: large trees tend to deviate more on the average from the regression surface than do small trees (i.e. heteroscedasticity). It is also usual in forest inventory to replace the simple random sampling by stratified, cluster or systematic sampling (Bruce and Schumacher, 1950; Spurr, 1952; Cochran, 1953).

Theoretically, weights should be employed that are inversely proportional to the variance of the residuals in order to achieve a homogenous variance. But in practice, it may be difficult to determine the most appropriate way to weight a particular function (Furnival, 1961). Another option is the use of logarithmic transformations of the equations.

When a logarithmic transformation is used to ensure that the assumptions of ordinary least squares are satisfied, it is often necessary to express estimated values of the variable of interest in original [i.e. untransformed] units (Baskerville, 1972). However, the conversion of the logarithmic estimates back to measured units produces a bias that must be corrected. This results from the fact that if the distribution of the residuals about the log-transformed model is normal, then the distribution of the untransformed residuals are skewed (Furnival, 1961; Baskerville, 1972). It is argued that the transformation from the logarithmic form back to measured units by simply determining the antilogarithm has, by failing to account for skewness of the distribution in arithmetic units, yields the median rather than the mean value of the estimates (Finney, 1941; Brownlee, 1967; Baskerville, 1972). This produces systematic underestimates of the dependent variable. Therefore a correction must be made for this inherent bias which is proportional to the amount of variation associated with the regression (Schlaegel, 1981)

The following correction for the skewness that results from this retransformation was proposed by Baskerville (1972).

$$\hat{Y} = \exp(\mu + \sigma^2/2) \tag{1}$$

$$\sigma_A^2 = \exp(2\mu + 2\sigma^2/2) - \exp(2\mu + \sigma^2/2) \tag{2}$$

where

$\hat{Y}$ = estimated mean in measured units

σ_A^2 = estimated variance in measured units

μ = estimated mean in logarithmic units

σ^2 = sample variance of the logarithmic equation

Beauchamp and Olson (1973) extended Baskerville's work and concluded that unless the variance of the residuals is quite large the correction provided by Baskerville (1972) gives close approximations to the unbiased value.

2.6 YIELD TABLES

2.6.1 Definition and Data Acquisition

Growth is the increase in a particular stand characteristic over a period of time. Yield refers to the total amount available for harvest at a given time (Avery and Burkhart, 1994). Growth can be calculated as the first derivative of the yield equation and yield as the integral of the annual increments [sum of growth] (Clutter, 1963).

A yield table is usually a table showing the volume per hectare at different ages for even-aged stands of trees growing on forest land of different productive capacities (Chapman and Meyer, 1949). Yield tables often include additional information such as number of trees/ha, basal area/ha, etc. A normal yield table shows the yields capable of being produced on forest sites when the "normal" capacity of site is fully utilized by even-aged stands of forest-grown trees. Empirical [or variable density] yield tables usually refer to yield tables that apply to "average" rather than full, or normal stocking (Avery and Burkhart, 1994).

The best method of obtaining data for yield table construction is to measure permanent plots located in the stands of interest at intervals of 5 or 10 years over the entire period of growth of the stands (Chapman and Meyer, 1949). The actual increase in the various yield variables and the number of trees that die from year to year and the volume of the surviving stand at any age are then a matter of record. However, this entire process would take a long time to complete, and the stand might be destroyed at any time by fire, disease or other agencies (Chapman and Meyer, 1949). Yield tables constructed by this method are referred to as real growth series yield tables (Turnbull, 1963).

The second type of yield tables, known as "abstract" growth series yield tables, are constructed by measuring a number of permanent sample plots (PSPs) located in stands of different ages and to remeasure these plots at 5- or 10-year intervals (Chapman and Meyer, 1949; Turnbull, 1963). By the overlapping of the ages chosen, the trend of the development for one or two decades for plots of all ages is obtained after the second or third measurement. It is however essential that lands for PSPs be in stable ownership, preferably in public forest, so that the owner's whim may not interfere with the experiment (Chapman and Meyer, 1949).

Chapman and Meyer (1949) contend that the two methods described above are too time-consuming and other methods are needed if yield tables are to be prepared for immediate use. To fill this need, a third standard method which has been extensively used is based on the principle of comparison of plots of different ages. The averages of stands for the same site but differing in age are combined into a curve assumed to show the trend of growth. If many plots of different ages on different sites are measured, each plot will show the yield obtained in a similarly stocked stand at the given age and for the site in which it is located.

2.6.2 Site Quality Evaluation

Clutter *et al.* (1983) describe both direct and indirect methods of site quality evaluation. Estimation of site quality based on historical yield records, stand volume data and stand height data constitute the direct methods. The indirect methods described are estimation of site quality from over story interspecies relationship, lesser vegetation characteristics and from topographic, climatic and edaphic factors.

Site quality estimation from stand height data is the most popular method and usually involves the use of site index curves. Any set of site index curves is simply a family of site development patterns with qualitative symbols or numbers associated with the curves for referencing purposes (Clutter *et al.*, 1983). Site index curves are derived either graphically or by statistical curve-fitting procedures (Alder, 1980; Clutter *et al.*, 1983). Data for the development of site index curves are obtained from three main sources: temporary sample plots (TSPs), PSPs and stem analysis. TSPs provide the most inexpensive and quickest data, but the use of such data involves the assumption that the full range of site indices is well represented in all age classes within the sample (Alder, 1980; Clutter *et al.*, 1983; Avery and Burkhart, 1994).

The statistical methods used for site index curves are of three general types: the guide curve, the difference equation and the parameter prediction methods (Clutter *et al.*, 1983). The most common equation forms used to fit site index curves are the Schumacher (1939) and Chapman-Richards equations (Richards, 1959; Chapman, 1961).

2.6.3 Yield Models

A discussion of the models commonly used for yield table construction is given by Clutter *et al.*, (1983). These are the Schumacher-Type model, Chapman-Richards function and Diameter-Distribution-Based yield models. The basic form of the Schumacher -Type yield model used is given by:

$$\ln Q = \alpha + \beta_1 A^{-1} + \beta_2 S + \beta_3 D_s \qquad (3)$$

where Q is some measure of yield (height, dbh, basal area, volume, and fresh weight), A is stand age in years, S is some function of site index, D_s is some function of stand density and α, β_1, β_2, and β_3 are regression coefficients. From this equation, the time to harvest that maximizes mean annual increment (MAI) is equal to the estimated β_1 coefficients (Stone *et al.,* 1993). Graphically, this is the point which a chord from the origin is tangent to the appropriate growth function (Stone *et al.,* 1993). Rotation age is sometimes set as the age of maximum annual increment (MAI) because for a given piece of land, that is the harvest that will maximize wood production for a perpetual series (Avery and Burkhart, 1994).

The Chapman-Richards growth model (Richards, 1959; Chapman, 1961) was first used for forest modelling in studies reported by Pienaar and Turnbull (1973). The model is derived from basic biological consideration and has proven to be very flexible in application. The basic form of the equation is given as:

$$dY/dt = \alpha Y^{\beta} - \gamma Y \tag{4}$$

where

Y = size of organism or population

t = time

α, β, γ = constants ($\alpha > 0$, $\gamma > 0$, $0 < \beta < 1$)

The parameters of the equation can be estimated using nonlinear least-squares techniques.

The most common continuous univariate distribution functions that have been used to describe diameter distributions are the Weibull distribution (Weibull, 1951), Gamma distribution (Nelson, 1964), lognormal distribution (Bliss and Reinker, 1964), beta distribution (Clutter and Bennett, 1965; Zöhrer, 1969) and Johnson's S_B distribution (Hafley and Schreuder, 1977). The Weibull distribution was developed by Weibull (1951) to evaluate the probability of material failure and was introduced by Bailey and Dell (1973) as a model for tree diameter distributions. The three-parameter Weibull distribution is defined by the probability density function (pdf):

$$f(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} \exp\left[-\left(\frac{(x-a)}{b}\right)^{c}\right] \tag{5}$$

where x is a specified diameter with the restrictions $x \geq 0$, $a > 0$, $b > 0$ and $c > 0$. The pdf shows the relative frequency of diameters over the range $a \leq x < \infty$. The Weibull parameter a is the location parameter, interpreted as the smallest diameter possible. The scale parameter, b, determines the relative range of values which the diameters may assume. The shape parameter, c, determines the general form of the distribution. For example when $c = 1$, the distribution if reversed J shape, typical of young stands. If $1 < c < 3.6$, the distribution will be bell shaped and positively skewed; that is, there will be more trees in the smaller diameter classes. As c increases above 3.6, the distribution becomes negatively skewed, illustrating the diameter distribution of older stands.

The Weibull cumulative distribution function F(x) can be found by integrating its pdf, which yields:

$$F(x) = 1 - \exp\left[-\left(\frac{(x-a)}{b}\right)^{c}\right] \qquad (6)$$

where F(x) is interpreted as the probability or relative frequency of a diameter class between a and x in the stand. More generally, the probability P that the diameter is between any two values, L and U [where L is the lower limit and U the upper limit] can be calculated as:

$$P = \exp\left[-\left(\frac{L-a}{b}\right)^{c}\right] - \exp\left[-\left(\frac{(U-a)}{b}\right)^{c}\right] \qquad (7)$$

Multiplying P by N, the number of trees in the stand, yields the number of trees between the limits L and U. Cohen (1965) proposed a maximum likelihood function for estimating the parameters of the Weibull distribution. Percentile methods of estimating the Weibull parameters are described by several authors including Zankis (1979), Clutter *et al.*, (1983) and Zarnoch and Dell (1985). The method of Moments is an alternative to Maximum likelihood and Percentile methods and is described fully by Shifley and Lentz (1985).

2.7 MODEL SELECTION CRITERIA

Some of the criteria that have been suggested for selecting appropriate biomass and volume models are reviewed below. It is difficult however to find a single criterion or statistic to demonstrate that one model is definitely better than another (Schlaegel, 1981).

2.7.1 Coefficient Of Determination

Probably the most commonly used model selection criterion is the coefficient of determination, R^2 value. This statistic indicates the proportion of the total sum of squares of the dependent variable explained by the regression. One major disadvantage of this statistic is that it can be used to compare two or more models only if the units of the dependent variable are the same between models. Secondly, inclusion of additional independent variables never decreases R^2 value, even though they may not be statistically significant (Schlaegel, 1981).

2.7.2 Standard Error

According to Schlaegel (1981), the use of the standard error of the estimate [$s_{y.x}$] as a selection criterion for models is only second to the coefficient of determination. The standard error is calculated from the residual sum of squares of the regression of any equation by:

$$s_{y.x} = \sqrt{\frac{\text{Residual sum of squares}}{(n-p)}} \tag{8}$$

where

n = the number of observations

p = the number of coefficients estimated in the model

[n - p] = degrees of freedom of the residual term

This is a measure of the variation in the observed dependent variable values not accounted for by the linear relationship with the independent variable[s] (Husch, 1963). The standard error is a function of the number of coefficients estimated from the model since the denominator is dependent on sample size and number of regression coefficients in the model. Transforming the dependent variable changes the magnitude of the standard error for the same equation making it inappropriate for comparing equations in different units or with different dependent variables. As Schlaegel (1981) noted, the standard error is difficult to interpret without additional information such as the distribution of the data, the mean and range of the dependent variable, etc.

