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Improving the sustainability of cocoa farms in Ghana through utilization of native forest trees in agroforestry systems

Anglaaere, Luke

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IMPROVING THE SUSTAINABILITY OF COCOA FARMS IN GHANA THROUGH UTILIZATION OF NATIVE FOREST TREES IN AGROFORESTRY SYSTEMS.

By

ANGLAAERE Luke Cyprian N-unkyer
B.Sc. (Hons) Natural Resources Management,
M.Sc. Forest Resources Management.

A thesis submitted in fulfilment for the Philosophiae
Doctor at the University of Wales, Bangor, UK

School of Agricultural and Forest Sciences
University of Wales, Bangor,
United Kingdom.

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ABSTRACT

The study investigated farmers' ecological knowledge and management relating to cocoa agroforests in the Atwima district of Ghana, with the view to selecting and developing the potential of native forest tree species for use as shade in multi-strata cocoa agroforestry systems. More specifically, the study investigate farmers' knowledge about the ecology and management of multi-strata cocoa systems, with the view to identifying native forest tree species preferred by farmers as shade for cocoa. Based on this preliminary survey of farmer knowledge and preferences, eight indigenous forest tree species were selected for field screening. Field studies involved: (i) assessment of their natural distribution in different landuse systems, to determine natural regeneration potential; (ii) evaluation of their phenological patterns and light regimes under their canopies, with the view to determining their suitability for shade provision; (iii) evaluation of growth performance, when planted as shade on cocoa farms; (iv) determination of potential below-ground complementarity in resource use (particularly water) between planted shade and the cocoa, through evaluation of root competitivity indices for the planted species, as well as determination of water use by means of sap flow measurement. The study also evaluated methods of seed pre-treatment to enhance germination of *T. tetraptera* seeds, which usually take a long time to germinate.

Farmers' knowledge on site selection for cocoa cultivation was based on soil types and biological indicators. Their description of soil types was based on soil texture and colour. Trees, shrubs, and herbaceous species are used as indicators of soil fertility status. Farmers identified over 50 forest tree species and their role in the cocoa farming system. Eight of these were selected for screening on-farm and on-station. These included: *Albizia adianthifolia*, *Entandrophragma angolense*, *Entandrophragma utile*, *Newbouldia laevis*, *Pericopsis elata*, *Terminalia ivorensis* and *Tetrapleura tetraptera*. The natural distribution of these species in mature cocoa farms, fallow lands and natural forest was evaluated and their regeneration potential discussed. Results of phenological patterns and crown characteristics of the shade tree species are presented and discussed with regards to their temporal complementarity in light (PAR and Red/Far Red light) capture. Seed pre-treatment and vegetative propagation techniques for *T. tetraptera* were investigated, with results indicating a good potential for the use of locally grown *Citrus jambhiri* Lush. (rough lemon) juice for seed pre-treatment. Auxin (IBA) application on leafy stem cuttings, at concentrations of 0.2%, 0.4%, 0.8% and 1.6% produced good rooting responses, compared to a control (0%), with 0.4% producing the highest response. Growth performance of all the planted species was evaluated over a two-year period, while root structure of, and rates of water uptake by, *E. angolense*, *T. ivorensis* and *T. tetraptera*, which appeared to be the most promising species in terms of initial growth performance on the field, were also investigated. The results showed that *T. ivorensis*, which appeared to be more shallow rooting than the others at this age (3 years), was drawing more water from the soil than the other two species while *T. tetraptera*, with its roots oriented more vertically, was using less water than the others. Above-ground biomass, carbon and nutrient content, as well as litterfall, decomposition and nutrient release patterns of a multi-strata cocoa-*Gliricidia* agroforest are also reported and discussed.

DEDICATION

To my wife Paulina Yelduna Anglaaere, my daughter Noella Besegnia Anglaaere, my son Desmond-Luke Mwinkum Anglaaere, who endured the pains of loneliness and deprivations while I was engrossed in these studies. To my mother Margaret Mary and my brothers and sisters, I am dedicating this piece of work to you. Finally I specially this work to the memory of my father Fabian Anglaaere, who was such an inspiration, and my little son Elwyn Jones Anglaaere who's conception and subsequent birth in January 2005 gave us such joy and fond memories. May your souls rest in peace.

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LIST OF SYMBOLS AND ABBREVIATIONS

AKT	Agroecological Knowledge Toolkit
ANOVA	Analysis of variance
CI	Competitivity Index
C_d	Crown Diameter
C_l	Crown Length
C_r	Crown Ratio
C_{sr}	Crown Shape Ratio
CRIG	Cocoa Research Institute of Ghana
CV	Coefficient of Velocity
DBH	Diameter at breast height
FAO	Food and Agricultural Organisation of the United Nations
FORIG	Forestry Research Institute of Ghana
GCGRA	Ghana Cocoa Growers and Research Association
GI	Germination Index
GLM	General Linear Model
IBA	Indole-3-butyric Acid
KBS	Knowledge Based Systems
Ln	Natural logarithm
PAR	Photosynthetically Active Radiation
PRA	Participatory Rural Appraisal
R/FR	Red/Far Red radiation
SAFS	School of Agricultural and Forest Sciences
SCD	Size class distribution
SE	Standard Error
TDP	Thermal Dissipation Probes

CHAPTER 1

INTRODUCTION

1.1. Background

The economy of Ghana is based mainly on agriculture, mining and forestry, with tourism recently emerging as an important foreign income earner. More than 70% of the country's population is currently engaged in agriculture, producing food crops for subsistence and cash crops for local and export markets, with cocoa as the main export crop.

Cocoa plays a very important role in the economy of the country as it constitutes the largest source of revenue to the government and the main source of wealth to the people of the forest region of Ghana (Anim-Kwapong, 1994). It accounts for about two-thirds of the value of exports from the country and, as an industry, is the largest employer of labour in the country (IFAD, 1986).

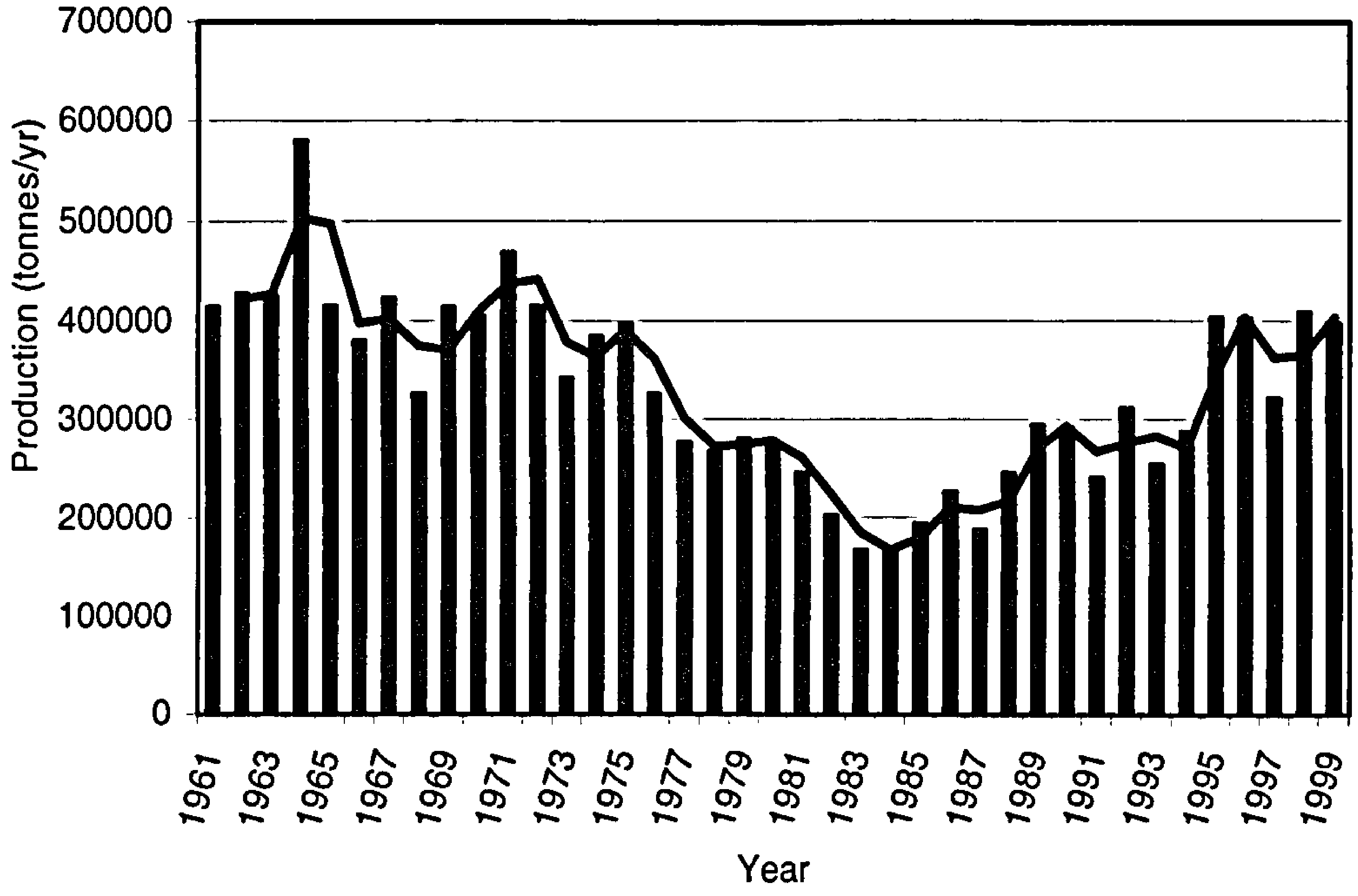
Cocoa cultivation in Ghana is restricted to the forest region where, as a natural understorey crop which grows under the shade of taller trees, its cultivation in the past has been based on thinning out the natural forest and planting the cocoa under the residual shade (Anim-Kwapong, 1994). Over time however, this has given way to a practice where the forest is now clearfelled, burnt and the cocoa planted. Shade is provided in this case by selectively managing coppice shoots of desirable tree species as they come up, and by inter-planting plantain and food crops.

This method of cocoa establishment, which is practiced extensively in the country, has been identified as a major cause of deforestation in Ghana (World Bank, 1987). Despite the fact that some trees are left for shade, as the cocoa growing expands into virgin forest, these areas eventually get depleted of trees (Ministry of Environment and Science, 2002). Current deforestation rate stands at 22,000 ha per year or about 1.7% with the current forest cover estimated at between 15,800 and 17,200 km^2. This represents between 10.9% and 11.8% of the original cover which was 145,000 km^2 (Ministry of Environment and Science, 2002). The bulk of this was attributed to forest clearance for farming. It has been noted that there is presently no unworked land in the country outside the reserves, although there are extensive degraded uncultivated parcels of land (Hepper, 1986; Agyemang and Brookman-Amissah, 1987). It has further been estimated that less than 1% of the current forest cover in Ghana is found outside forest reserves, with much of it in scattered patches in swamps and sacred groves (Hawthorne, 1990). The traditional cocoa-growing areas are in many places denuded and have been abandoned. Re-establishing cocoa in these areas has proven difficult due to low soil fertility, bush fires, diseases and pest, and inappropriate vegetation cover to provide shade for young cocoa (Adams, 1962; Ayanjala, 1983).