2.7.3 Fit Index

An index of fit [Fit Index] comparable to the R^2 value can be obtained for every equation. In the case of untransformed linear regressions, the Fit Index is equal to the coefficient of determination (Schlaegel, 1981). To calculate the FI, the predicted values are transformed back to the original units and corrected for bias if needed. The total corrected sum of squares is given by:

$$TSS = \sum (Y_i - \bar{Y})^2 \qquad (9)$$

and residual sum of squares by:

$$RSS = \sum (Y_i - \hat{Y}_i)^2 \qquad (10)$$

where

Y_i = value of the ith observation in actual units

$\bar{Y}$ = arithmetic mean of Y, in actual units

$\hat{Y}_i$ = the ith predicted value of Y_i converted to actual units

The fit index is:

$$FI = 1 - \frac{RSS}{TSS} \qquad (11)$$

2.7.4 Standard Error of Estimate in Actual Units

Using the residual sum of squares of the regression in the actual units of measure, a standard error of the estimate in actual units, s_e may be calculated as follows:

$$s_e = \sqrt{\frac{\sum (Y_i - \hat{Y}_i)^2}{(n-p)}} \qquad (12)$$

where Y_i and $\hat{Y}_i$ are observed and predicted values of Y in actual units respectively, n is the number of observations, and p is the number of coefficients in the model (Schlaegel, 1981).

2.7.5 Coefficient of Variation

A useful statistic for making quick comparisons between models is the coefficient of variation [CV] expressed in actual units as per cent:

$$CV = \frac{s_e}{\bar{Y}} \times 100 \qquad (13)$$

The CV is an index of the variation among means of the predicted Y's after accounting for the variation due to the measured variables. This statistic should be much smaller than the coefficient of variation of the sample tree mean (Schlaegel, 1981).

2.7.6 Furnival Index

The usual index of fit, the root mean square residual [standard error], and the coefficient of determination can only be used to compare equations that have the same dependent variable but is not suitable when transformations of the dependent variables are involved (Furnival, 1961; Crow, 1971).

Furnival (1961), proposed an index for comparing equations used in constructing volume tables with different dependent variables, based on the maximum likelihood principle. The index, known as the Furnival Index [I] is computed in three stages. First, the standard error of the residuals are obtained by fitting all equations to the data. Next, the geometric means of the derivatives of the several dependent variables with respect to volume are computed with the aid of logarithms. Finally, the standard error is multiplied by the inverse of the appropriate geometric mean (Furnival, 1961). The Index is given by:

$$I = [f'(V)^{-1}]\, s \tag{14}$$

where I is the Furnival Index, $f'(V)^{-1}$ is the reciprocal of the derivative of the transformation applied to the dependent variable [volume] with respect to volume and s is the standard error of the fitted regression. For the common transformations, the corresponding geometric means are as follows (Furnival, 1961; Alder, 1980):

Transformation	*Geometric mean*
$\log V$	$\text{antilog}\dfrac{2.30\sum \log V}{n}$
$\ln V$	$\text{antilog}\dfrac{\sum \log V}{n}$
V/D^2	$\text{antilog}\dfrac{\sum \log D^2}{n}$
V/D^2H	$\text{antilog}\dfrac{\sum \log D^2H}{n}$

where D is the dbh, H is height and n is the number of observations. The equation with the smallest index is selected as the one that gives the best fit to the data. In the case of an untransformed equation [i.e. where the dependent variable is volume], the Furnival Index reduces to the usual estimate of the standard error of the regression.

3.0 MATERIALS AND METHODS

3.1 STUDY AREA

This study was conducted in the Tamale Forest District in the Northern Region of the Republic of Ghana. This district is located in the Guinea Savanna vegetation zone and lies between 9°18' and 9°36' N and between 0°15' E and 1°24' W longitude. Tamale Forest District is currently made up of West Dagomba (Tamale) and Tolon-Kumbungu political districts.

3.1.1 Brief Description of the Natural Vegetation Zones of Ghana

Ghana occupies an area of about 238,549 km^2 and lies north of the equator (between 4° 45' and 11°11' North latitude and between 1°14' East and 3°07' West longitude) and wholly within the tropics. The country forms a roughly rectangular block about 400 km from east to west and 640 km from north to south. The high forest zone, which is made up of the Rain Forest [Wet-and Moist Evergreen] and the Semi-deciduous Forest [Moist- and Dry-Semi-deciduous], covers an area of 81,342 km^2 and is found in the southwestern third of the country. Figure 1 shows the natural vegetation zones of Ghana. The four broad ecological types - Wet Evergreen, Moist Evergreen, Moist Semi-deciduous and the Dry Semi-deciduous have been identified to be floristically synonymous with the *Cynometra-Lophira-Tarrientia, Lophira-Triplochiton,*

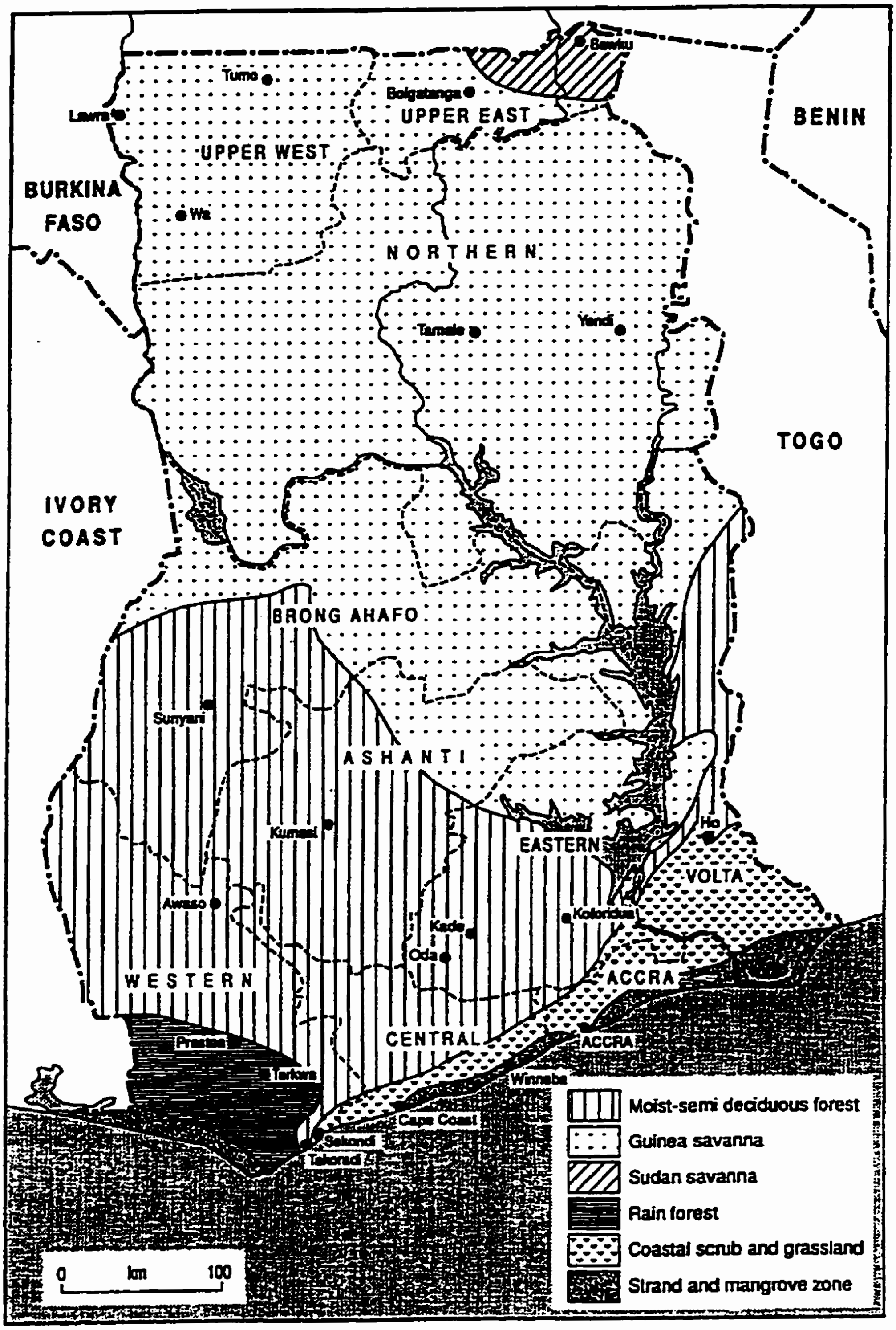

Figure 1. Natural vegetation zones of Ghana.

Celtis-Triplochiton and the *Antiaris-Chlorophora* associations respectively, recognized by Taylor (1952). There is however no distinct line of demarcation between these associations as one imperceptibly merges into another (Prah, 1994). The other 157,198 km^2 which constitutes the remaining two-thirds of the country is mainly Savanna. The Savannas are conveniently divided into northern and southern types. The latter, occupying the low-rainfall coastal plains forms a relatively narrow strip along the coast south of the high forest beginning from Takoradi and widening as it stretches east towards the border with Togo. The northern Savanna woodland which is mainly Guinea Savanna, stretches north of the Semi-deciduous forest to the border with Burkina Faso and occupies by far the largest area of Ghana (Lawson, 1968).

3.1.2 Description of the Guinea Savanna Vegetation Zone

3.1.2.1 Vegetation

The characteristic vegetation of the Guinea Savanna zone consists of short deciduous, widely spaced, fire-resistant trees. These do not form a closed canopy and overtop an abundant ground flora of grasses and shrubs of varying heights (Taylor, 1952). The most frequent and characteristic tree species are *Isoberlina doka*, *Monites kerstingii*, *Burkea africana*, *Danielia oliveri* and *Terminalia avecinoides*. Two indigenous species, *Buterospermum paradoxum* (shea tree) and *Parkia clappertoniana* (dawadawa), are conserved by farmers because of their economic value and are therefore common on farmlands. The ground vegetation, which includes *Panicum maximum*, *Andropogon* *gayanus* var. *gayanus* and *Cassia mimosoides* , desiccates during the dry season and predisposes the savanna to annual fires which leave the soil surface bare.

3.1.2.2 Climate

The Guinea Savanna zone is characterized by distinct wet [rainy] and dry seasons of about equal duration. Two air masses of very contrasting characteristics determine the climate in this zone. These are the harmattan winds generally called the North East Trade Winds that usher in the dry season and the South Atlantic Maritime Air Mass referred to as the south west monsoon winds which transport moisture into the area during the rainy season. There is a moderate mean annual rainfall of 960-1200 mm falling in one season from March/April to October and showing a very irregular distribution within a rainy season and great differences from year to year (Fisher, 1984). Maximum rainfall during the year is achieved in July-August. Mean annual temperature is 28.3°C which does not vary significantly during the seasons. Table 1 summarizes rainfall and temperature data recorded by the Meteorological Services Department at Tamale from 1984 to 1995. A rainy month is defined as a month in which at least 1 mm of rainfall was recorded.

Table 1. Summary of temperature and rainfall data recorded at Tamale from 1984 to 1995.

Year	Mean annual temperature (°C)	Rainfall: Annual rainfall (mm)	Rainfall: Number of rainy months	Rainfall: Months without rain
1984	28.1	926	9	Jan., Feb., Dec.
1985	27.9	1034	8	Jan., Feb., Nov., Dec.
1986	30.2	1082	9	Jan., Feb., Dec.
1987	29.0	957	8	Jan., Feb., Nov., Dec.
1988	28.4	1121	9	Jan., Feb., Dec.
1989	28.1	1427	9	Jan., Feb., Nov.
1990	28.8	1070	10	Jan., Mar.
1991	27.8	1580	9	Jan., Nov., Dec.
1992	28.1	764	9	Jan., Feb., Dec.
1993	27.7	1000	10	Jan., Dec.
1994	28.2	1159	8	Jan., Feb., Nov., Dec.
1995	27.6	996	11	Jan.

3.1.3 Soils

The soils of Guinea Savanna zone are varied because of the varied nature of the underlying geology. In general, however, two broad groups of soils are recognized: the Savanna Ochrosols and the Groundwater laterites. The Savanna Ochrosols are found on the Voltaian sandstones (Boateng, 1966). They consist of well-drained, friable, porous loams and are mostly red or reddish-brown in colour. Most of the area covered by these soils have a gently undulating topography. Soils in the depressions are quite thick, but upland soils usually have a zone of ironstone concretions from 10 cm to one metre below the surface (Boateng, 1966). The soils tend to be eroded and form surface crusts under the impact of strong rainfall, but they have only a small capacity to keep water. According to Boateng (1966), despite their deficiency in nutrients, notably phosphorous and nitrogen, these soils are among the best soils in the northern Savanna zone and are extensively farmed. A typical soil profile shows a dark grayish humus loam on the surface and subsequent layers show from gray to brownish loam with quartz gravel through light brown clay into moderately compact clays at about 70 cm below ground level (Lawson *et al.*, 1968).

The Groundwater Laterites are very extensive and are formed on the Voltaian shales and granites. They consist of a pale-coloured, sandy or silty loam with a depth of up to 65 cm underlain by an ironpan or a mottled clayey layer so rich in iron that it hardens to form an ironpan on exposure (Boateng, 1966). Drainage on these soils is poor; they tend to get waterlogged during the rains and to dry out during the long dry season. These soils, especially those developed on the Voltaian shales are considered to be among the poorest soils in Ghana and little cultivation takes place on them Boateng (1966).

3.2 SURVEY PROCEDURE

3.2.1 Silvicultural Information

The information on the current silvicultural practices for neem in Northern Ghana was obtained from Forestry Technical Officers working in the area and from the author's own experience working with the species in the Northern Region.

3.2.2 Data Collection

The data were collected from 120 temporary sample plots selected from 30 plantations within the study area from early June to late July, 1995 using a stratified two-stage sampling design. Table 2 shows the distribution of sample plantations, plots and the number of trees which were measured. Figure 2 shows the locations of towns and villages nearest to the sample plantations.

Table 2. Distribution of sample plantations, plots and trees measured by town/village.

Town/Village	No.of Plantations observed	No. of sample plots measured	No. of trees measured
Tamale	8	32	580
Nyankpala	6	24	563
Kumbungu	5	20	500
Kumbungyili	3	12	300
Katariga	2	8	185
Vitin	1	4	100
Nyashie	1	4	100
Tarikpaa	1	4	100
Jangyili	1	4	100
Dalogyili	1	4	100
Choggo	1	4	65
Total	30	120	2, 693

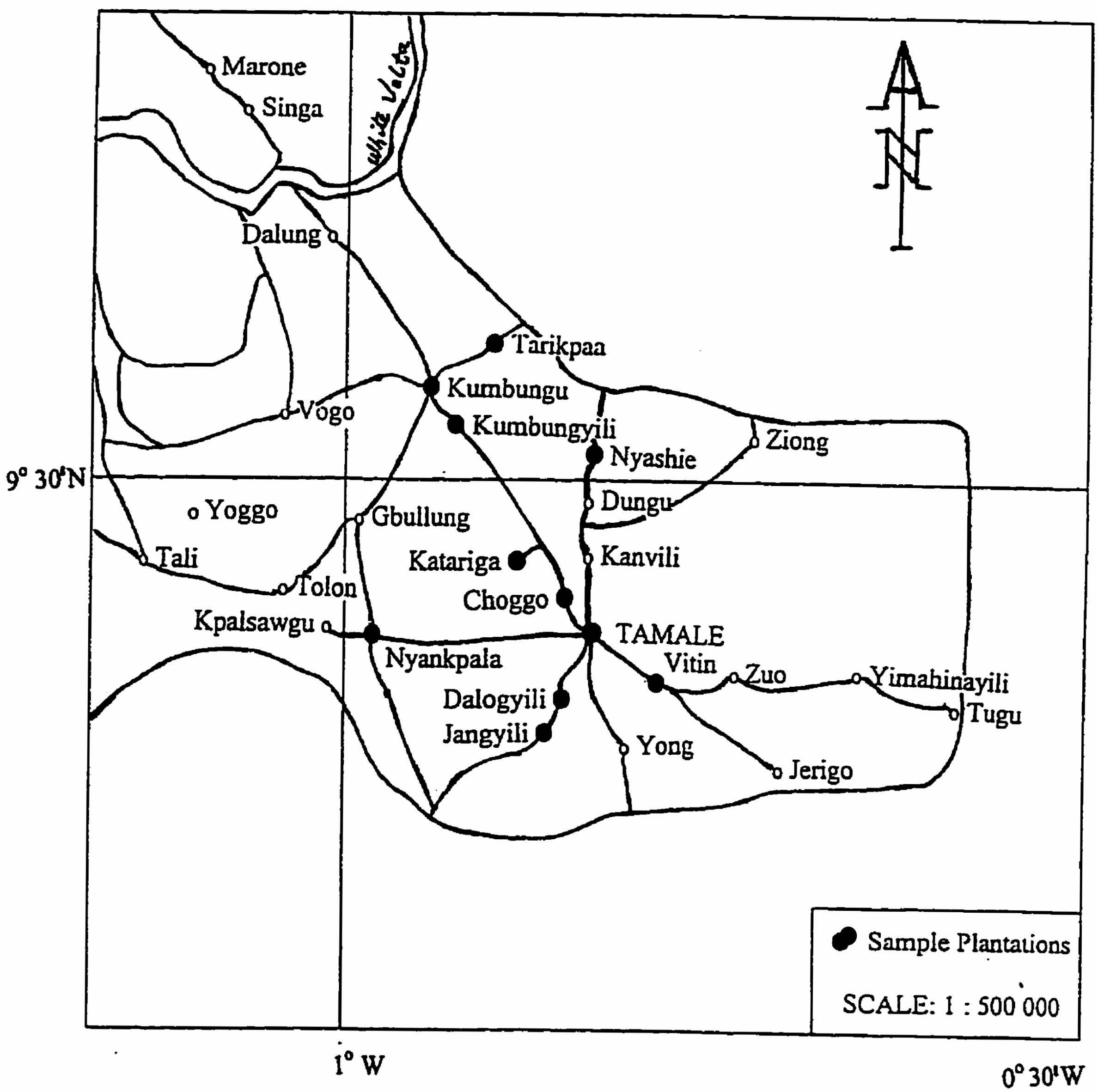

Figure 2. Locations of towns and villages nearest to sample plantations.

All plantations of neem planted from 1986 to 1994 within the study area were stratified by age into five groups [1-, 2-, 3-, 4-, and 5-year age groups]. Five plantations were selected randomly for measurement in each stratum. In addition, three and two plantations from six- and nine-year age groups respectively were also selected randomly for measurement. In all plantations selected for study, the following procedures were carried out:

a) four square plots with a 10 x 10 m sides [1/100 ha] were set up in each stand. To avoid the effect of errors in locating plot boundaries, plot boundaries were laid exactly half-way between the lines of trees. Since the usual initial spacing for neem and other plantation species in the area is 2 x 2 m, in the absence of mortality, each sample plot contained 25 trees. It was realized after measuring a few plantations that selective felling had been done in some of the plantations above three years. It was therefore decided that instead of setting up random plots within the plantations, selective sampling should be done in areas as fully stocked as possible. It was therefore not possible to estimate mortality as this was confounded with human effects. The plot size [10 x 10 m] was chosen after a series of measurements which showed that the 25 trees contained in each fully stocked plot were sufficient to provide statistically accurate estimates of stand characteristics. The measurements also showed that a large number of small but adequate sized plots provided superior sample data than a small number of large plots. This was particularly so because many of the plantations sampled were less than one hectare in area.

b) all trees in each plot were measured for diameter at 50 cm above ground and diameter at breast height [dbh] with either digital calipers or a diameter tape [for the larger trees] to the nearest mm, and for total height with height poles to the nearest cm. For any tree less than or equal to 130 cm in height, only diameter at 50 cm and height were measured. Each stem of a tree forking below breast height was measured at 130 cm and recorded separately and the height of only the tallest stem was measured. A single diameter corresponding to the diameter of the tree of the same basal area as the total basal area of all the forked stems was then calculated using the formula:

$$D_m = 2\times\sqrt{\sum_{i=1}^{n} D_i^2} \qquad (15)$$

where D_m is the mean diameter, D_1, D_2,.. D_n are the diameters at breast height of the first, second etc. to the *n*th forked stem.

c) the basal areas of all trees measured on each plot were calculated using the diameters at 50 cm. One tree from each plot with dimensions as close to the tree of mean basal area [at 50 cm] and height as possible was selected and felled close to the ground with a cutlass. Just after felling the sampled tree, the following variables were recorded:

i) diameter at 50 cm above ground level,

ii) diameters at 0, 25, 50 and 75% of the total height,

iii) diameter at breast height,

iv) total height,

v) fresh weight of the whole tree with a spring balance,

vi) fresh weight of a 10 to 30 cm stem section in the centre of the stem for determination of dry to fresh weight ratio.

The stem sections were air dried and their air-dry weights taken with the same spring balance.

3.3 DATA ANALYSIS

3.3.1 Individual Tree Volume Computation

Smalian's formula was used in conjunction with the dbh, height and diameters at 0, 25, 50 and 75% of total height to compute the volumes of the 120 sample trees. As the sample trees were measured at equal intervals along the stems, the formula was reduced to:

$$V = \frac{H}{8}(B_1 + 2B_2 + 2B_3 + 2B_4) \qquad (16)$$

where

V = total tree volume

H = total height

B_1, B_2, B_3, and B_4 = basal areas at 0, 25, 50 and 75% of total height

3.3.2 Local and Standard Volume Table Equations

The individual tree volumes were used to develop local and standard volume table equations using regression analysis. Prior to the analysis, 12 of the sample trees were discarded because they were shorter than 130 cm and therefore had no diameters at breast height. The remaining 108 trees were used for the development of the volume tables. Fifteen of the common regression models [listed in Appendix III] used in volume estimation (Unnikrihnan and Singh, 1984) were fitted to the computed volumes in order to determine the most appropriate model. Six of these models have single independent variables and the remaining nine have two independent variables. The independent variables used were either dbh or height or combinations of both. The criteria for selecting the best regression models were the: R^2 value, Standard Error, Fit Index, Furnival Index and the Coefficient of Variation.