From a peak production in the 1960s, cocoa production in Ghana fell to its lowest level in the early 1980s due to prolonged drought and widespread bush fires in 1983 that swept through almost the entire country and destroyed most cocoa farms. Cocoa production levels remained low through the early 1990s to the mid-1990s due to a drastic fall in world prices of cocoa and withdrawal of government subsidies as part of the World Bank and International Monetary Fund (IMF) conditionalities. These factors resulted in many farmers either converting their cocoa farms into food crop farms for quick cash returns or abandoning their cocoa farms to grow into secondary forest. These food crop farms, cultivated on a slash-and-burn basis, have rendered most of the land relatively degraded.

It therefore means that farmers have to re-establish their cocoa farms on such degraded secondary forestland, which has a sparse tree cover and few trees suitable as cocoa shade.

With the introduction of incentives, by way of improved producer prices being paid to farmers and most recently by way of free government sponsored mass spraying of cocoa farms, cocoa production levels have risen quite steadily from the all time low in the 1980s to the present (Fig. 1).



(Source of data: FAO (2003))

Figure 1: Trends in cocoa production in Ghana (1961 - 2002).

This increased production is accompanied by an increased clearance of forest land resulting in further deforestation. To sustain the cocoa industry in the face of dwindling natural forest, and to curtail further deforestation, there is the need to rehabilitate degraded and abandoned old cocoa lands; particularly in the Ashanti, Eastern and Western regions, where soils are considered suitable for cocoa cultivation. There is therefore an urgent need to actively develop models for incorporating trees firmly in the cocoa growing system and contribute to the rehabilitation of some of these areas to contribute to developing sustainable farming systems and reduce the migration of farmers to new forest frontiers.

1.2. Justification

While it has been shown that well established cocoa on good soils in a forest environment can give very high yields (Murray, 1955; Cummingham and Arnold; 1962; Ahenkorah *et al.*, 1974; 1987), it has also been found that shade removal/reduction can lead to a number of deleterious effects prominent among which are increases in mired, psylid and leafhopper damage (Entwistle, 1985). Other effects include increases in mealybug (Homoptera) infestations (Campbell, 1984), and Anthracnosis (*Collectotrichum gloeosporioides*) disease (Porras and Sanchez, 1991). Higher weed growth and higher nutritive demands of the cocoa have also been observed (Ahenkorah *et al.*, 1974). Furthermore it has been reported that young and unshaded cocoa produced a high percentage of small category G beans (Adu-Ampomah *et al.*, 1998).

Despite modernization efforts to maximise cocoa production by using fertilizer and no-shade while substituting agro-chemicals for the beneficial role of the overhead trees, cocoa yields have hardly increased, and average production levels have remained low, in the order of 350kg dry beans per hectare (Wessel and Gerritsma, 1994). Although shade limits cocoa yield, it provides several agro-ecological benefits (Beer *et al.*, 1998). The major physiological benefits that cocoa receives from shade trees can be grouped into two main categories both associated with reduced plant stress namely;

1. Amelioration of climatic and site conditions through:
    - (i) reduction of air and soil temperature extremes;
    - (ii) reduction of wind speed;
    - (iii) buffering of humidity and soil moisture availability;
    - (iv) improvement or maintenance of soil fertility including erosion reduction; and
2. Reduction in the quantity and quality of transmitted light and hence avoidance of overbearing and/or excessive vegetative growth (e.g. flushing in cocoa).

Shade also reduces nutritional imbalances and die-back (Beer *et al.*, 1998).

It has also been pointed out that the relative yield advantage of unshaded cocoa may be limited to: (i) ideal soil conditions; (ii) one or two decades of production, after which environmental degradation, especially soil erosion and pesticide residues, may seriously reduce productivity and/or environmental quality; (iii) frequently replanted plantations since unshaded cocoa trees have a short economic life time (Ahenkorah et al., 1974; Beers et al., 1998). Under sub-optimal conditions serious die-back diseases and, in good environments, excessive vegetative growth at the expense of pod production has been observed under no-shade conditions (Wessel and Gerritsma, 1994). The inputs required for unshaded cocoa are also likely to be too expensive and beyond the reach of smallholder farmers who produce the bulk of Ghana's cocoa, thus leading to poor yields.

The proper selection and proper management of permanent shade species can reduce labour input and weeding cost considerably (de Silva et al., 1990), and these can amount to 70% of all cost during the first two to three years of a cocoa plantation (Corven, 1993 cited by de Silva *et al.*, 1990).

In addition to modifying light availability, tree canopies also negatively affect light quality (Wiley, 1975; Nair, 1979; Bainbridge *et al.*, 1996). They also affect the spectral composition of the light. This is because leaf canopies preferentially absorb, and therefore 'filter out', the visible wavelength used in photosynthesis, and different shade tree species may filter out visible light to different degrees and these differences could occur between different types of forest trees (Coombe, 1975; Willey, 1975). Ong et al., (1996) also point out that shade affects the radiation environment experienced by understorey crops by altering not only the quantity of radiation received but also its spectral composition. Thus shade light tends to have a lower proportion of useful wavelengths, or photosynthetically active radiation (PAR), and a greater proportion of infra-red, the latter being the wavelengths largely responsible for raising temperatures (Willey, 1975; Ong et al., 1996). For the selected forest tree species therefore, it will be important, at least as part of the screening process, to investigate the extent to which each species will affect the quantity and/or quality of light passing through its canopy to reach the understorey cocoa crop.

The main physiological drawback with shade trees however is competition for light, water and nutrients. Whereas there has been an appreciable amount of studies carried out on competition for light (e.g. Asomaning et al., 1971; Hutcheon, 1981; Raja Harun and Hardwick, 1987; Gerritsma and Wessel, 1994), competition within the root zone for water and nutrients between the shade trees and the cocoa crop remains a relatively unexplored area, yet this could be a critical determining factor for the use of shade for cocoa establishment. Novel simultaneous agroforestry systems have generally failed to deliver the sustainably increased crop yields which were expected of them (Sanchez, 1995), while competition for resources rather than complementarity in resource sharing has been frequently reported for simultaneous agroforestry. In semi arid sites in particular, below ground competition can outweigh the perceived advantages of having trees and crops simultaneously occupying the land (Ong et al., 1996). Competition for water can occur, even in tropical forest areas, during short dry periods (Kozlowski, 1982). The influence of shade trees on water availability for the understorey crop in seasonally dry zones is a very important research topic (Beer et al., 1998) as there is currently a dearth of relevant information on this area (Anderson and Sinclair, 1993).

The rehabilitation of the cocoa agroecosystem in the study area can best be achieved through the inducement of natural regeneration and enrichment planting of desirable forest tree species which are relatively fast growing and capable of providing suitable shade for cocoa all year round. Although a number of candidate forest tree species have been identified as suitable shade trees for cocoa (Bonaparte and Danquah, 1985; Manu and Tetteh, 1987), the germplasm base is still relatively narrow and there is a need to broaden the range. This could be done through a survey of farmer knowledge and preference and a search of the literature on the ecology of Ghanaian forest tree species (e.g. Hawthorne, 1995; Swaine *et al.*, 1997).

With the exception of a few species, very little is known about the artificial regeneration potential of most of the potential forest tree species suitable as shade for cocoa as they still remain largely undomesticated. For most of these native forest tree species problems in the production of planting stock may limit their use in any rehabilitation programme. There is currently a dearth of information on the propagation of most of these commonly occurring forest trees encountered in the cocoa agroecosystem.

Agroforestry is a promising landuse practice to maintain or increase agricultural productivity while preserving or improving fertility (Schroeder, 1993). The trees in an agroforestry system provide many benefits to the system including nutrient pumping from deeper soil profiles, fixation of nitrogen, reduction of evaporation from the soil surface, mitigation of soil erosion, improvement of soil organic matter levels, improvement of soil nutrient status and improvement of soil structure (MacDaniels and Leibermann, 1979; Myers, 1980; Campbell et al., 1990; Kamara and Hague, 1992;

Kessler, 1992). Trees can potentially improve soils by recycling nutrients from deeper soil layers through litterfall and decomposition, among other processes. The rate of nutrient return to upper soil layers through litter decomposition is influenced to a large extent by the quality of the litter (Campbell, et al., 1994). Shade trees, by their influence on soil and micro-environmental factors present an avenue for farmers to achieve sustained yield while increasing diversity of products from their farms. Thus a quantification of the rate of nutrient cycling in cocoa-shade tree agroforestry systems will add to the knowledge of how such systems operate and what their potential benefits are, thereby allowing us to be able to manipulate system composition and configuration for enhanced production.

From the perspective of climate change and the global carbon cycle, Schroeder (1993) points out that agroforestry hold an attraction for at least two reasons. The first is that the tree component fixes and stores carbon from the atmosphere. Trees can function as carbon sinks for periods of many years and continue to store carbon until they are cut or die. The second interest in agroforestry is its apparent potential to reduce the need to clear new forest land by providing an alternative to shifting cultivation

In the face of fluctuating cocoa prices and limited resources of cocoa farmers it will be attractive to develop cocoa production systems which use low inputs and economically beneficial shade trees that will provide such benefits as timber, fruits, fuelwood, medicine, etc, in addition to the cocoa (Wessel and Gerritsma, 1994) in order to diversify farmers' benefits and income from the farm. There is considerable interest in the carbon budget (sources and sinks of carbon dioxide) of individual countries and the potential of various measures such as growing trees to offset the carbon dioxide emission of individual corporations/countries. Even though the cocoa – *Gliridia* shade tree system is a relatively short term sink an assessment of the carbon storage potential of such a system will give us an idea of the potential of such shade tree systems to filter the atmosphere of carbon dioxide and add to the much needed information on global carbon balance.

1.2.1. Past Research

There has been some work done in the past on the identification of native forest tree species and their suitability for inclusion in cocoa production systems as shade (Bonaparte and Danquah, 1985; Manu and Tetteh, 1987). Both of these works list a number of indigenous Ghanaian forest tree species found on the cocoa landscape and comment on their suitability, or otherwise, as cocoa shade, especially with respect to pest and disease incidence. However, their work was based largely on researcher surveys on farmers' fields and did not take farmers knowledge and perceptions into account. There has been very little work done in identifying how much knowledge farmers have about shaded cocoa systems and the interactions between, and management of, system components. Thus the study in objective (i), which involves a survey of farmers' ecological knowledge of multistrata cocoa agroforestry systems was aimed at augementing their earlier research. It will also complement and facilitate comparison with, the results of a similar survey of farmers' ecological knowledge of multistrata cocoa agroforestry systems in Cameroun (Bidzanga, 2005), as well as complement the study on the socio-economics of shaded cocoa systems in the Atwima district of Ghana (Obiri, 2003).