3.3.3 Plot Volume Computation

The best standard volume equation among the 15 models compared on the basis of the Furnival Index was:

$$\ln V = -1.689 + 1.165 \ln D + 1.124 \ln H \qquad (17)$$

where V is the total tree volume in dm^3, D is diameter at breast height in cm and H is total height in m. This equation was used to compute the volumes of all trees on each measured plot. Plot volumes were then calculated as the sum of the volumes of all individual trees on that plot.

The computed chi square value between the actual sample tree volumes and the volumes predicted by Equation (17) was 28.78, which was not statistically significant at the 0.05 probability level [$\chi^2_{(0.95,\ 104)} = 124.34$]. The average errors in using Equation (17) to predict volumes was - 6.07% [self-validation].

3.3.4 Estimation of Weibull Parameters

The three-parameter Weibull function was used to describe the diameter distributions of the neem plantations. The Maximum Likelihood Estimators (MLE) of the three parameters (*a*, *b*, and *c*) of the Weibull distribution were estimated from formulae given by Zankis (1979) and Gove and Fairweather (1989).The location parameter, *a*, was estimated by the method proposed by Zankis (1979). This method utilizes x_1, x_2 and x_n to estimate the location parameter:

$$\hat{a} = \frac{(x_1 x_n - x_2^2)}{(x_1 + x_n - 2x_2)} \qquad \text{if: } x_2 - x_1 < x_n - x_2;\ \text{else: } \hat{a} = x_1 \qquad (18)$$

where x_1 = smallest diameter in the sample

x_2 = the second-smallest diameter

x_n = the largest diameter in the sample

Estimates of *c* and *b* were obtained from equations given by Gove and Fairweather (1989) for trees grouped into discrete diameter classes:

$$\left[\frac{\sum_{i=1}^{n} f_i x_i^{\hat{c}} \ln x_i}{\sum_{i=1}^{n} f_i x_i^{\hat{c}}} - \frac{1}{\hat{c}}\right] - \frac{1}{n}\sum_{i=1}^{n} f_i \ln x_i = 0 \tag{19}$$

This nonlinear equation was solved iteratively for *c*, the parameter *b* was then estimated from:

$$\hat{b} = \left[\frac{1}{n}\sum_{i=1}^{n} f_i \ln x_i\right]^{\frac{1}{\hat{c}}} \tag{20}$$

where x_i is the ith diameter class midpoint, n is the sample size and f_I is the ith diameter class frequency. The Moments procedure described by Shifley and Lentz (1985) and the Percentile method described by Zankis (1979) were also used to obtain the Moment and Percentile estimators of the Weibull function respectively. The Moments method described by Shifley and Lentz (1985) determines the Weibull shape and scale parameters directly from the mean and variance of a sample using Equations (21) and (22) and two special tables (not given here).The parameter *c* is estimated from:

$$\mu_a/\sigma = \frac{\Gamma[1+(1/\hat{c})]}{\sqrt{\Gamma[1+(2/\hat{c})] - \Gamma^2[1+(1/\hat{c})]}} \tag{21}$$

where Γ signifies a gamma function of the expression in parenthesis, μ is the mean, σ is the standard deviation, $\mu_a = \mu - a$ is the adjusted mean of the Weibull distribution and a is the Weibull location parameter. The scale parameter, b, is estimated from:

$$\hat{b} = \frac{\mu_a}{\Gamma[1 + (1/\hat{c})]} \tag{22}$$

The Percentile procedure by Zankis (1979) estimates the location parameter, a, using Equation (18). The shape parameter, c, is estimated as

$$\hat{c} = \frac{\ln\left[\dfrac{\ln(1-p_k)}{\ln(1-p_i)}\right]}{\ln\left[\dfrac{x_{[npk]} - \hat{a}}{x_{[npi]} - \hat{a}}\right]} \tag{23}$$

and the scale parameter, b, from:

$$\hat{b} = -\hat{a} + x_{[0.63n]} \tag{24}$$

where $p_i = 0.1673$, $p_k = 0.97366$, $0.63n$ = 63rd percentile in the sample and n = sample size.

3.3.5 Allocation of Stands to Site Classes

All plantations were designated Site Class I, II or III in relation to their mean dominant and codominant height/plantation age. The method used was the minimum -

maximum procedure described by Alder (1980). In each age class, the minimum, mean and maximum top heights were calculated. Three separate linear regressions were then fitted to the minimum, mean and maximum sets of observations using the logarithmic transformation of Schumacher's (1939) equation:

$$H_o = H_{max} \cdot \exp(\beta A^{-k}) \tag{25}$$

where H_o is the mean top height, H_{max} represents the maximum height the species could reach on the site, A is the age of the stand, β and k are coefficients; in this study k was estimated to be 1.0 using the procedure suggested by Alder (1980). This procedure requires that the residual sum of squares for the linear forms of Equation (25) for various trial values of k be computed. The value of k at which the minimum sum of squares is observed provides the best estimate of k. The regressions are then recalculated using this value of k to give the corresponding best estimates of the α [H_{max}] and β parameters.

3.3.5 Yield Table Construction

The basic form of the Schumacher (1939) equation was used for the development of yield tables for Site Classes I, II and III:

$$\ln Q = \alpha + \beta_1 A^{-1} + \beta_2 S + \beta_3 D_s \tag{26}$$

where Q is some measure of yield [height, dbh, basal area, volume, and fresh weight], A is stand age in years, S is some function of site index, D_s is some function of stand density and α, β_1, β_2, and β_3 are regression coefficients.

Site and stand density were excluded as explanatory variables from Equation (26) since individual equations were developed for each site class and a uniform stand density of 2500 stems/ha was used in all site classes. The reciprocal of stand age had a high correlation with ln Q. For these reasons Equation (26) was reduced to:

$$\ln Q = \alpha + \beta_1 A^{-1} \tag{27}$$

which was then used in constructing yield tables for each site class. According to Alder (1980), the β_1 parameter is negative and α is usually between 2 and 7.

4.0 RESULTS

4.1 CURRENT SILVICULTURAL PRACTICES FOR NEEM

4.1.1 Seed Procurement and Storage

Neem seeds are usually picked from open-grown neem trees. If the seeds are fresh, they are dried in the sun for a few hours before storage. Seeds are stored on the office floor or plastic containers at room temperature for not more than two weeks prior to sowing in the nursery.The seeds are not given any chemical treatment in storage.

4.1.2 Nursery

Neem seedlings are raised in tree nurseries by the Forestry Department and supplied free of charge to individual farmers, communities and other institutions such as schools, government departments, etc. Each nursery within the District is supervised by a Forestry Technical Officer.

Nursing of seedlings starts in December/January for outplanting in May/June of the same year. No pre-sowing treatment is given to neem seeds before sowing in the nursery. Seedlings are raised either in polythene tubes or as bare-root stock. In either case, the seeds are first broadcast on a germination bed and pricked out into one- or half-litre polythene tubes or transplant beds about a week after germination. Germination starts three days after sowing and about 80% of the seeds germinate within 20 days. Polythene tubes are usually filled with one part animal dung, two parts rice chaff and three parts mineral soil. Natural regeneration is usually profuse under mature neem trees. This can be used to supplement nursery stock, though this is not currently done.

4.1.3 Land Acquisition and Preparation

Neem plantations are commonly established on either farmlands or abandoned lands which are out of cultivation mostly as part of the cycle of shifting cultivation. In either case, lands are prepared in March/April prior to the rains. Land preparation is often done by the farmer with his family or the community in "communal labour" programmes in the case of community plantations. Almost all farmers use their own lands or those of the community.

4.1.4 Outplanting

Outplanting of neem seedlings is done exclusively during the rainy season [from May to end of August]. The beginning of the planting season however depends on when the rains start and therefore varies from year to year. In most years, planting starts before the end of May. Sometimes planting is carried on into September but this practice is undesirable since the newly transplanted seedlings do not get enough water to establish themselves well to survive the long dry season starting from October to March.

The seedlings are planted at 2 x 2 m apart, giving 2500 trees/ha. Neem may be planted out as a pure stand or mixed with other species. Some farmers grow food crops such as maize and millet until canopy closure. Shade tolerant food crops [e.g. pepper] are also grown under older neem trees on farmlands.

4.1.5 Tending Operations

Weeding is done on plantations which are intercropped with food crops. But most farmers do not weed their plantations. Pruning is not done except that dead branches are cut when they are a nuisance or when they are needed for fuelwood. Thinning is done when the farmer or community needs the product and not for the sake of improving the stand.

4.1.6 Protection

Most farmers and communities make fire belts around their plantations to exclude fire from the trees. These are made using hoes and cutlasses to clear brush in the form of belts one to two metres wide. This is often done at the end of the rainy season [October/November]. Despite these preventive measures, some plantations especially those established on unfarmed lands are still burnt by annual bushfires during the dry season.

4.1.7 Harvesting

The rotation length of neem in Northern Ghana is not currently defined and stands are generally selectively felled based on individual and community demand. It was however observed that this ranged between five to nine years. Harvesting of neem is done by cutting the trees with a cutlass as close to ground level as possible. In certain villages, trees are cut at about 1.5 m above ground level in order to prevent cattle from destroying the new coppice shoots. The major factor determining cutting height however is the end use to which the tree is to be put. Cutting is usually done to maximize bole length. Selective felling is usually done in which the trees of best form which can serve as poles or rafters are cut first. It is difficult if not impossible to encounter an intact neem plantation three years or older. The plantation or whatever is left of it, can best be described as coppice with standards, where the standards are the crooked or malformed trees.

4.2 DIAMETER AND HEIGHT GROWTH

The diameter and height statistics of the sample plantations is summarized in Table 3. The summaries of the individual plantation data are given in Appendix I.

Table 3. Diameter and height statistics of measured neem plantations.

Age (years)	dbh (cm)			Height (m)		
	Mean	SE	Range	Mean	SE	Range
1	0.82	0.02	0.16 - 2.65	1.42	0.02	0.53 - 3.11
2	2.26	0.03	0.35 - 4.60	2.14	0.03	0.60 - 5.21
3	4.22	0.05	1.14 - 7.05	4.67	0.04	2.11 - 7.76
4	5.43	0.08	2.00 - 8.72	4.74	0.04	3.11 - 9.34
5	6.07	0.09	2.50 - 11.61	5.41	0.05	3.63 - 10.61
6	8.18	0.14	4.71 - 12.26	5.85	0.10	3.71 - 11.73
9	11.40	0.27	9.05 - 16.81	9.21	0.17	7.64 - 12.57

The annual diameter increment ranged from 0.64 to 2.11 cm and averaged 1.41 cm. The standard error of the mean dbh [SE] ranged from 0.02 to 0.27 cm and increased with age. The mean annual height increment was 0.93 m and ranged from 0.07 to 2.53 m. The standard error of the mean height [SE] increased with age from 0.02 m in the first year to 0.17 m nine years after planting [Table 3].

A simple linear relationship between height and dbh was developed to predict height for any given diameter. This equation is given as:

$$H = 1.167 + 0.675\,D \tag{28}$$

$$R^2 = 0.97$$

Where H is the total height and D is the diameter at breast height.

Individual Weibull models were developed for each age class. The estimated parameters are given in Table 4. In all methods, the location parameter, a, was taken as x_1 since in all age classes, $x_2 - x_1$ was greater than $x_n - x_2$.

Table 4. Estimated Weibull parameters by the Maximum likelihood, Moments and Percentile methods.

Age (yrs)	Method of Estimation								
	Maximum Likelihood			Moments			Percentile		
	a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
1	0.500	0.712	1.906	0.500	0.704	1.800	0.500	0.713	1.415
2	0.500	0.997	1.645	0.500	0.977	1.514	0.500	0.940	1.397
3	0.500	4.130	3.422	0.500	4.127	3.451	0.500	4.034	4.602
4	1.500	4.442	2.584	1.500	4.436	2.624	1.500	4.348	2.635
5	1.500	5.164	2.472	1.500	5.152	2.475	1.500	4.944	2.523
6	4.500	4.059	2.933	4.500	4.071	2.896	4.500	4.154	3.166
9	7.500	4.280	2.130	7.500	4.287	2.189	7.500	4.169	2.240

The method of Moments used for the computations in Table 4 was that described by Zarnoch and Dell (1985), whilst the Percentile estimators [PE] were obtained using Zankis (1979) procedure. The results show that the estimators from the different estimation methods were close especially those between the method of Moments [ME] and the Maximum likelihood method [MLE]. The differences in predicted diameter distributions produced by the Maximum likelihood and Moments methods were small.

The MLE of *a*, *b* and *c* were found separately for each plantation, giving 30 sets of *a*, *b* and *c*. Linear regressions were then fitted to relate the MLE to three stand characteristics: stand age, mean dbh and mean height. In Table 5, A is the stand age, D is the dbh and h is the mean height.

Table 5. Results of the regressions of Maximum Likelihood Weibull parameter estimators on stand age, mean dbh and mean height.

Regression	R^2
$a = -0.886 + 1.271A + 0.408D - 0.931h$	0.91
$b = 0.478 - 1.893A + 0.935D + 1.232h$	0.71
$c = 1.884 - 1.841A + 1.115D + 0.483h$	0.83

The parameter prediction equations given in Table 5 can be used to estimate the three Weibull parameters at any given age, mean dbh and height. Regressions of the parameter estimates on mean dbh and mean height and on mean dbh alone are also given in Appendix XI. These equations were provided for use in places where stand age and/or mean height determination is not possible.

The observed and expected frequencies produced by each Weibull parameter estimation method together with the expected frequencies when the data were fitted to the Normal and Log-normal distributions are presented in Appendix X. The differences between the observed and predicted diameter distributions were compared using the Kolmogorov-Smirnov [KS] criterion. The results are shown in Table 6.

Table 6. Results of the test of no difference between observed and predicted distributions within the 7 age groups [criterion = KS; $\alpha = 0.05$].

	Distribution				
	Normal	Log-normal	Weibull		
			MLE	ME	PE
Hypothesis rejected (out of 7 age groups)	6	2	5	4	5
Hypothesis accepted (out of 7 age groups)	1	5	2	3	2
Acceptance rate (%)	14	71	29	43	29

In five out of seven age groups [71%], the Log-normal distribution produced predicted diameter distributions that were not significantly different from the observed diameters based on the Kolmogorov-Smirnov criterion. The Normal distribution gave the worse fit, with only one out of the seven [14%] age groups fitting the Normal distribution well [Table 6].

4.3 FORM FACTORS

The cylindrical and conical form factors were computed for each sample tree and the means for each year calculated. The summary is presented in Table 7.

Table 7. Summary statistics of form factors.

Age	Cylindrical Form Factors			"Conical" Form Factors		
(years)	Mean	SE	Range	Mean	SE	Range
1	0.25	0.01	0.20 - 0.33	0.76	0.05	0.59 - 0.99
2	0.29	0.01	0.26 - 0.32	0.87	0.03	0.78 - 0.96
3	0.31	0.01	0.21 - 0.48	0.94	0.02	0.69 - 1.44
4	0.30	0.01	0.25 - 0.34	0.90	0.02	0.74 - 1.04
5	0.28	0.01	0.24 - 0.32	0.93	0.03	0.73 - 0.95
6	0.38	0.04	0.28 - 0.42	1.15	0.11	0.84 - 1.35
9	0.41	0.05	0.35 - 0.48	1.25	0.15	0.99 - 1.42

The mean cylindrical form factors varied from 0.25 in the first year of growth to 0.41 in the ninth year. The "conical" form factors [calculated as the ratio of the volume of the tree to that of a cone of the same height and diameter as the dbh of the tree] ranged from 0.76 to 1.25 in the ninth year. The standard errors of the form factors showed that the variation in form within each age class was small [Table 7].

4.4 RELATIONSHIP BETWEEN STEM DRY WEIGHT AND FRESH WEIGHT

Form this study, a simple relationship was established between dry weight and fresh weight of the stems of the sample trees. A linear regression model that can be used to predict stem dry weight from fresh weight is given by:

$$Dw = 0.7159 + 0.3294Fw \qquad (29)$$

$$R^2 = 0.96$$

where Dw is the dry weight of the stem and Fw is its fresh weight.

4.5 LOCAL AND STANDARD VOLUME TABLE EQUATIONS

The standard errors, R^2 values, Fit Indices, Furnival Indices and coefficients of variation of the 15 equations compared for volume table construction are presented in Appendix IV. The most appropriate equations of the fifteen tested that were used for the construction of local and standard volume tables are as follows:

$$\ln V = -0.780 + 1.711 \ln D \qquad (30)$$

$[n = 108, R^2 = 0.96, \text{Correction Factor} = 1.038]$

$$\ln V = -1.689 + 1.165 \ln D + 1.124 \ln H \qquad (31)$$

$[n = 108, R^2 = 0.97, \text{Correction Factor} = 1.027]$

where

V = overbark stem volume in dm^3,

D = dbh in cm, and

H = total height in m.

In order to correct for log-normal bias, correction factors were calculated as $\exp(s^2/2)$ where s^2 is the variance of the respective logarithmic equations (Baskerville, 1972). The arithmetic means were estimated by multiplying the geometric means by the correction factors. The complete Local and Standard Volume Tables are presented in Appendices V and VI. The coefficients of the local and standard volume table equations for each site class are presented in Appendix VIII.

4.6 TOP HEIGHT/AGE BY SITE CLASS CURVES

Equation (25) was used to develop the top height/age curves in Appendix II. This figure shows means and ranges of top height in Site Classes I, II, and III.

4.7 YIELD TABLES

The coefficients of Equation (27) which were used to develop the empirical yield tables for neem in Northern Ghana are presented in Table 8. The R^2 values for the various yield parameters were high, ranging from 0.78 to 0.94. This means that between 78% to 94% of the variation in yield was explained by variation in age.

Table 8. The coefficients of Equation (27) used to develop the empirical yield tables for neem (*Azadirachta indica* A. Juss.) in Northern Ghana.

Variable	Site Class I [Yield Class 12]			Site Class II [Yield Class 8]			Site Class III [Yield Class 4]		
	α	β_1	R^2	α	β_1	R^2	α	β_1	R^2
Diameter	2.75	-2.78	0.94	2.56	-3.17	0.92	2.34	-3.18	0.89
Height	2.50	-1.89	0.93	2.37	-2.14	0.87	1.99	-2.10	0.94
Basal Area	3.90	-5.45	0.89	3.45	-6.33	0.84	3.07	-6.23	0.82
Volume	5.20	-5.17	0.90	4.97	-6.53	0.78	4.80	-10.52	0.98
Fresh Wgt.	5.29	-4.83	0.92	4.84	-5.26	0.94	4.74	-7.42	0.91

The Yield Table developed from Equation (27) using the coefficients given in Table 8 is presented in Appendix VII. The Yield Table is divided into Site Classes I, II and III; these are equivalent to Yield Classes 12, 8 and 4 m^3/ha/year respectively at optimum rotation.

The biologically optimum rotation length for each site class is given by the estimated volume β_1 coefficients in Table 8. These rotation lengths are 5, 7 and 11 years for Site Classes I, II and III respectively. It should be noted that the optimum rotation age for Site Class III is outside the range of the data and was therefore extrapolated.

5.0 DISCUSSION

5.1 USES OF NEEM IN NORTHERN GHANA

Neem is a common tree species in Northern Ghana which is planted around home and school compounds, in avenues, in plantations and on farmlands. Traditionally, neem has been planted for shade, protection against wind, and for medicinal purposes. However, planting of neem in plantations or on farmlands for poles and fuelwood has not been practised by rural and urban communities. Neem trees on farmlands have always been natural regeneration from seeds dispersed mostly by birds which are the main agents of neem seed dispersal in the area.

Mature neem trees around homes are usually managed by the coppice system for the continuous production of poles and rafters for building construction. With the advent of the Rural Afforestation Programme, neem is grown for poles and fuelwood in small to medium plantations [0.5 - 3.0 ha] adjacent to villages where they are easily maintained and readily accessible for harvesting. Since all building in rural communities is done using only local materials, the major use of neem in the Tamale Forest District is for building and fencing purposes. The crooked trees and the smaller branches from pole and rafter wood are used as fuelwood. Though the literature reveals several other uses of neem, not as much use is made of the tree in Northern Ghana as in other parts of the world.

5.2 ASSESSMENT OF CURRENT SILVICULTURAL PRACTICES FOR NEEM

Seed collection is adequate at the current scale of operations. However, the current practice of seed collection which is not confined to superior phenotypes may result in poor quality trees on the plantations. If the current planting programmes are to be expanded, it is probable that improvements will be needed in seed collection practices. In particular, seed collection must be confined to desirable phenotypes growing in plantations in Northern Ghana.

Nursery practice can be improved by developing modern container nurseries. Seedlings raised in polythene tubes have a higher survival rate than bare-root stock, but have the disadvantage of being more expensive to raise and transport. It should be possible to outplant bare-root stock in the early part of the rainy season when they have higher chances of survival and to outplant the container stock in the latter part of the rainy season when the rains are erratic. This will reduce nursery cost and also ensure a high survival of outplanted stock in both cases. A further reduction in nursery costs can be achieved by teaching farmers to use wildlings from superior phenotypic trees for outplanting on their farms. Conducting demand surveys during the dry season to obtain reasonable estimates of the quantities of neem seedlings that will be needed by farmers, communities and other institutions will eliminate over production of seedlings by the Forestry Department in any given year.