Successful incorporation of native forest trees into cocoa farming systems will depend largely on how well such species can regenerate naturally in fallow lands and in the natural forest. Extensive work has been published on the distribution and population structure of virtually all tree species in different forest types in Ghana (Hall and Swaine, 1981; Hawthorne, 1990; 1995; Hawthorne and Abu-Juam, 1995). However, apart from the work of Anim-Kwapong which reports on the population structure and regeneration potential of *Albizia zygia* in different landuse systems – natural forest, fallow land and cocoa farm - very little information exists that compares the distribution and population structure of the different shade tree species in different landuse systems. This kind of information is essential as it provides an insight into the natural regeneration potential of the shade tree species based on which the species can be manipulated to provide the required products and services.

One of the major premises of agroforestry systems is that of complementarity between system components. However, inspite of reports from intercropping in savannah systems which suggest that successful co-exixtence in mixed cropping systems depends on temporal complementarity (Ong and Black, 1994), tree phenology is a neglected aspect of agroforestry research (Broadhead *et al.*, 2003a). There is some literature on the phenological patterns of trees in agroforestry systems (Ong and Black, 1994; Broadhead *et al.*, 2003a & b; Okullo *et al.*, 2004) and of various forest trees (Borchert, 1980; Reich and Borchert, 1984; Reich, 1995). With respect to multistrata cocoa agroforestry systems, Bonaparte and Danquah (1985) report work done on the phenological patterns of various cocoa shade tree species in Ghana. However, none of these studies relates phenology, especially leaf cover, to light interception; and there is virtually no literature on work done in relation the relationship between light interception and crown structural characteristics of the native forest tree species used as cocoa shade in Ghana.

With regards to objective (iv), this work was carried out to address the peculiar seed germination problem encountered in *Tetrapleura tetraptera*; all the other species selected for the field studies did not have any problems with seed germination. Difficulty in the germination of seeds of *T. tetraptera* and seed pre-treatment to overcome this difficulty has been reported by Odoemena (1988) in Nigeria. Although concentrated sulphuric acid treatment was identified as a good method for breaking seed dormancy and enhancing germination, its inaccessibility to farmers as well as the dangers involved in its handling calls for the need to explore and find alternative, easily adaptable seed pretreatment techniques for this species. It was also decided to explore the possibility of raising planting stock through vegetative propagation, and since there is no report in the literature on this aspect for this species a study was conducted to investigate the rootability of juvenile stem cuttings.

There are a number of reports on studies of species survival and growth performance in planted agroforestry systems. For instance, Balandier and Dupraz (1999) reported on the growth performance of widely spaced trees in young agroforestry systems in France, while Deans *et al.* (2003) reported on the comparative growth of nitrogen-fixing tree species in a semi-arid climate in Senegal. With regards to multistrata perennial agroforestry systems, the work of Somarriba *et al.* (2001) report on the survival, growth, timber productivity and site index of *Cordia alliodora* in forestry and cocoa agroforestry systems in Costa Rica while Williams *et al.* (2001) reported on on-farm evaluation of the establishment of clonal rubber in multistrata agroforests in Jambi, Indonesia. In Ghana, Osei-Bonsu *et al.* (2002) have reported on the agronomic and economic perspectives of a planted cocoa-coconut agroforestry system while Anim-Kwapong (2003) has reported on the comparative growth performance of ten *Albizia* species and *Gliricidia sepium* planted on screening trials at the Cocoa Research Institute of Ghana. The growth performance of planted trees of the species used in this study has not been evaluated in agroforestry systems in Ghana and the results from this study will help in deciding on the suitability of the species for use as planted cocoa shade.

On the issue of interaction between crops and companion trees in agroforestry systems, there is a wealth of knowledge on below-ground interactions. A number of reports are available on root structure and below-ground interactions between trees and crops in various environments (e.g. Schroth, 1995; van Noordwijk and Purmonosidhi, 1995; Lehmann *et al.*, 1998; Rao *et al.*, 1998; Ong *et al.*, 1999; Schroth, 1999; Wahid, 2000; Odhiambo *et al.*, 2001; schroth *et al.*, 2001; Smith, 2001; Mulatya *et al.*, 2002; Lehmann 2003). Substantial work has also been reported on the comparative water use by trees in agroforestry systems (e.g. Allen and Grime, 1995; Lott *et al.*, 1996; Howard *et al.*, 1997; Green and Clothier, 1999; Bayala, 2002; Lott *et al.*, 2003; Deans and Munro, 2004). However, most of these studies were conducted in semi-arid environments and/or on exotic tree species. Little information exists on parallel studies on indigenous forest tree species, as these have seldom been used in planted agroforestry systems in Africa. Thus results of the study on objective (vi), as well providing valuable information on below-ground complementarity between cocoa and shade tree species, will add to, and complement, the body of knowledge on tree-crop interactions in agroforestry systems in the tropics.

One of the main tenets of agroforestry is the maintenance of soil fertility by trees. In spatially mixed systems such as coffee and cocoa plantations that include upper storey trees, the trees are said to provide nutrients from litterfall and periodic prunings, in addition to the shade provided to the lower storey tree crops (Heuvelop *et al.*, 1988). Several studies have reported the influence of trees on soil fertility (e.g., Campbell *et al.*, 1990, 1994; Belsky *et al.*, 1989, 1993; Dunham, 1991; Isichei and Muoghalu, 1992; Kessler, 1992; Buresh and Tian, 1998). There are a good number of studies documenting the contribution of agroforestry trees to dry matter production and nutrient cycling in various agroforestry systems (e. g. Lehmann *et al.*, 1995; Palm, 1995; Sharma *et al.*, 1995; Khanna, 1998; Mafongoya, 1998; Gillespie *et al.*, 2000; Salako and Tian, 2001; Nolte *et al.*, 2003). A greater proportion of this published data, however relates to natural systems and to alley cropping systems, with data and literature on planted multistrata perennial agroforestry systems still very limited. Data on dry matter production and nutrient dynamics in planted cocoa agroforestry systems, especially in Africa, is still very limited. Thus this study (objective vii) was intended to generate information on dry matter production, nutrient dynamics and carbon content of a planted multistrata cocoa agroforestry system, to complement the wealth of data for alley cropping and other agroforestry systems, as well providing valuable information for the manipulation of such planted systems to enhance system productivity. The choice of a *Glicidia sepium*-cocoa agroforestry system for this study was mainly due to the fact that *Gliricidia sepium* is currently the most commonly planted shade tree for cocoa in Ghana (Anim-Kwapong, 2003).

1.3. Study Objectives.

The general objective of this study was to select and develop the potential of native forest tree species that have desirable qualities and are of socio-economic benefits to farmers, for use as shade for cocoa agroforestry systems so as to ensure sustainable cocoa production and diversified income for farmers, while helping to conserve forest biodiversity and slow down the rate of deforestation in the country.

The specific objectives included:

(i) Identification of indigenous forest tree species that have potential for use as cocoa shade trees;

(ii) Determination of the natural distribution of selected tree species in different ecological systems;

(iii) Evaluation of the phenology and crown structure of some selected forest tree species;

(iv) Determination of alternative means of raising planting stock of some promising tree species;

(v) Evaluation of the field performance of selected forest tree species;

(vi) Determination of the competitive effect of the selected forest tree species on the cocoa crop on the field;

(vii) Evaluation of the contribution of a cocoa-shade tree agroforestry system to nutrient cycling and the carbon budget.

1.4. Scope of the project

The project consisted of on-farm trials conducted on farmers' fields in one major cocoa producing village in the Atwima District of Ghana. There were also two on-station trials, one at the research station of the Forestry Research Institute of Ghana (FORIG) in South Formangso, in the Asante Akim South District, and the other at the experimental farm belonging to the Ghana Cocoa Growers and Researchers Association (GCGRA) in Bontomuruso, in the Atwima District.

It involved the identification of indigenous forest tree species considered by farmers as suitable shade for cocoa cultivation, and subsequently selecting a number of them for field trials. Species identification was carried out using Participatory Rural Appraisal (PRA) techniques, augmented with a formal approach to the acquisition of local knowledge using the methods outlined by Dixon *et al* (2001).

The on-farm trials involved seven (7) indigenous forest tree species while the on-station trials examined five (5) species.

The criteria for the selection of species for the field trials were mainly based on farmers' preferred attributes of cocoa shade trees. These attributes include:

- Tree crown density
- Tree height
- Effect of the species on soil moisture levels
- Economic value of the tree and/or its products

Final choice was however influenced by the availability of seed for propagation at the time of project initiation.

Based on the above, the forest tree species selected for the field screening trials on-farm included:

- *Albizia adianthifolia* (Schumach.) Wight
- *Entandrophragma angolense* (Welw.) DC.
- *Entandrophragma utile* (Dawe and Sprague) Sprague.
- *Khaya anthotica* (Welw.) C. DC.
- *Pericopsis elata* (Harms) van Meeuwen
- *Newbouldia laevis* (P. Beauv.) Seeman ex Bureau.
- *Tetrapleura tetraptera* (Schum. and Thonn) Taub.

The on-station trial species included:

- *Entandrophragma angolense* (Welw.) DC.
- *Entandrophragma utile* (Dawe and Sprague) Sprague
- *Newbouldia laevis* (P. Beauv.) Seeman ex Bureau
- *Terminalia ivorensis* A. Chev.
- *Tetrapleura tetraptera* (Schum. and Thonn) Taub.

1.5. The study sites

1.5.1. Location

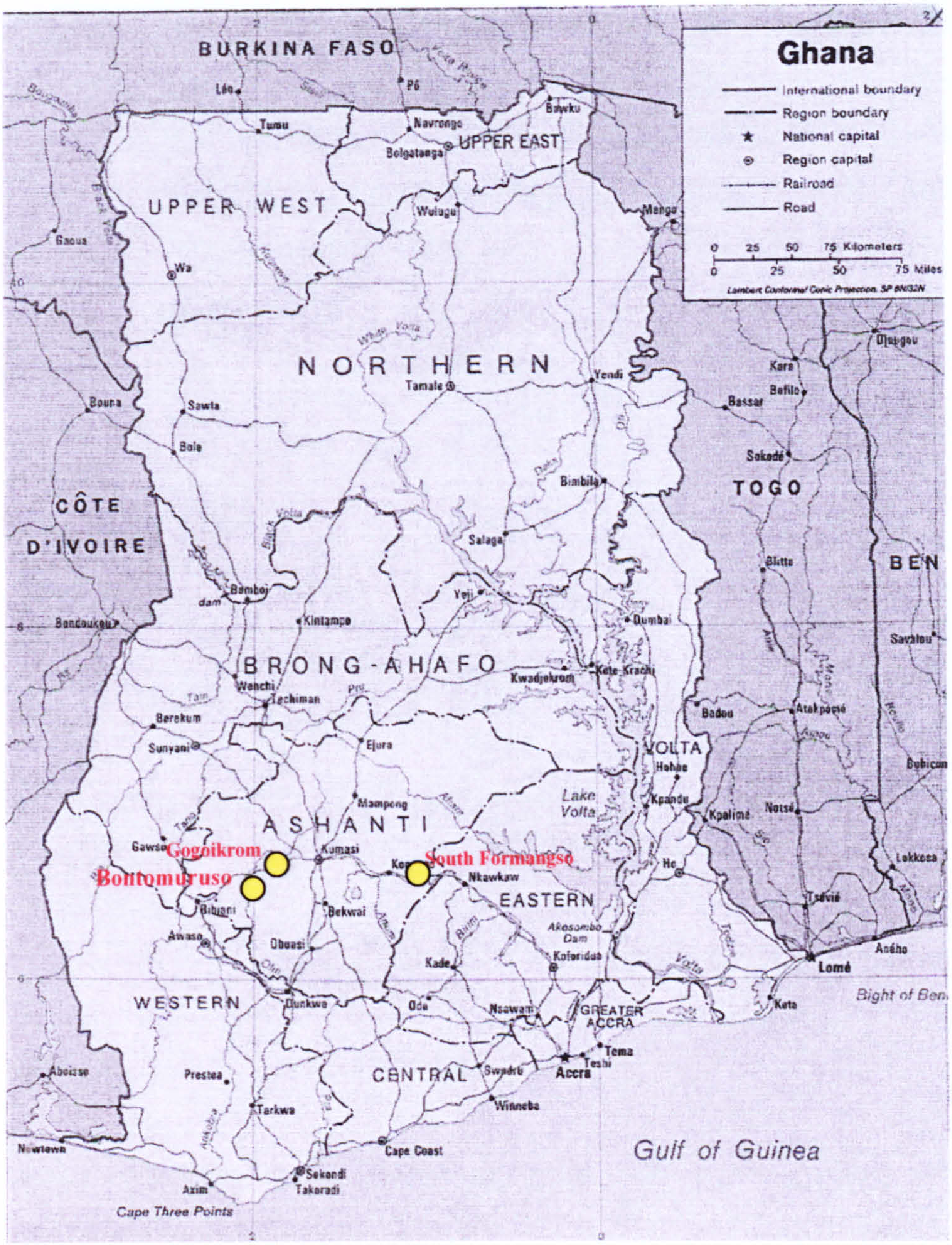
The on-farm trials were conducted in Gogoikrom which is situated about 72 km from Kumasi, the Ashanti Regional capital of Ghana, while one of the on-station trials was located in Bontomuruso which is about 80km from Kumasi. In addition to Gogoikrom, a second village, Kyereyease which is situated about 56 km from Kumasi, was selected for the elicitation and compilation of farmers' ecological knowledge on multistrata cocoa agroforestry systems. All three villages are situated in the Atwima District which is located between latitudes 6^o 22' and 6^o 46'N and longitudes 1^o 52' and 2^o 20'W in the south-western part of the Ashanti Region of Ghana.

The second on-station trial was located in South Formangso in the Asante Akim South District, which is situated between latitudes 6° 23' and 6° 41' N and longitudes 0° 56' and 1° 28' W. It is about 95 km to the south-east of Kumasi (Figure 1.2).

1.5.2. Climate

Both Atwima and Asante Akim South Districts lie within the wet semi-equatorial climatic zone, marked by double maxima rainfall. Mean annual rainfall ranges between 1700 mm and 1850 mm. The main rainfall season occurs from March to July with a minor season starting from September and lasting until November. The main dry season lasts from December to mid-March, during which period the desiccating harmattan winds blow over the area.

Temperatures are uniformly high throughout the year, with mean monthly minimum and maximum temperatures of 27°C and 31°C occurring in August and March respectively. The relative humidity is generally high throughout the year.



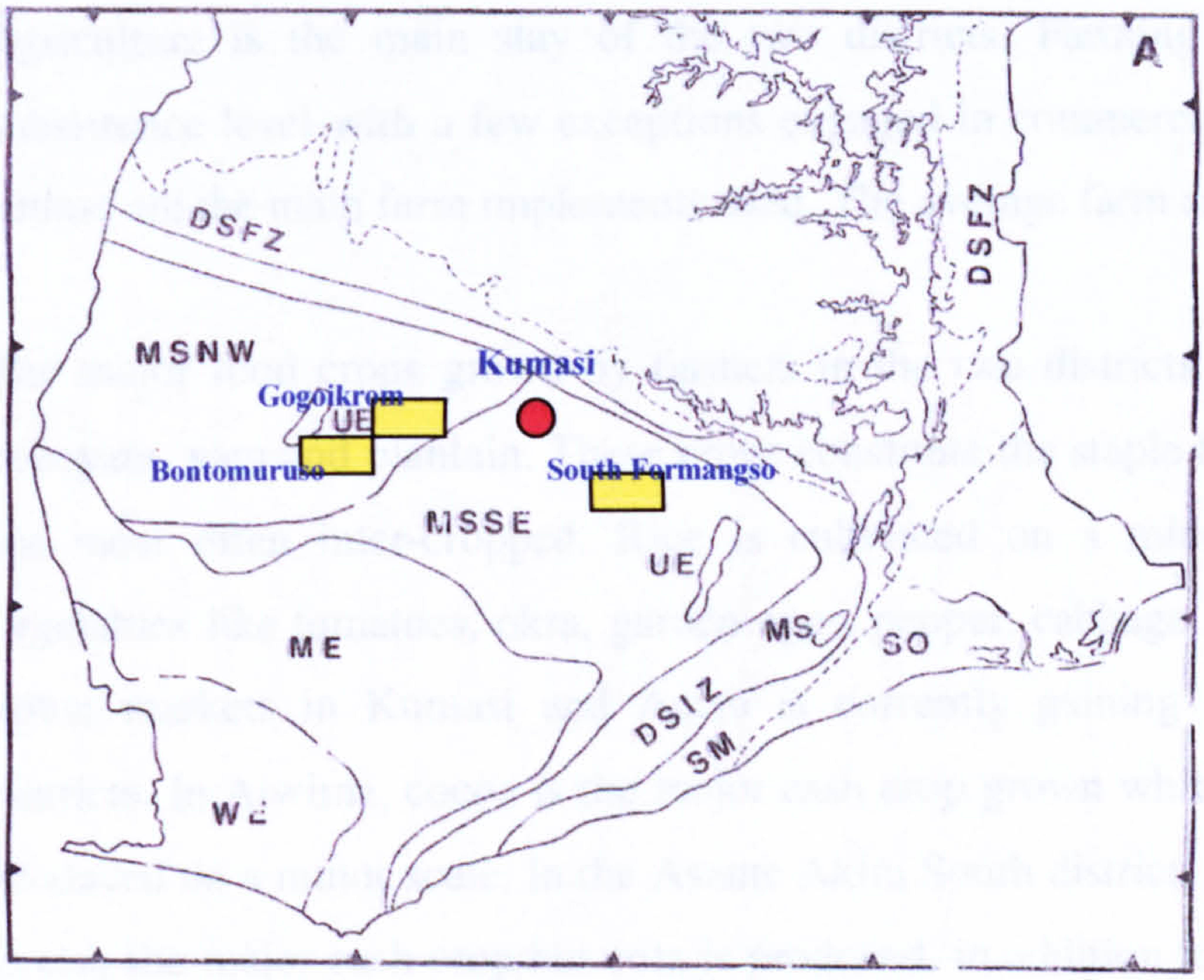
(Source of map: HTTP://WWW.LIB.UTEXAS.EDU/MAPS/AFRICA/GHANA_POL96).

Figure 1.2: Map of Ghana showing location of the trial plots.

1.5.3 Vegetation and soils

The Atwima and Asante Akim South districts are located within the moist semi-deciduous ecological zone, which is characterised predominantly by the *Celtis–Triplochiton* Floristic Association as described by Taylor (1960). This is the most extensive of all the forest types in Ghana, and trees here become taller than in any other

(Hall and Swaine, 1981). The vegetation in this zone is further divided into a slightly drier North-west subtype (MSNW), within which Atwima district is located, and a more moist South-east subtype (MSSE), where Asante Akim South district is situated. Figure 1.3 shows the forest types in Ghana, and the location of the trial sites relative Kumasi, the Ashanti regional capital.



(Adapted from Hall and Swaine, 1981).

Figure 1.3: Forest zones of Ghana – showings locations of study sites.

The moderate rainfall within the moist semi-deciduous forest zone leads to more depletion of soil nutrients than in types of lower rainfall. Base saturation is generally high, however, (60 to 80%) providing a pH of about 5 – 6. Total exchangeable bases (TEB) are generally below 10 m – equiv/100 g soil, but this appears adequate for the considerable tree growth characteristic of the type. The type as a whole has only a moderate elevation of 150 – 600 m, with higher elevations within the area carrying a forest of distinct type – Upland Evergreen (Hall and Swaine, 1981).

The moist semi-deciduous forest zone is the most productive in the forest zone. The soil here is ideal for most of the forest zone crops, including cocoa. Cocoa and other farms are very much in evidence all over the Moist Semi-deciduous forest type, and there is a great demand for more farmland. Although the type is well supplied with forest reserves, most have been heavily exploited for timber (Hall and Swaine, 1981). Pressure on these reserves from both timber contractors and farmers is increasing.

1.5.4 Agriculture

Agriculture is the main stay of the two districts. Farming here is generally at a subsistence level with a few exceptions engaged in commercial farming. The hoe and cutlass are the main farm implements used. The average farm size is 1 ha.

The major food crops grown by farmers in the two districts include cassava, maize, cocoyam, yam and plantain. These crops constitute the staple foods in the districts and are most often inter-cropped. Rice is cultivated on a minor scale. Production of vegetables like tomatoes, okra, garden eggs, pepper, cabbage, etc., particularly for the urban markets in Kumasi and Accra is currently gaining prominence in the two districts. In Atwima, cocoa is the major cash crop grown while oil palm and citrus are produced on a minor scale. In the Asante Akim South district, on the other hand, cocoa is also the major cash crop but cola is produced, in addition to the oil palm and citrus, as the minor cash crops.

1.5.5 Landuse pattern

Much of the available land surrounding the project villages is under cultivation. This forms the farmland, which was initially derived from virgin forest off reserve but currently, derived mainly from secondary forests. Much of the secondary forests have been derived from old and/or abandoned cocoa farms of 20 or more years old. Currently much of these forests are being converted into cocoa farms, most of which are in the establishment phase, and mixed with food crops such as plantain, cocoyam and cassava as nurse crops. These young cocoa farms eventually mature into cocoa plantations with few timber and fruit tree species casting shade for the cocoa.