As the number and extent of plantations expands, the competition for land between agriculture and forestry is likely to increase. The adoption of agro-forestry practices will ease this competition. Neem has been successfully intercropped with the major food crops grown in Northern Ghana, but the practice has not been widely adopted. Though there is no quantitative measure of the improvement in crop yields due to intercropping with neem in Northern Ghana, the potential benefit is generally recognized. Studies in Burkina Faso indicate that intercropping neem with food crops gives markedly increased yields (e.g. Tilander, 1993). Intercropping neem with food crops has the potential of increasing the growth and yield of neem since farmers will be prepared to grow the tree on more fertile lands which hitherto have been reserved only for food crops. This will also ensure that plantations are weeded [hoed] and well protected from fires since it is known that most plantations burnt during the dry season are those on unfarmed lands. Hoeing loosens the soil and has been found to reduce yellowing of neem trees which usually leads to mortality on poor soils (Mackay, 1952).

It will be essential to have information of the growth, yield and rotation length of neem plantations on various land types so that their value can be compared with other forms of land use. In particular, there must be a clear understanding of the initial spacings, thinning regimes and rotation lengths needed to optimize the growth and yield of neem. Currently most plantations are prematurely 'thinned' by village dwellers for poles and rafters when they reach approximately three years of age. Premature thinning and short rotation lengths encountered on these plantations are indications of the severity of wood shortages for rural building and fuelwood needs. The effect of this uncontrolled 'thinning' at wide initial spacing creates 'gaps' and understocking.

Since almost all neem plantations are established in close proximity to villages, intensive silviculture is not only feasible, but is beneficial to the communities. The adoption of closer initial spacing and thinning regimes will circumvent the current problem of pole and rafter wood removal by the villagers which interferes with the development of fully stocked plantations.

The current initial spacing of 2 x 2 m for neem appears to be wider than optimum because its form factors show that the trees are more conical than cylindrical. The form factors tend to increase with age though they are uniform within the age groups as shown by their standard errors [Table 7]. The uniformity in form factors is probably due to the similarity in spacing and other stand treatments in all plantations in the study area. Closer initial spacings will ensure straighter and more cylindrical boles which are both desirable qualities for poles and rafters. An initial planting density of 3265 stems/ha is suggested here [1.75 x 1.75 m]. A higher density than this will lead to increased plantation costs and also likely to produce inferior poles and rafters since there will be a proliferation of many small stems and branches rather than increases in diameter of individual trees.

5.3 ASSESSMENT OF DIAMETER AND HEIGHT GROWTH

Summaries of diameter and height growth statistics are given in Table 3 and Appendix I. The mean diameter at four years was 5.43 cm. This is slightly higher than the mean diameter at the same age of 5.14 cm reported for neem in northeastern Nigeria by Verinumbe (1991). In this study, the mean heights at two and five years were 2.14 and 5.41 m respectively. These were lower than mean heights reported for the same ages as 3.6 and 7.5 m respectively by Streets (1962). Streets (1962) did not indicate which part of northern Ghana nor the type of neem plantations from which the measurements were taken. Therefore it is difficult to compare these results with those found in this present study. The mean heights of plantations on Site Classes I and II [as defined in this study] are close to these mean heights at two and five years.

In this study, suitability of the Normal, Log-normal and Weibull distributions and the Weibull parameter estimation methods to model neem plantations was evaluated based on comparisons of observed and predicted diameters using the Kolmogorov-Smirnov [KS] criterion. Table 6 shows the results of the test of no differences in observed and predicted diameter distributions using the KS statistic. The Log-normal distribution was clearly the best; with 71% of the hypotheses accepted. The null hypothesis was rejected in the six- and nine-year age groups. The lack of fit in the older age groups is probably due to the fact that the observed distributions of the these two age groups are negatively skewed, whilst the Log-normal distribution is generally positively skewed (more trees in the smaller diameter classes). Hafley and Schreuder (1977) also noted that the log-normal distribution was limited to shapes that are positively skewed whilst the Weibull distribution was more flexible, taking both positively and negatively skewed shapes. The ME of the Weibull distribution was satisfactory, as 43% of the null hypotheses were accepted. These results suggest that the Log-normal distribution can be used to fit diameter distributions of plantations within the 1 - 5-year age groups and the ME of the Weibull function be used for plantations older than five years. If however a single distribution is necessary, the

Weibull function should be used as this distribution exhibits more flexibility in terms of skewness. The parameters can be estimated easily by either the method of Moments or the regression equations given in Table 5 and Appendix XI.

The results of this study show that the Weibull distribution parameters estimated from Moments techniques are quite close to the Maximum likelihood estimators [MLE]. The MLE are usually considered the best estimators for the Weibull function because of their desirable statistical properties such as precision and asymptotic minimum variance (Shifley and Lentz, 1985). A comparison of the predicted diameter frequencies produced by the MLE and ME show a close correspondence between the diameter distributions produced by the two methods of parameter estimation.

The estimators and the predicted diameter distributions from the Percentile method were inferior to those from the Maximum likelihood and Moments methods. Zarnoch and Dell (1985) also found the PE to be inferior to the MLE and ME when applied to pine plantations.

As neem is used mostly for poles and rafters in the Tamale Forest District, a knowledge of the diameter distributions of the plantations at each age is very important to farmers and the Forestry Department in planning thinning regimes.

5.4 LOCAL AND STANDARD VOLUME TABLE EQUATIONS

None of the fifteen equations compared in the study emerged as best for all five criteria. Equation (30) was selected as the best local volume table equation based on the Furnival Index (Furnival, 1961) to provide quick volume estimates in places where height measurement is difficult or not possible to undertake. Separate local volume table equations were developed for each site class and compared with Equation (30) using the test of coincidence [Appendix IX]. The test showed that there was no significant difference in coefficients between the overall equation [Equation (30)] and the separate equations. Equation (30) underestimates volumes compared to Equation (31) but is satisfactory for field volume estimations. It is however recommended that Equation (31) be used whenever precise volume estimates are needed.

Equation (31) was selected for the standard volume table because it had the lowest Furnival Index (Furnival, 1961). This equation had the following characteristics: dbh and height explained 97% of the variation in stem volume and the Fit Index was 0.90. Test of coincidence showed that there was a statistically significant difference between Equation (31) and separate equations for the different site classes.

The separate local and standard volume table equations for each site class are given in Appendix VIII. The separate equations can be used in places where more accurate volume estimates are needed for a particular site class. In cases where it is not possible to determine the site class of the stand of interest or where only rough estimates of the volumes are required, then Equation (31) could be used.

The remaining equations performed better on other criteria, but were found to have violated some of the assumptions of linear regression, in particular, homogeneity of variance. For example, Model 5 [Appendix III and IV] proved to be the most appropriate for the standard volume table in terms of the R^2 value, Fit Index [FI], standard error in actual units [s_e], and the coefficient of variation [CV]. However, the error terms of this equation were heteroscedastic. The Furnival Index [I] takes into account the sizes of the residuals as well as possible departures from linearity, normality, and homoscedasticity.

Without the necessary correction for log-normal bias, volume Equations (30) and (31) underestimate volumes by only 3.8 and 2.7% respectively and therefore the Correction Factors can be neglected when making rough estimates. To correct for bias, the Correction Factor is multiplied by the geometric mean to obtain the unbiased arithmetic mean. These Correction Factors were applied in the construction of both volume tables. The addition of form factor to the independent variables in both equations showed that change in form had an insignificant effect.

5.5 TOP HEIGHT/AGE BY SITE CLASS CURVES

The top height over age by site class curves shown in Appendix II are to be used to classify stands into site classes for yield estimation. To determine the site class of a particular stand, it is necessary to determine the top height and age of the plantation. It might be difficult to determine plantation age on the field since there are no annual rings. The ages of plantations can usually be obtained from records at the Forestry Office in Tamale or by the Forestry Technical Officer in charge of the area where the plantation is located. Individual farmers and community leaders will also be able to help determine the ages of their plantations.

The accuracy of the method used for the site index curves depends critically on the assumption that all sites have an equal likelihood of being represented in each age class (Alder, 1980; Clutter *et al.*, 1983). Since the plantations were randomly selected with no conscious effort to include any particular site type, the above assumption cannot be guaranteed to be satisfied by the present study. This is particularly true of the six- and nine-year age groups where only three and two plantations were measured respectively. It is also possible that older age plantations are found on poorer sites and the younger ones on good sites, which can lead to bias in the site index curves. Several factors operate to prevent equal representation of all sites in the various age classes. Good sites produce bigger and taller trees more rapidly than poorer sites and therefore both selective felling and harvests take place earlier on good sites. Secondly, most of these lands on which neem is planted have been removed from agricultural production and since the poorer lands are removed first, older age plantations are more likely to be found on poorer sites. For these reasons, the site index curves produced by this method should be regarded as provisional. Permanent sample plot data will be needed to validate these curves.

It is worthy of note that the site index curves for neem in Northern Ghana given in Appendix II were found to be similar to those for neem in Sumaru in Northern Nigeria and in the Prachinburi Province (near Bangkok) of Thailand. At a base age of 7 years, Appendix II shows that the average top heights for Site Classes III, II and I are about 8, 9 and 11 m respectively. In Sumaru, the top heights at the same base year and Site Classes are reported as 7, 9 and 12 m respectively (Gravsholt *et al.*, 1967), whilst in the Prachinburi Province, the top heights are 7, 9 and 11 m respectively (Hoamuangkaew *et al.*, 1990).

5.6 YIELD TABLE

The Yield Table presented in Appendix VII is for the standard initial spacing of 2 x 2 m. The mean annual increment (MAI) for Site Class I and II are given in the Yield Table (Appendix VII). Because the MAI at optimum rotation for Site Class III occurs outside the range of the data [at 11 years], it was estimated as 4.23 m^3/ha from Equation (31) using the coefficients in Table 8. Yields can either be estimated by use of Equation (31) [coefficients in Table 8] or the yield table presented in Appendix VII. The use of Equation (31) will eliminate rounding errors that would result from the use of the Yield Table.

The first step in estimating yields is to determine the site class to which the stand belongs. To do this, it is necessary to determine the mean height of the dominant and co-dominant trees and the stand age.

The basal area of any stand can be determined by measuring plots or from a wedge prism. The stocking factor for the stand is then found by taking the ratio of the actual basal area to average basal area [given in the yield table]. The current basal area [per ha] is then computed by taking the product of the stocking factor and the average basal area [per ha] predicted by the yield table [or equation].

Stand volume is found by first determining the volumes of individual trees measured on a plot. Depending on the degree of precision desired, volumes can be computed with either the local or standard volume table equations. The plot volume is then the sum of all the volumes of the individual trees on the plot. The stand volume per ha is then calculated by multiplying the stocking factor [obtained using the basal area] by the average volume per ha given in the yield table or yield equations.

Fresh weight estimation is best achieved by multiplying the weight of the tree of mean basal area and mean height by the number of stems/ha in the stand.

The Yield Table probably underestimates the growth and yield potential of neem plantations in Northern Ghana since some of the plantations measured had been selectively harvested. Selective harvesting usually removes the largest trees for poles and rafters. Secondly, most of these plantations are established on either abandoned or infertile agricultural lands.

The mean diameters and heights given for the plantations on Site Classes I and II in the Yield Table [Appendix VIII] indicate that trees on these good and medium sites can be used as rafters at age three. Site Classes I and II can probably be thinned in the third year, Site Class III in the fourth. The time for thinning suggested here coincides with that being practised by the farmers.