In Gogoikrom, where the on-farm trials were carried out, cocoa is the major crop of the village. Oil palm appears to be relatively recent and is preferably established in moist or valley areas. Few pockets of citrus stands may be found near cocoa plantations. Very old cocoa farms (over 50 years and no more productive) may be converted into food crop farms or new cocoa farms, or they may be abandoned to eventually grow into secondary forests.

CHAPTER 2

LITERATURE REVIEW

2.1 Cocoa production in Ghana

Cocoa is perhaps the most important export crop for countries in the forest zone of West Africa and is the main source of foreign exchange for some of them, including Ghana (Padi and Owusu, 1998). In Ghana cocoa occupies a key position in terms of foreign exchange revenues and domestic incomes, as well as being the major source of revenue for the provision of socio-economic infrastructure (Cocoa Board, 1995). Production is dominated by smallholder farmers with average farm holdings ranging from 0.4 ha to 4.0 ha (Cocoa Board, 1998).

For sixty six years (i.e. from 1910 – 1977), Ghana retained world leadership in cocoa production with market share ranging from 30-40% of the world's total production (Bateman, 1988). This production peaked at 566,000 tonnes in 1964/65 but dropped to 159,000 tonnes in 1983/84 and has since then fluctuated over the past years between 150,000 and 350,000 tonnes per annum, with Ghana losing her first position to Côte d'Ivoire (Gill and Duffus, 1989; Jaeger, 1999). A survey carried out by a Government of Ghana Task Force in 1995 showed that majority of farmers were producing less than 250 kg dry beans of cocoa annually, with productivity of land estimated at about 390 kg per hectare (Cocoa Board, 1995). This yield rate was found to be less compared to countries like Côte d'Ivoire and Malaysia, with their yields of 600 kg and 800 kg per hectare respectively.

The total area under cultivation to cocoa in Ghana is estimated at 1.2 million hectares (Cocoa Board, 1998). This value represents a decline of 0.6 million hectares compared to the area of productive land in the sixties. In addition to this, production of dry cocoa beans has declined from an average of 400,000 tonnes in the 1960s and 1970s to a stagnated average of 370,000 tonnes from 1995 to 2000, even though there are reports that output is increasing (Cocoa Board, 2000).

2.2 Cocoa cultivation in West Africa

Cocoa (*Theobroma cacao* L.) is an understorey tree that is traditionally cultivated under the canopy of shade trees that may be remnants of the original forest or may have been deliberately planted (Wood and Lass, 1985; Power and Fletcker, 1998; Ruf and Zadi, 1998; Whinney, 1998; Klein, *et al.*, 2002; Anim-Kwarpong, 2003). It has been cultivated by smallholders in the shade of primary or secondary forest trees for generations throughout the tropics (Purseglove, 1968). The dominant cultural practice of cocoa cultivation in the humid west and central Africa involves planting cocoa trees in secondary forest or forest fallow, selectively cleared and planted to various food crops for one or two seasons (Duguma *et al.*, 1990; Duguma and Franzel, 1996). When land is cleared, indigenous fruit, medicinal and timber tree species are deliberately retained both for their economic value and to provide shade for the cocoa plant. Clearing is done manually (with the exception of the use of chain saw to fell big trees) which, together with the no-tillage method used when planting, causes minimum or no disturbance to the fragile soils (Duguma, *et al.*, 2001). The system may be enriched by planting additional tree crops such as mango (*Mangifera indica*), avocado (*Persea Americana*), coconut (*Cocos nucifera)*, orange (*Citrus sinensis*), cola (*Cola nitida*) mandarin (*Citrus reticula*) and oil palm (*Elaeis guineensis*), depending on the density of the retained natural tree species and the mortality of the cocoa seedlings (Oladokun, 1990; Amoah *et al.*, 1995; Duguma *et al.*, 2001). As the cocoa tree and the other components grow to maturity, the agroforest becomes a more diverse and structurally complex, closed-canopy multi-strata system that resembles natural forest (Duguma *et al.*, 2001). Such systems exhibit a high degree of habitat heterogeneity, and they appear to serve as good surrogates of natural forest for many faunal species (Terborgh, 1989; Perfecto *et al.*, 1996). These systems are long-lived, remaining productive for many decades (Power and Flecker, 1998).

According to Wessel (1987) the major management requirements for cocoa agroforests are shade control, weeding, pest and disease control, harvesting of pods and processing of beans. He points out that the role of shade in the management of cocoa agroforests is rather complex as it bears an impact on several other growth factors, such as reduction in light intensity, temperature, air movement and relative humidity, and these all indirectly affect photosynthesis and the incidence of pest and diseases. The level of shade required for cocoa may vary significantly, depending on the age of the cocoa tree, the location of the farm or even the provenance of the cocoa trees (Duguma, *et al.*, 2001). However, it has been suggested, in the past, that optimal growth and productivity is promoted by a level of shading that allows 20 to 30% of full sunlight to reach the cocoa (Okali and Owusu, 1975), though this position has changed over the years.

Among the most important problems facing cocoa farmers in the region are the ravages caused by pests, especially capsids (Heteroptera: Miridae), and diseases, such as swollen shoot caused by the swollen shoot virus and black pod caused by the fungi *Phytophthora palmivora* and *P. megakarya* (Ollennu *et al.*, 1989; Anon, 1995; Freud *et al.*, 1996; Duguma, *et al.*, 2001). Bakala and Kone (1998 cited by Duguma *et al.*, 2001) estimated yield loss due to disease to be 10 to 80% in West Africa, 10 to 30% in Côte d'Ivoire, 30 to 50% in Ghana and Togo and 50 to 80% in Cameroun. Cocoa yield losses due to black pod disease in Ghana previously caused by *P. palmivora* alone, was estimated at 4.9 – 19% (Dakwa, 1984). Recently, however, an outbreak of a more severe disease caused by *P. megakarya* caused losses due to black pod disease in Ghana to rise dramatically to 60 – 100% (Dakwa, 1987). Present recommendations for the control of the black pod disease in Ghana involve spraying to protect apparently healthy pods with copper-based fungicides at four weekly intervals, about 6 – 7 applications per year during the rainy season (Hislop and Park, 1960). This measure, though effective, has major drawbacks. Apart from the concern about the amount of the copper-based fungicides which may end up in the soil, the average Ghanaian cocoa farmer finds the repeated application of fungicides unaffordable and the majority of farmers either do not treat their farms at all, or do only one or two applications per year, thus incurring heavy crop losses every year (Henderson, *et al.*, 1994; Opoku, *et al.*, 1997).

With regards to capsids, also known as mirids, recent studies have indicated that about 25 – 30% of the national cocoa acreage in Ghana has significant mirid damage, with an annual crop loss of about 100,000 tonnes (Owusu-Manu, unpublished information). Climatic factors, mainly light and humidity are believed to influence the abundance of cocoa capsids (Gibbs, *et al.*, 1968). Control of capsids in Ghana, as in other West African countries is mainly by spraying with synthetic insecticides, mainly Gammalin

20 (Lindane) and Unden 20 (Propoxur) (Collingwood, 1971). Other pest and parasite problems of cocoa farmers include termites, which have gained economic importance in some parts of Ghana in recent times, rodents (i.e. rats and squirrels) which cause damage to pods, and parasitic mistletoes and nematodes (Taylor, 1961; Asare-Nyarko and Owusu, 1981; Ackonor, 1995; Appiah and Owusu, 1997).

Depending on the prevailing climatic conditions in a given area, chemical, cultural practice or biological control methods can be used to control cocoa pest and diseases. Enhancing air circulation through regular weeding and pruning, ensuring there is adequate drainage, and removing pod husks immediately after harvesting and extracting the beans are some of the cultural practices that have been recommended by Maddison and Griffin (1981). Duguma *et al* (2001) have also pointed out that developing cost effective and environmentally sustainable integrated pest and disease management is a strategy likely to promote cocoa agroforests. They also emphasise the importance of the need to minimize farmer's risk of crop failure at times of drastic institutional changes and fall in commodity price.

2.2.1 Shade in cocoa plantations

The World Commission on Forests and Sustainable Development (WCFSD) has pointed out that about 14 x 10^6 ha of forests have been lost each year since 1980 as a result of changes in landuse from forest to agriculture (WCFSD, 1999). The rapid rate of deforestation has resulted in a race among conservationist to protect remaining forested land. Often overlooked, however, is that conversion of tropical forest for agricultural use is rarely complete, and often not permanent. Within the agricultural landscape, one can find a significant amount of forested area in the form of managed multi-storey agroforestry systems, or agroecosystems, whose features of structural complexity microclimate buffering, and diversity of canopy food plants retain high biodiversity and contribute to the protection of forest biota (Beer, 1987; Alcorn, 1990; Michon, 1995; Perfecto, *et al.*, 1996). Plantations of cocoa and coffee constitute one of the most important forms of landuse and are of enormous economic importance for developing countries (Graaff, 1986; Wood and Lass, 1985). These crops are usually grown under shade trees in agroforestry systems based on two or more perennial species (Nair, 1993).

Traditionally in West Africa, cocoa shade relates to the density of forest trees left in the field after the initial clearing of the forest. Growing cocoa under shade stems from the belief that cocoa, being a second storey tree, thrives best under heavy forest shade (Padi and Owusu, 1998; Ruff and Zadi, 1998). It has been suggested that the main objective for growing cocoa under heavy shade, in the past, was to lengthen the economic life of the cocoa tree, with other reasons having to do with the technical difficulty of cutting down large trees due to absence of the necessary equipment in those days, or for socio-cultural reasons (N'Goran, 1998; Ruff and Zadi, 1998). However, this earlier notion of cocoa thriving best under heavy forest shade has given way to a prescription of mild shade, for both yield levels and precocity (Paddi and Owusu, 1998). In Ghana the recommendation is to reduce overhead shade down to a maximum of 10 large and 15 medium sized trees per hectare or 4 trees per acre (Osei-Bonsu and Anim-Kwarpong, 1997). In Côte d'Ivoire, however, the recommendation is to plant cocoa without shade (Freud *et al.,* 1996; Ruff and Zadi, 1998). A study by Freud *et al* (1996) into the levels of permanent shade in cocoa farms in Ghana and Côte d'Ivoire showed that about 50% of the total cocoa area in both countries was under mild permanent shade whilst an average of about 10% in Ghana and 35% in Côte d'Ivoire was under no shade; indicating a gradual shift towards eliminating shade trees from the cocoa agroecosystem.

There are different forms of shade management systems employed in cocoa cultivation. Whilst Ruff and Zadi (1998) recognise that mature cocoa farms can be classified into six types of shade management systems, viz;

i. Selected jungle trees saved by selective cutting and partial burning. In this case, the shade trees form a stratum 20 – 40 metres above the cocoa groves,

ii. Spontaneous and selected regrowth of jungle trees previously cut down (and burnt but the fire does not destroy the entire root system). The shade stratum is much lower than in the previous case,

iii. Trees planted by farmers. The most frequent are leguminous trees supposed to have a positive impact in terms of shade and nitrogen supply,

iv. Tree-crops such as various fruit trees planted for direct agricultural and economic purposes but which may also provide some shade and wind breaks to cocoa,

v. Plantains and bananas which are supposed to provide only temporary shade to young seedlings but in a number of situations mats regenerate every year,

vi. 'Zero shade' systems or strict monoculture after complete forest clearing and regular elimination of any shoots during weed control,

Greenberg (1998) and Rice and Greenberg (2000), however, identify three basic shade management systems in cocoa, namely:

i. Rustic cocoa management: This is widespread in humid West Africa and local in Latin America and is characterised by the planting of cocoa under the canopy of thinned or older secondary forest;

ii. Planted shade systems: These vary widely and range from :
   a. Traditional polycultural system – having multiple species of planted shade trees with occasional remnant forest species,
   b. Commercial shade – where other crop trees are interspersed amongst planted shade trees and the cocoa,
   c. Monocultural specialized shade – where the shade is dominated by one or a few tree species or genus (genera). Some indigenous shade systems are truly diverse agroforests. However in most planted systems where a multitude of shade species is found, generally one or a few species comprise the "backbone" shade in which other fruiting and timber species are inserted. In some

areas, cocoa is grown under or intercropped primarily with fruit trees;

iii. Zero-shade cocoa or technified cocoa systems without shade – cultivation, without shade, is common in Malaysia and is becoming more widespread in parts of Colombia and Peru.

N'Goran (1998) identified two main types of cocoa shade management in Côte d'Ivoire. These are: (i) cultivation under shade trees, and (ii) cultivation without shade. The first method is widely employed by small-holder cocoa farmers in West Africa and entails three shade management techniques, described by N'Goran (1998):

i. Cultivation on the cleared forest floor. This involves clearing all the undergrowth on the forest floor, and then eliminating certain species of trees that are harmful to cocoa trees, either through their competition for water, especially in areas of low rainfall, their role as host to insects and diseases that threaten cocoa trees, or because their foliage is too dense or too low. This method is similar to the rustic shade management method described by Greenberg (1998) and Rice and Greenberg (2000) and that described by Ruff and Zadi (1998);

ii. Cultivation in areas of natural regrowth. This entails clear-cutting forest land several months before planting and managing the regenerating trees for shade;

iii. Cultivation under artificial shade. This method consists of planting shade trees according to a specific plan involving the clear-cutting of forest land, thereby eliminating all harmful species, and introducing new local or exotic ones. N'Goran (1998) however, points out that unlike the first two methods above which have been researched in Côte d'Ivoire; no research has been conducted on this method.

N'Goran (1998) however pointed out that over the last few years, the lack of remaining forest land has forced farmers into making use of their last alternative: cultivating cocoa trees in former orchards or on land left fallow and colonised by *Chromolaena odorata*, which blocks or greatly inhibits forest regeneration.

The origin of the use of shade is usually attributed to early cultivators mimicking the natural sub-canopy environment of wild cocoa trees in the forest (Murray, 1958) of the upper Amazon and Orinoco river basin (Simpson and Ogorzaly, 1986).

2.2.2 The importance of shade in cocoa

A number of reasons have been outlined in support of the maintenance of shade trees in perennial cropping systems. In the first instance, traditional, shade-grown cocoa has tended to be well integrated with local agricultural practices and traditions, and compatible with biodiversity conservation (Young, 1994; Perfecto *et al.*, 1996; Beer *et al.*, 1998). Being a natural understorey tree in humid tropical forests, a multi-layered forest system continues to be the optimum environment for the cultivation of cocoa as well as for its sustainability. Cocoa grown in this type of system holds enormous potential for environmental and cultural conservation in regions under intense pressure from logging, development and conventional, monocrop agriculture (Whinney, 1998).

The use of shade in cocoa is an ancient practice dating back to the domestication of the crop. As the use of leguminous shade trees such as *Gliricidia sepium* for cocoa occurs at what are generally considered to be the points of domestication, it was generally assumed that shade trees, and more especially leguminous shade trees, were essential for the cultivation of the crop (Sanchez, *et al.,* 1990). Consequently permanent shade trees in tree crop plantations have been a traditional package (Webster and Wilson, 1969).

2.2.2.1. Shade and cocoa productivity

In Ghana, cocoa is usually cultivated under the shade of thinned forest (Wood and Lass, 1985). This agroecosystem is apparently ideal for the cultivation of the crop since the leaves of cocoa have low light saturation point of 400 μ E m^{-2} s^{-1} and a low maximum photosynthetic rate (7mg dm^{-1} h^{-1}) at light saturation (Hutcheon, 1981). Raja Harun and Hardwick (1988) state that the photosynthetic rate of the crop is known to decrease if the photosynthetic apparatus is exposed to light intensities exceeding 60% full sunlight, while prolonged exposure to high light intensities damage the photosynthetic mechanism of the leaves.

While the use of shade appears to have been a universal practice formerly, in this century the shade requirement of the cocoa tree has been questioned and the practice has been subject to wide experimentation. In the 1950s and 1960s the controversy over cocoa shade and productivity intensified with the emerging worldwide availability of agrochemical technologies, and, most importantly, the development and introduction of new cocoa varieties that require little or no shade. Efforts to incorporate these technologies were largely guided by state sponsored research in Latin America and Africa. A principal line of inquiry was to uncover whether shade was an innate requirement of the cocoa tree itself or whether it serves a secondary role by maintaining appropriate soil, insect population, and other conditions for the cocoa plant; conditions that could be potentially maintained with the application of suitable chemical inputs (Johns, 1999).

It has been noted that on the most appropriate sites, the production of cocoa generally increases if shade is decreased (Murray, 1958; Cunningham and Lamb, 1959; Cunningham and Arnold, 1962; Willey, 1975; Alvim, 1977; Johns, 1999). It has also been found that shade or low light intensity decreases or suppresses flower production in cocoa trees, and that light levels under 1800 hours per year have a considerable depressing effect on production, all other factors set aside (Asomaning *et al.*, 1971; Gerritsma and Wessel, 1994). Such changes, however, bring on other problems (Alvim, 1977). The increased yield under no-shade conditions is usually followed by yield decline due to a number of factors such as: high loss of exchangeable bases in the soil; damage by insect pests; increased soil moisture evaporation and excessive leaf transpiration (Ahenkorah *et al.*, 1974; Bonaparte, 1975).

Trees on croplands bring about microclimate changes under their canopies by reducing soil and air temperature, irradiance and wind speed. These changes will have direct influence on soil water evaporation and humidity, which in turn may significantly affect crop growth, depending on the climate (Rao *et al.*, 1997). The reduced radiation load and wind speed under canopies reduce water demand by crops and soil evaporation, which are particularly important during drought periods (Rao *et al.*, 1997). Wallace (1996) noted that trees contribute to loss of rainfall through evaporation of canopy interception, and modify conditions under canopies by shading and redistribution of intercepted rain through stem flow and canopy drip. Working in a semi-arid site in Kenya, Wallace *et al* (1997) predicted that the reduction in soil evaporation under tree canopies would be sufficient to offset the increased losses due to canopy interception, depending on rainfall intensity and annual total rainfall amount.

Shade reduces photosynthesis, transpiration, metabolism and growth and therefore, the demand on soil nutrients and so enables a crop to be obtained on soils of lower fertility (Purseglove, 1968). Depending on the species involved, shade trees can also fix atmospheric nitrogen and hold it within the soil layer (Beer, 1987). Young cocoa trees benefit from the protection of shade trees and the influence shade has on growth form. The shade trees also serve to reduce the winds at or near the ground level within the cocoa agroforestry system (Rice and Greenberg, 2000). In Ghana, Ahenkorah *et al* (1974) evaluating the outcome of shade and fertilizer experiments, found that shade promotes greater long-term production of older cocoa plants with low levels of fertilization. While shade is invariably recommended for the establishment of cocoa it has also been recommended that the shade should be gradually removed on optimal sites as the cocoa becomes self-shading (Cunningham and Arnold, 1962; Alvim, 1977). Willey (1975) however points out that in cases where intensive management, particularly the regular application of fertilizers, can not be guaranteed, some shade trees should be retained for cocoa. The extra expenditure associated with clear-felling and growing unshaded cocoa with large amounts of fertilizers would probably be justified only when yields of 3,360kg/ha and over are obtained (Cunningham, 1963).

2.2.2.2. The Role of Shade in Biodiversity Conservation

Globally, there is growing evidence of the effects that cocoa cultivation has on biodiversity conservation (Rice and Greenberg, 2000). Firstly, forest clearance for cocoa threatens biodiversity by degrading both the physical structure and species diversity of the canopy, and increasing the fragmentation of the landscape. Once forests are cleared, however, cocoa farms have positive benefits especially when grown under the shade of secondary forest or other species-rich tree canopies because they provide a wider array of ecological niches for wildlife than do many other cultivated landuses (Leakey and Tchoundjeu, 2001). In terms of their architecture and ecology, many traditional shaded coffee and cocoa plantations resemble natural forest more than most other agricultural systems (Beer *et al.*, 1998).

Considerable research has been directed at the potential for shade crops, such as coffee and cocoa in maintaining otherwise lost biodiversity in deforested landscapes (Estrada *et al.*, 1997; Perfecto *et al.*, 1996; Greenberg *et al.*, 1997; Parrish *et al.*, 1998; Power and Flecker, 1998; Greenberg *et al.*, 2000; Reitsma *et al* 2001). Such habitats can enhance the existence and maintenance of biological diversity by providing additional habitat and resources for organisms visiting from intact forest, or they can support forest-dependent organisms throughout the annual cycle. In the latter case, shade crops provide a refuge for biodiversity in areas that have lost most or all of their natural forests. In the former, shade crops could be useful as a buffer zone crop for forest reserves (Greenberg *et al.*, 2000). Greenberg *et al* (2000) also point out that planted coffee and cocoa 'forests' are a mode of reforestation that could provide both revenue for local land owners as well as wildlife habitat. Cocoa is sometimes cultivated under thinned forest canopy (rustic cocoa), but more often it is found beneath a diverse canopy of planted shade trees (planted shade) and these alternative systems probably support very different level of diversity of tropical forest organisms (Greenberg *et al.*, 2000). They can serve as pathways or stopover points for the migration of animal species between natural reserves (Beer *et al.*, 1998; Rice and Greenberg, 2000). When native trees are used as shade trees in a buffer zone, a larger gene pool of these species can be maintained than would be possible in the protected area alone (Beer *et al.*, 1998).