In using either the equations or yield table, caution should be exercised in predicting yields beyond the range of the data used in their derivation. It should also be appreciated that the yield equations and table represent averages to be expected for all stands in a given site and age class. Finally it should be noted that these yield table/equations are applicable to pure neem stands with an initial spacing of 2 x 2 m. Neem plantations with different initial spacings [e.g. 1 x 1 m or 1.5 x 1.5 m] or those intercropped with food crops will be expected to differ in their growth and yield characteristics. For these reasons, it is possible for observed yields for a given stand on the field to differ from those predicted by this Yield Table [equation].

6.0 CONCLUSIONS AND RECOMMENDATIONS

- Neem plantations can be grown successfully in Northern Ghana on biologically optimum rotations that range from 5 to 11 years. It is probable that neem may be grown to larger size on longer, less productive rotations.

- The current silviculture for neem in Northern Ghana is adequate for present levels of plantation establishment. The following improvements are urgently needed if the current programme is to be expanded: a) seed collection must be confined to desirable phenotypes, b) nursery practice must be improved, c) outplanting should be confined to periods with reliable rainfall [May to August], d) the plantations must be well protected from savanna fires.

- The Forestry Department should provide technical advice to farmers on the use of wildings to supplement nursery stock. This will help reduce the cost of seed collection, nursing and transportation of seedlings which is currently borne solely by the Forestry Department.

- Equations (30) and (31) were adjudged the best local and standard volume table equations respectively based on the Furnival Index. These equations were corrected for log-normal bias with the respective correction factors as 1.038 and 1.027.

- The diameter distributions of the neem plantations in Northern Ghana can be modelled using either the Log-normal distribution or the Weibull function. The method of Moments, which is simpler to use, gives estimators that are close to those obtained by the more complex Maximum likelihood method.

- The Yield Table developed for neem in Northern Ghana shows that the mean annual increment of Site Class I and II and III plantations was 12.9, 8.1 and 4.3 m^3/ha on optimum rotations of 5, 7 and 11 years respectively.

- The current initial spacing of 2 x 2 m [2500 trees/ha] used for neem plantations in Northern Ghana should be reduced to 1.75 x 1.75 m [3265 trees/ha] on Site Classes I and II. This will maximize early productivity, allow for pole and rafter wood removal by villagers without jeopardizing the future stand, and permit a thinning three years after outplanting.

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APPENDICES

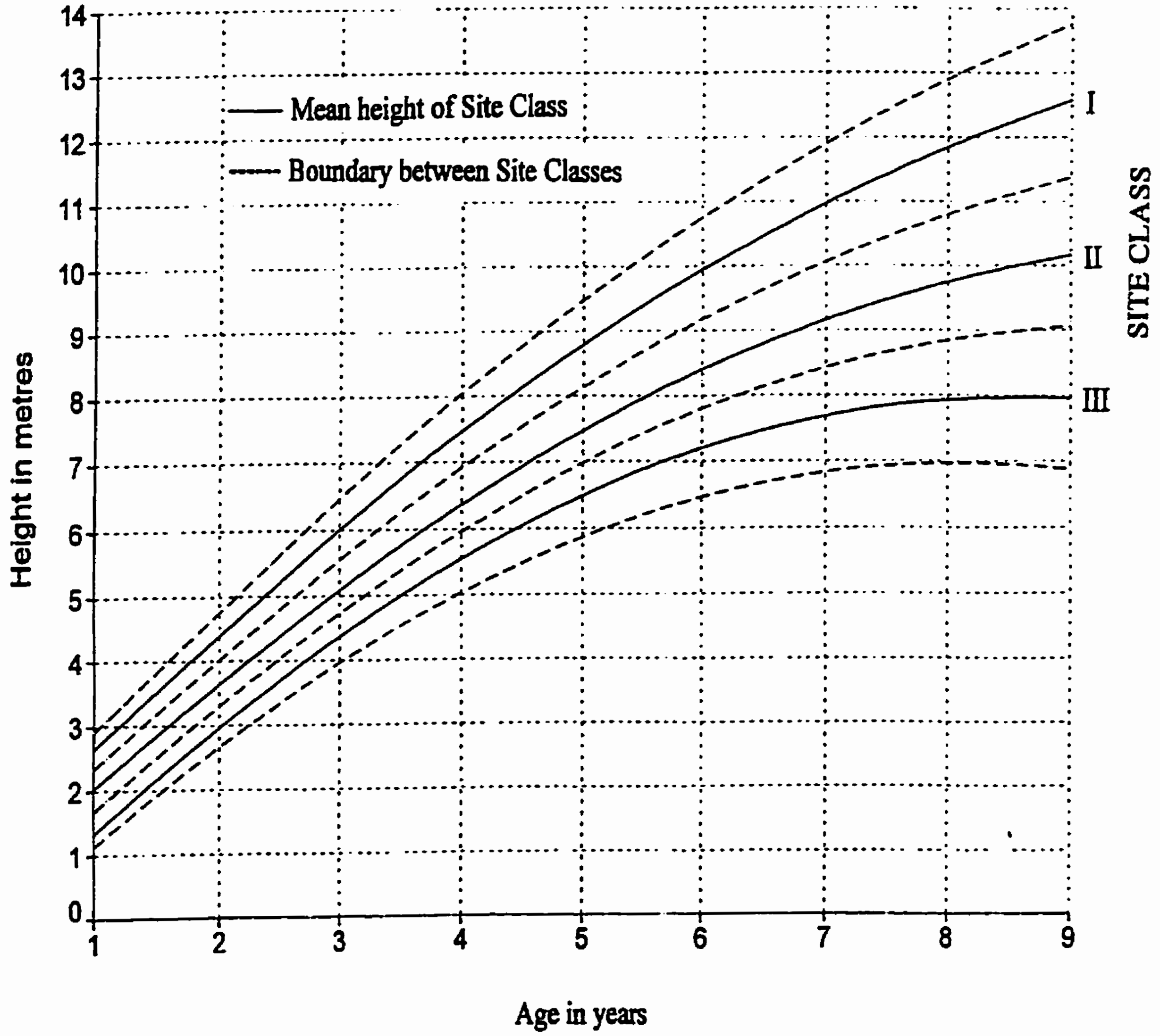
APPENDIX I

SUMMARY OF DIAMETER AND HEIGHT DATA OF SAMPLE PLANTATIONS

Plantation No.	Age (years)	dbh (cm)		Height (m)	
		Mean	Range	Mean	Range
1	1	0.57	0.26 - 1.30	1.01	0.53 - 1.61
2	1	0.47	0.27 - 0.71	1.24	0.70 -2.00
3	1	0.72	0.16 - 1.70	1.47	0.70 - 2.62
4	1	0.75	0.40 - 1.51	1.39	0.70 -2.30
5	1	1.08	0.27 - 2.65	1.99	1.42 - 3.11
6	2	1.84	0.35 - 2.43	1.44	0.60 -2.46
7	2	3.84	0.41 - 2.60	1.93	0.60 - 2.99
8	2	3.00	0.40 - 4.60	2.43	1.42 - 3.65
9	2	1.70	0.42 - 3.51	2.57	1.56 - 3.96
10	2	1.33	0.56 - 2.96	2.24	1.46 -3.35
11	3	3.19	1.14 - 6.50	3.92	2.11 - 5.98
12	3	4.60	2.82 - 6.91	5.16	3.15 - 7.11
13	3	4.95	2.79 - 6.76	5.48	3.46 - 7.46
14	3	4.03	2.13 - 5.93	4.20	2.99 - 5.60
15	3	4.31	2.98 - 7.05	4.60	3.40 - 7.11
16	4	5.27	2.74 - 10.36	4.19	3.28 - 5.91
17	4	6.49	3.60 - 11.51	4.59	3.37 - 6.71
18	4	5.55	2.61 - 9.63	5.06	3.13 - 6.79
19	4	4.45	2.00 - 7.69	5.11	3.11 - 7.64
20	4	6.90	2.42 - 8.72	6.85	3.42 - 8.23
21	5	6.42	2.54 - 11.61	5.57	3.63 - 8.60
22	5	5.35	2.95 - 7.93	5.13	3.36 - 7.23
23	5	4.79	2.50 - 7.24	4.88	3.35 - 6.81
24	5	6.17	3.00 - 11.40	5.58	3.92 - 8.21
25	5	7.63	4.18 - 12.23	5.89	4.37 - 9.15
26	6	8.11	5.07 - 11.29	5.69	3.73 - 8.18
27	6	8.24	4.71 - 10.80	6.00	3.71 - 7.95
28	6	9.57	5.27 - 12.26	9.02	4.21 - 10.14
29	9	11.40	9.05 - 16.81	9.21	7.64 - 10.80
30	9	11.93	9.65 - 15.63	10.24	8.31 - 11.52

APPENDIX II

TOP HEIGHT OVER AGE BY SITE CLASS CURVES FOR NEEM



APPENDIX III

LIST OF MODELS COMPARED FOR VOLUME TABLE CONSTRUCTION

Model Number	Equation
1	$V = b_o + b_1D$
2	$V = b_o + b_1D + b_2D^2$
3	$V = b_o + b_1D^2$
4	$V = b_o + b_1D^2H$
5	$V = b_o + b_1D^2 + b_2H + b_3 D^2H$
6	$V = b_o + b_1D^2 + b_2DH + b_3 D^2H$
7	$\ln V = b_o + b_1\ln D$
8	$\ln V = b_o + b_1\ln D + b_2\ln H$
9	$V/D^2 = b_o + b_1(1/D) + b_2(1/D^2)$
10	$V/D^2 = b_o + b_1(1/D^2)$
11	$V/D^2H = b_o + b_1(1/D^2H)$
12	$V/ D^2 = b_o + b_1(1/D^2) + b_2(H/D^2) + b_3H$
13	$V/D^2H = b_o + b_1(1/H) + b_2(1/D^2) + b_3(1/D^2H)$
14	$V/D^2 = b_o + b_1(1/D^2) + b_2(H/D) + b_3H$
15	$V/D^2H = b_o + b_1(1/H) + b_2(1/D) + b_3(1/D^2H)$

where D = diameter at breast height in cm,

H = total height in m,

V = volume in dm^3,

b_o = regression constants

b_1, b_2, b_3 = regression coefficients.