Referring to shade in coffee, it has been proposed that the shaded tree crops can serve as refuges for biodiversity because they can potentially preserve high diversity of organisms such as birds, arthropods, mammals and orchids (Gallina *et al* 1996; Perfecto *et al.*, 1996, 1997; Greenberg *et al.*, 1997). The floristic and structural diversity of shade grown coffee and cocoa farms provides habitat for native fauna (Siebert, 2002). He noted that farmers in Sulawesi, Indonesia, have reported that small mammals, deer, wild pigs, macaques and other forest fauna are regularly observed and occasionally hunted in their shaded coffee and cocoa farms, as opposed to no birds and the rarity of forest animals in full-sun farms, even where these farms are adjacent to shade farms and remnant primary forest patches. According to Greenberg *et al* (1997), canopy height and structural complexity (i.e., number of layers) are often associated with increased bird species diversity to the increased foraging and nesting opportunities such vegetation provides. A diversity of vegetation types and structure also modifies microclimatic conditions, thereby providing a wide range of niches for other plant, animal and insect communities. In addition, flora and fauna may interact to maintain and even enhance biological diversity (Siebert, 2002).

A wider diversity of tropical forest organisms occurs in shaded cocoa plantations than in most other lowland tropical agricultural systems. Rustic plantations incorporating natural forest shade trees are probably the best in this regard. However, to the degree that these rustic systems are not stable, they may not provide in the long term. Cocoa grown under planted shade may provide the best long-term protection for tropical forest biodiversity (Rice and Greenberg, 2000). Monocultural, high yield production systems also require high rates of nutrient addition, typically through the use of chemical fertilizers. These chemicals can have significant effects on the highly diverse community of soil micro organisms and invertebrates that regulate nutrient cycling in ecosystems. Minimizing the use of agrochemicals can result in the conservation of beneficial organisms and conservation of functional processes such as decomposition and nutrient cycling. Thus the conservation of biodiversity within the agroecosystem affects plant and soil processes that can, in turn, affect crop productivity (Mason *et al.*, 1997).

Structurally diverse forest farms that provide sites for birds and bats to feed and perch may enhance seed dispersal and establishment of woody vegetation. They may also provide connectivity between isolated primary forest fragments (Galindo-Gonzales *et al.*, 2000 cited by Siebert, 2002). Canopy height is a function of forest age, but also of the history and intensity of cultivation. Some of the trees planted in agroforestry farms are long-lived species that reach 20–40 m in height. Thus, both canopy height and structural diversity may increase with time, enhancing the biodiversity conservation value of these farms. Furthermore, even when young and relatively low in height and structural complexity, agroforestry farms provide a much more diverse range of biophysical conditions (i.e., niches) than full-sun farms (Siebert, 2002). Rice and

Greenberg (2000) therefore advocated two approaches to enhancing the impacts of cocoa on biodiversity: (i) the continuation in existing cocoa farms of the practice of using a diversity of shade trees rather than the change to monocultures or low-diversity shade systems, and (ii) in deforested areas, the promotion of cocoa establishment under a wide range of shade species.

The loss of biodiversity thus has a range of negative ecological and societal consequences. More immediately, loss of biodiversity can have significant impacts on ecosystem function within agroecosystems and economic returns from the cropping system. Thus the conservation of biodiversity provides a number of benefits to agriculture (Andow, 1991).

2.2.2.3. The Role of Shade in Pest and Disease Control

The equilibrium in natural undisturbed systems does not permit one or more species to cause major damage as a large number of predators will be present. In a disturbed system such a balance may not exist because the reduced plant diversity and the absence of trees do not provide sufficient resources and niches for predators and antagonist. According to the 'natural enemies hypothesis' (Altieri and Smith, 1986; Russell, 1989) agro-ecosystems with high floristic and structural diversity have low abundance of phytophagous species. Alternative food resources in such systems may support higher populations of entomophagous arthropods, and a shade canopy may enhance predator populations that would not survive in unshaded plantations (Greenberg *et al.*, 2000).

Genetically uniform monocultures are often more vulnerable to pest and diseases and therefore require higher inputs of pesticides (Power and Flecker, 1998). Agrochemicals are commonly used to control pests, diseases and weeds in cocoa holdings (Soule *et al.*, 1990 cited by Rice and Greenberg, 2000). In addition to the health and environmental problems this may engender, the chemicals themselves often induce resistance in target species. Capsids developed resistance to aldrin and lindane in the early 1960s in Ghana (Rice and Greenberg, 2000). Also, Gordon (1976) reports that in the early 1920s cocoa farmers on the African islands of Fernando Pó and São Tomé, then among the leading world producers, cut much of their cocoa canopy in an effort to boost production.

Shortly thereafter, however, most of these farms were wiped out by insect attacks. In Bahia, Brazil, serious leaf burns caused by severe attacks of insect pests, particularly thrips (*Selenothrips rubrocinctus*) and monalonia (*Monalonian spp.*), on cocoa under low shade conditions have also been reported by Alvim (1960 cited by Johns, 1999).

On the other hand excessive shade has been found to have negative effects on the disease and pest status of cocoa farms. *Phytophthora palmivora* (black pod disease of cocoa) and other pests and diseases are reported to be favoured by increased humidity due to increased shading (Ahenkorah *et al.*, 1994; Dakwa, 1974; Smith, 1981; Akrofi *et al.*, 2003). In Brazil and Ghana, a reduction in the fungal black pod disease of cocoa was also recorded under low shade conditions (Dakwa, 1974 Smith, 1981). Excessive shade increases the incidence of other economically important fungal diseases, especially in very moist situations such as river sides or valley bottoms (Beer *et al.*, 1998). However, the positive aspects of reduced shade can be offset by several deleterious effects, the most prominent of which are the increases in mirid, psyllids and leafhopper damage, and increases in mealybug (Homoptera) infestations (Campbell, 1984; Entwistle, 1985). These are the reasons why cocoa monocultures are not economically justified despite the initial production advantage (Ahenkorah *et al.*, 1974).

Increasing crop diversity through the use of polycultures can augment the resources available to pollinators and to pest natural enemies such as parasitic wasps, resulting in higher populations of these beneficial organisms (Andow, 1991). The use of shade can lessen a farmer's dependence on chemicals, and is thought to affect the physiology of the cocoa plant and the physical environment as well (Rice and Greenberg, 2000). Several authorities have suggested that the removal of shade and the spraying of insecticides are two major contributing factors in the development of pest species in cocoa (Leston, 1970; Wood and Lass, 1985). Beer *et al* (1998) however suggest that the provision of more or less shade to help control these diseases must seek a balance since they occur together in many plantations, while Rice and Greenberg (2000) also suggest that the manipulation of the cocoa habitat in order to retain the co-evolved ecological relationships characteristic of natural forest should be the first approach to be taken to prevent disease or pest problems.

2.2.2.4. The economic value of shade trees

The significance of diverse shade vegetation in providing secondary products such as fruits, medicine, spices timber/building material, animals (protein), root crops, firewood and other materials, and thereby providing a diversified diet and income for small-holder cocoa and coffee farmers has been noted by a number of people (De Row, 1987; Herzog, 1994; Escalante, 1985 Beer *et al* 1998; Whinney, 1998; Peeters *et al.*, 2003). For instance, Herzog (1994) points out that in Côte d'Ivoire cocoa producers make use of some 27 mostly wild forest species as shade, 13 of which provide fuelwood and medicine, 11 provide food products and 6 are used in construction. The advantage of these economic shade trees is that they have a low maintenance cost and are considered a 'saving account' that can be realized at times of low prices or failure of the underlying crop (Mussak and Laarman, 1989; Somarriba, 1992; Beer *et al.*, 1998). Also, it has been pointed out that income from fruit trees, timber and fuelwood, and other perennial crops used as shade for cocoa can be significant, and may result in better financial performance than would occur in plantations using conventional, leguminous, shade trees (Glover, 1981; Kajomulo-Tibaijuka, 1985; O'ktin'ati and Mongi, 1986).

Referring to *Cordia alliodora* in coffee plantations, Beer *et al* (1998) give a conservative estimate of the merchantable timber increment from 100 trees ha^{-1} to be 4 - 6 m^3 ha^{-1} yr^{-1}, and posit that the earnings from the timber could compensate for lost coffee yields of 17% when coffee prices are high, 33% when prices are intermediate, and up to 100% of any lost production when prices are low, and assumed similar earnings could apply to cocoa. Peeters *et al* (2003) have noted that insecurity in prices does not always allow farmers to obtain profits, hence counting on a permanent timber stock for their own use or local selling can help to cope with lack of housekeeping funds. The practice of perennial tree crop intercropping is an attempt to spread the financial risk in cocoa farming (Benneh, 1987).

Research has shown that low-input cocoa systems that include commercial fruit production fare quite well during periods of low cocoa prices and that the break-even cocoa price for these virtually chemical-free holdings is just over 50% the price needed to break even in cocoa without fruit trees (Duguma *et al.*, 1998). Beer *et al* (1997, cited by Peeters *et al.*, 2003) state that in a coffee plantation producing 1380 pounds of coffee/ha (626 kg/ha) and shaded with *Cordia alliodora*, a timber species, profits from the timber are higher than profits from the coffee if its price sinks below US$60/100 pounds. It has also been pointed out that 1 ha of coffee plantation with a diverse shade vegetation covers all the necessities of timber, firewood and fruits of a seven-person peasant family in Costa Rica, and that simplifying these plantations would be economically disadvantageous for them, even if coffee production increases (Espinoza, 1986 cited by Peeters *et al.*, 2003).

2.2.2.5. Shade trees and nutrient cycling

The greatest long-term incentives for promoting the management of a diverse shade canopy can be found in the ecological and agronomic services provide by the shade trees (Beer, 1987). One of the major biophysical factors that contribute to the sustainability of these systems is the nutrient cycling facilitated through the leaf litter from the overstorey trees (Long and Nair, 1999). Other advantages arise from the higher soil organic matter from litterfall, the provision of soil mulch, and the reduction of soil erosion made possible by the presence of continuous plant cover (Hadfield, 1981; Glover and Beer, 1986; Beer *et al.*, 1998; Long and Nair, 1999).

The leaf litter provides mulch and a supply of organic matter for the soil. This, in turn, can increase aeration, infiltration, and drainage, as well as result in a slow and steady release of nutrients into the mineral soil. The decaying litter provides resources for a greater diversity of soil and litter organisms, which may be critical in nutrient breakdown and cycling (Beer *et al.*, 1998, Rice and Greenberg, 2000). Soil organic matter content may increase with time under agroforestry systems of cocoa. For example, over a 10-year period following conversion of sugar cane fields to cocoa plantations in Costa Rica, Beer *et al* (1990) found that soil organic matter had increased by 21% under pruned leguminous *Erythrina poeppigiana* and by 9% under unpruned non-leguminous *Cordia alliodora*. Nair and Rao (1977) found that the association of cocoa with coconuts increased the number of bacteria and fungi in the coconut rhizosphere, and attributed this positive effect to increased litter inputs.