APPENDIX IV

STANDARD ERRORS, R^2 VALUES, FIT INDICES, FURNIVAL INDICES AND COEFFICIENTS OF VARIATION OF THE 15 MODELS COMPARED FOR VOLUME TABLE CONSTRUCTION

Model Number	Standard error ($s_{y.x}$)	R^2	Fit Index (FI)	Standard error in actual units (se)	Furnival Index (I)	C.V in actual units (%)
1	3.2459	0.8230	0.8230	3.2459	3.2459	43.49
2	1.6722	0.9538	0.9538	1.6722	1.6722	22.41
3	1.7283	0.9498	0.9498	1.7283	1.7283	23.16
4	1.3420	0.9697	0.9697	1.3420	1.3420	17.98
5	1.2945	0.9728	0.9728	1.2945	1.2945	17.34
6	1.3232	0.9715	0.9715	1.3232	1.3232	17.73
7	0.2737	0.9603	0.9039	2.3942	1.0829	32.08
8	0.2320	0.9720	0.9001	2.6932	0.9177	36.09
9	0.1273	0.4931	0.9411	1.8887	1.5804	25.31
10	0.1281	0.4788	0.9487	1.7474	1.5896	23.42
11	0.0423	0.8620	0.7147	4.1211	2.1747	55.22
12	0.0902	0.7597	0.9628	1.5125	1.1197	20.26
13	0.0300	0.9327	0.9682	1.3982	1.5435	18.73
14	0.0845	0.7803	0.9443	1.8515	1.0489	24.81
15	0.0292	0.9366	0.9518	1.7234	1.4989	23.09

APPENDIX V

LOCAL VOLUME TABLE FOR NEEM IN NORTHERN GHANA [DEVELOPED FROM EQUATION (30)]

Diameter Class (cm)	Volume (dm^3)
1	0.48
2	1.56
3	3.12
4	5.10
5	7.47
6	10.21
7	13.29
8	16.70
9	20.42
10	24.46
11	28.79
12	33.41

APPENDIX VI

STANDARD VOLUME TABLE FOR NEEM IN NORTHERN GHANA DEVELOPED FROM EQUATION (31) [VOLUME IN CUBIC DECIMETRES]

Diameter Class (cm)	Height (m)									
	1	2	3	4	5	6	7	8	9	10
1	0.19	0.42	0.65	0.90						
2	0.43	0.93	1.46	2.02	2.59	3.19				
3		1.49	2.35	3.24	4.17	5.11	6.08			
4			3.28	4.53	5.82	7.15	8.50	9.88		
5			4.25	5.88	7.55	9.27	11.02	12.81		
6				7.27	9.34	11.46	13.63	15.84		
7					11.18	13.72	16.31	18.96		
8					13.06	16.03	19.06	22.15		
9						18.39	21.72	25.40		
10						20.79	24.72	28.77	32.79	36.90
11							27.62	32.10	36.64	41.24
12							30.57	35.52	40.55	45.64

APPENDIX VII

YIELD TABLE FOR NEEM IN NORTHERN GHANA

Site Class	Age (years	Dbh (cm)	Total Height (m) mean	Total Height (m) Range	Basal area (m^2/ha)	Stem Volume (m^3/ha) Gross	Stem Volume (m^3/ha) CAI	Stem Volume (m^3/ha) MAI	Fresh Wgt. (t/ha)
	1	0.98	1.84	1.42 - 3.11	0.21	1.03	-	1.03	1.59
	2	3.92	4.74	2.49 - 5.21	3.25	13.71	12.68	6.86	17.80
	3	6.28	6.54	3.15 - 7.76	8.04	33.01	19.30	11.00	40.44
	4	7.85	7.60	4.32 - 9.34	12.66	49.92	16.91	12.48	59.50
I	5	9.01	8.36	5.61 - 10.61	16.63	64.64	14.72	12.93	75.74
	6	9.88	8.90	6.44 - 11.73	19.93	76.67	12.03	12.78	88.82
	7	10.57	9.31	6.89 - 11.80	22.69	86.88	10.21	12.41	99.82
	8	11.10	9.63	7.02 - 12.21	25.01	95.26	8.48	11.92	108.78
	9	11.54	9.89	7.79 - 12.57	26.98	102.94	7.58	11.44	116.38
	1	0.54	1.26	0.65 - 2.49	0.06	0.21	-	0.21	0.69
	2	2.65	3.67	1.00 - 3.90	1.33	5.50	5.29	2.75	9.35
	3	4.50	5.24	3.12 - 5.98	3.82	16.34	10.83	5.45	22.67
	4	5.85	6.27	3.35 - 7.64	6.47	28.15	11.81	7.04	34.38
II	5	6.86	6.97	4.46 - 9.15	8.88	39.02	10.87	7.80	44.59
	6	7.63	7.49	5.23 - 9.45	10.97	48.51	9.49	8.08	52.96
	7	8.23	7.88	5.75 - 9.80	12.75	56.66	8.16	8.10	60.05
	8	8.70	8.19	6.25 - 10.21	14.28	63.67	7.01	7.96	65.88
	9	9.10	8.43	8.36 - 10.80	15.59	69.72	6.05	7.75	70.86
	1	0.44	0.90	0.53 - 1.55	0.04	0.003	-	0.003	0.07
	2	2.12	2.55	0.60 - 2.98	0.96	0.63	0.63	0.32	2.81
	3	3.64	3.65	2.11 - 3.73	2.70	3.65	3.01	1.22	9.91
	4	4.69	4.31	3.11 - 6.71	4.54	8.76	5.11	2.19	17.93
III	5	5.50	4.79	3.63 - 7.23	6.19	14.82	6.06	2.96	25.98
	6	6.11	5.13	3.71 - 8.14	7.62	21.05	6.23	3.51	33.18
	7	6.60	5.40	4.53 - 8.82	8.84	27.04	5.99	3.86	39.70
	8	6.98	5.61	5.32 - 9.14	9.88	32.62	5.59	4.08	45.30
	9	7.30	5.77	7.64 - 9.50	10.78	37.76	5.13	4.20	50.26

APPENDIX VIII

COEFFICIENTS OF LOCAL AND STANDARD VOLUME TABLE EQUATIONS BY SITE CLASS

Type of Equation	Site Class	Coefficients			R^2	Correction Factor
		Constant	D	H		
	I	-0.775	1.178		0.90	1.066
Local	II	-0.780	1.678		0.97	1.027
	III	-0.764	1.740		0.97	1.038
	I	-2.148	0.568	1.876	0.99	1.005
Standard	II	-1.527	1.207	0.933	0.97	1.025
	III	-2.398	0.823	2.064	0.98	1.022

Local Volume Table Equation: $\ln V = b_o + b_1 \ln D$

Standard Volume Table Equation: $\ln V = b_o + b_1 \ln D + b_2 \ln H$

where

D = diameter at breast height

H = total height

APPENDIX IX

ANOVA TABLE FOR TESTS OF COINCIDENCE FOR THE LOCAL AND STANDARD VOLUME TABLE EQUATIONS

Type of Equation	Source of variation	SS	df	MS	F
Local	Overall Regression	7.946	2	0.073	0.973
	Separate Regresions (Site Classes I, II and III)	7.800	104	0.075	
Standard	Overall Regression	4.926	3	0.384	10.378*
	Separate Regresions (Site Classes I, II and III)	3.774	102	0.037	

* Significant at the 0.05 probability level

The F-test for coincidence (equal intercept and slope coefficients) shown in the above table was

calculated as follows:

$$F = \frac{[SS_T - (SS_I + SS_{II} + SS_{III})/k]}{(SS_I + SS_{II} + SS_{III})/n - 2k}$$

where

SS_T is the sum of squares of the regression of the whole data set (Site classes I, II and III combined)

SS_I is the sum of squares of the regression of Site Class I

SS_{II} is the sum of squares of the regression of Site Class II

SS_{III} is the sum of squares of the regression of Site Class III

k is the number of coefficients to be estimated

n is the total sample size

For the Local volume Table,

$$F = \frac{[7.946-(3.104+2.619+2.077)]/2}{[3.104+2.619+2.077]/[108-2(2)]}$$

$$F = 0.073/0.075$$
$$= 0.973$$

For the Standard Volume Table,

$$F = \frac{[4.926-(0.245+2.379+1.150)]/3}{[0.245+2.379+1.150)]/[108-2(3)]}$$

$$F = 0.384/0.037$$
$$= 10.378$$

APPENDIX X

OBSERVED AND EXPECTED DIAMETER DISTRIBUTIONS OF THE NORMAL, LOG-NORMAL AND WEIBULL DISTRIBUTIONS

Age (years)	Diameter Class (cm)		Method of Estimation				
		Observed	Normal	Log-normal	MLE	ME	PE
1	1	910	833	939	878	873	825
	2	110	154	90	151	155	191
	3	10	43	1	1	2	14
	Total	1030	1030	1030	1030	1030	1030
2	1	1150	875	1132	1087	1106	1139
	2	485	671	515	554	520	479
	3	70	51	60	70	82	86
	≥ 4	10	118	8	4	7	10
	Total	1715	1715	1715	1715	1715	1715
3	1	15	26	2	19	19	4
	2	140	158	153	180	177	92
	3	540	496	653	507	507	465
	4	825	797	788	764	769	974
	5	600	658	514	652	655	780
	6	305	280	240	295	293	164
	7	55	61	95	63	60	5
	8	5	9	37	5	5	1
	Total	2485	2485	2485	2485	2485	2485

.......more

Age (years)	Diameter Class (cm)		Method of Estimation				
		Observed	Normal	Log-normal	MLE	ME	PE
4	2	12	67	17	52	49	51
	3	231	202	210	246	241	251
	4	494	414	551	462	462	481
	5	625	586	652	574	584	5
	6	613	575	501	523	531	531
	7	267	386	296	359	361	347
	8	162	180	151	186	183	167
	9	38	58	71	72	68	58
	10	38	13	31	21	19	14
	11	14	12	14	4	4	3
	≥ 12	6	74	6	1	1	1
	Total	2500	2500	2500	2500	2500	2500
5	2	5	56	11	38	37	39
	3	135	137	129	166	166	178
	4	350	261	360	310	312	336
	5	520	388	492	409	411	440
	6	425	447	452	428	428	446
	7	325	281	329	257	257	237
	8	185	152	208	151	150	125
	9	150	65	126	74	73	53

..... more

Age (years)	Diameter Class (cm)	Observed	Method of Estimation				
			Normal	Log-normal	MLE	ME	PE
	10	95	21	66	30	29	18
	11	20	0	18	3	3	1
	12	5	0	9	0	0	0
	Total	2240	2240	2240	2240	2240	2240
6	5	75	57	41	42	43	28
	6	275	222	254	254	258	208
	7	375	515	591	550	546	515
	8	750	714	694	679	688	720
	9	650	589	504	563	559	616
	10	300	292	261	288	293	312
	11	75	94	105	90	95	88
	12	0	17	50	16	18	13
	Total	2500	2500	2500	2500	2500	2500
9	8	125	111	102	106	104	100
	9	125	249	278	334	328	339
	10	688	421	497	489	489	512
	11	563	532	569	518	523	545
	12	438	496	473	437	443	448
	13	375	358	306	303	306	296
	14	62	186	162	176	176	158
	≥ 15	124	147	113	137	131	102
	Total	2500	2500	2500	2500	2500	2500

Note: MLE, ME and PE refer to Maximum likelihood, Moments and Percentile Estimators of the Weibull function respectively.

APPENDIX XI

REGRESSIONS OF MAXIMUM LIKELIHOOD ESTIMATES [MLE] OF THE WEIBULL FUNCTION ON MEAN DBH AND MEAN HEIGHT

Regression	R^2
$a = -0.877 + 1.356D - 0.88h$	0.89
$a = -1.576 + 0.714D$	0.86
$b = 0.464 - 0.478D - 1.165h$	0.62
$b = 1.384 + 0.366D$	0.51
$c = 1.871 - 0.259D + 0.418h$	0.19
$c = 2.201 - 0.044D$	0.06

where D is mean dbh and h is mean height