Palm (1995) points out that nutrient cycling within intercropped systems will be directly affected by the type of shade species, since these species differ significantly in aboveground biomass productivity, rate of biomass decomposition and fine root biomass turnover. Also, according to Beer (1987), depending on the species involved, shade trees can fix atmospheric nitrogen and hold it within the soil layer. However, the level of nitrogen fixation by leguminous shade trees in cocoa plantations is influenced by management practices (Wood and Lass, 1985). Shade trees in many plantations are allowed to grow freely while in more intensively managed areas several pollardings per year may be carried out. Pruning residues may be left around the trees, chopped and spread around the ground, or exported for fodder and firewood. All of these practices will affect levels of N_2 fixation and N availability in plantations (Beer *et al.*, 1998). Citing literature, Beer *et al.*, (1998) however conclude that there is a relatively low contribution of N through N_2 fixation from shade trees in cocoa plantations, while Beer (1988) suggest that the ability of a shade species to produce large quantities of organic material, as litter and pruning residues, can be more important than N_2 fixation because of the positive effects on soil chemical and physical properties.

In many regions, cocoa is traditionally grown under the shade of timber and fruit tree species, which are either retained when clearing the forest or specifically planted. Through their litter, throughfall and stemflow, timber trees contribute to the cycling of organic matter and nutrients (Schroth et al.,., 2001a). For instance, Beer (1988) mention 5.7 tons of leaf litter ha^{-1} yr^{-1} containing 114 kg N, 7 kg P and 54 kg K, from a *Cordia alliodora* shade trees in a Costa Rican coffee plantation, while Murray (1975) talks of 5 tons of leaf litter ha^{-1} yr^{-1} containing 79 kg N and 4.5 kg P in a typical cocoa farm shaded by forest trees in West Africa. Trees with deep roots can take up subsoil nutrients that are beyond the reach of crops and recycle them to the surface through litterfall (Buresh and Tian, 1998). Deep nutrient capture by trees increase the total nutrient availability of the system. However, an important difference between fallow systems and tree-crop associations is that, in the latter, the nutrients in the tree biomass do not necessarily become available to the crops. The nutrients are released from the trees into the soil through prunings, litterfall and dying roots, or is leached from the crown by throughfall and stemflow (Schroth et al.,., 2001b).

Schroth et al., (2001b) point out that landuse systems based on tree crops, such as multistrata agroforestry systems, have clear advantages over annual cropping systems for the maintenance soil fertility in the humid tropics. These include permanent soil protection, a more favourable environment for soil biological processes that affect litter decomposition and soil structural improvement, and more efficient nutrient cycling. The diversification of output through association of different species for domestic use and commercialization, including valuable timber trees, can increase the access to external nutrient sources and thereby help to equilibrate the nutrient balance of the system. The reduction of nutrient leaching and recycling of subsoil nutrients by deep-rooting trees can improve the availability of nutrients in the system and reduce negative environmental impacts. Beer (1987), however, points out the potential for the shade trees to compete with the cocoa for nutrients, and the potential export of nutrients from the system through the removal of wood or fruit products as harvests.

Schroth et al., (2001a) assert that information about the spatial and temporal patterns of water and nutrient availability is required to design effective measures, such as optimal spacing of trees, inclusion of additional crop species, altered management of a cover crop, or reduced quantities and altered distribution of fertilizer.

2.3. Resource capture and use.

The relative importance of the different effects of shade trees, and hence the need for shade, is strongly affected by site conditions (Willey, 1975; Beer, 1987). Trees and crops interact wherever they are grown in close temporal or spatial proximity, and the effect of this on crop growth can be separated into positive interactions such as those which improve soil fertility or microclimatic conditions and negative interactions such as competition for resources (Vandenbelt *et al.*, 1990). A number of positive and negative interactions have been postulated for the tree and crop components of agroforestry systems, and the direction and magnitude of these interactions are determined by the patterns of resource sharing (Gillsepie *et al.*, 2000). By changing resource availability trees can either increase or reduce plant productivity of the understorey (Belsky *et al.*, 1993; Anderson *et al.*, 2001). Scholes and Archer (1997) have noted that trees affect nutrient, light and water availability of the understorey vegetation. It has been pointed out that growing trees with crops is only of benefit when trees use resources that the crop cannot acquire and/or provide substantial value per unit of resources obtained in competition with the crop (Cannelll *et al.,* 1996; Vandermeer *et al.,* 1998).

Howard *et al* (1997) have suggested that the degree of competition, and ultimately crop yield, in multi-species systems is dependent on the partitioning of resources such as light, water, and nutrients. The success of a complex multi-species system depends primarily on minimising the negative interactions between trees and crops both aboveground, mainly for light, and belowground, for water and nutrients (Jose *et al.,* 2000; Friday and Fownes 2002). Friday and Fownes (2002) point out that in agroforestry systems competition for light, water and nutrients between trees and crops is a major constraint. Nair (1993) has also stated that the presence of overstorey trees may result in reduced radiation availability and buffered temperatures in the understorey and altered plant water relations. Aboveground competition for light is likely between taller trees and shorter crops under humid conditions, while belowground competition for water may predominate in semiarid conditions. It has been suggested that competition can be reduced by selecting trees species which have limited lateral root extension and/or are deep rooted than crops, by root pruning the tree roots to reduce their density under the crop and by pruning the tree crowns (van Noordwijk an Purnomosidhi, 1995; Schroth, 1995). Knowledge of the specific mechanisms of competition would allow for the development of optimum management strategies and avoid technologies which have little chance of success in a given locale (Friday and Fownes, 2002).

Menalled *et al* (1998) have suggested that the selection of species to combine in mixed plantings demands more attention to the compatibility of growth characteristics. The concept of competitive exclusion suggests that if two species are identical in their growth characteristics (i.e. there is complete overlap in their ecological niches) one will be more successful in a given habitat and exclude the other thus, it is necessary to combine species that differ in such characteristics as height growth, shade tolerance, crown structure, phenology, or rooting depth. If the species differ sufficiently, they will capture growing space and use resources differently when grown together in mixture. Such species will be able to coexist and are said to have complementary characteristics or 'ecological combining ability' (Harper, 1977 cited by Menalled *et al.,* 1998). The intensity of interspecific competition in such mixtures is likely to be less than that of intraspecific competition, and this has been found in some cases to lead to greater overall productivity in the mixtures than in monocultures of the component species – an outcome referred to as the competitive production effect or competitive reduction (Vandermeer, 1989; Kelty, 1992; Menalled *et al.,* 1998). However, the opportunity for complementarity of resource use between species is restricted by the fact all plants are competing for the same, usually finite, resources, such as light, CO_2, water and nutrients (Ong *et al.,* 1996).

Ong *et al* (1996) point out that the components of agroforestry systems often differ greatly in size, with the result that the growth of the smaller understorey species may be inhibited by shading, and possibly by competition for water and nutrients. Competition for light is the primary limitation when water or nutrient availability rather than light is the major limiting factor. They, however, point out that it is not always straightforward to establish which is the primary limitation when more than one factor is marginal.

Despite the apparent simplicity of the principles involved in resource capture, few attempts have been made to quantify resource capture in intercropping or agroforestry systems, largely because of the technical difficulties and expense involved in intensive studies of light and water use (Ong *et al.,* 1996).

2.3.1. Light capture

2.3.1.1. PAR interception

Light is a primary source of energy for plants (Stuefer and Huber, 1998) and its capture by plants depends on two factors: first the fraction of the incident photosynthetically active radiation (PAR) that is intercepted by each species, and second the efficiency of conversion of the intercepted radiation by photosynthesis (Ong *et al.,* 1996). Shading may influence crop growth by reducing the supply of PAR, and hence assimilate production (Lott *et al.,* 2000). PAR has been defined by several workers as radiation in the visible part of the spectrum from 400 – 700 nm (McCree, 1981; Alados *et al.,* 1996; Ross and Sulev, 2000; Bellow and Nair, 2003; Finch *et al.,* 2004). It is the source of energy for the photosynthetic reduction of carbon dioxide to carbohydrates by plant canopies, and a critical determinant of the amount of PAR available for photosynthesis is the ability of the individual plant or the canopy to intercept the incident radiation. Intercepted PAR (IPAR) is, therefore, an important variable in canopy photosynthesis and net primary production, and can be expressed as the product of incident PAR and the fractional interception efficiency (f_{PAR}) of the canopy (Hanan and Bégué, 1995).

According to Ong *et al* (1996), intercepted radiation (S_i) is normally simply taken as the difference between the quantity of solar radiation incident upon the canopy (S) and that transmitted to the soil (S_t). They, however, point out that this method of determining S_i does not make allowance for the fraction of incident radiation that reflected from the canopy surface. Light interception by crops growing in different climatic regions may be best compared by using the ratio S_i/S to describe the fractional interception (f), rather than the absolute values for intercepted radiation, as these absolute values vary between regions (Ong *et al.,* 1996). For monocrops, they defined a relationship between fractional interception leaf area index (L) for environments where water is not a limiting factor, by the expression:

$$f = 1 - \exp(-kL)$$

where k is an extinction coefficient for the canopy which is dependent on leaf angle and distribution. Fractional interception therefore increases as k and L increase. Based on this model, they point out that light penetration into the canopy is greater when the leaves are erect (low k value) than when they are horizontally oriented (high k value). Values for k differ greatly between species with different canopy structures.

2.3.1.2. Canopy shape and crown architecture

It has been pointed out that canopy shade not only reduces light quantity but also changes light quality and often represents one of the most important 'stresses' that plants experience in competitive environments, and that photosynthetic rates decrease with decreasing light intensity (Méthy and Roy, 1993). They suggest that because green leaves preferentially absorb red and blue light, the spectral composition of light under canopies is different to natural radiation and is particularly rich in far-red wavelengths. The red:far red ratio (R:FR ratio), which is the photon flux density ratio in 10 nm bandwidths, centred, respectively, in the red (655 – 665) and far-red (725 – 735) wave bands, is considerably reduced, depending on the optical properties of the plant canopy (Smith, 1982; 1994). In general the effects of a low R:FR ratio are similar to those of a reduced PAR, and a combination of a low R:FR ratio and low PAR normally has a greater effect than those caused by either factor alone (Smith, 1982; Deregibus *et al.,* 1985; Casal *et al.,* 1986; Méthy and Roy, 1993). In multistrata agroforestry systems, transmitted PAR is often a limiting factor for the establishment, growth and yield of annual and perennial intercrops. Knowledge of the radiative climate under a given stand is thus of major interest for the management of multi-strata agroforestry systems (Mialet-Serra *et al.,* 2001).

Crown structure represents an important factor affecting individual tree and stand-level growth (Cannelll *et al.,* 1987; Dalla-Tea and Jokela, 1991). Many factors, such as inclination and orientation of leaves and geometric properties of twigs and branches, can contribute to variations in crown characteristics (Wang and Jarvis, 1990). Shoot morphology and the distribution of shoot types within the branching framework of a plant contribute to the characteristic form or architecture of that plant (Seleznyova *et al.,* 2002). Crown characteristics, which are affected by many factors such as inclination and orientation of leaves and the geometric properties of twigs and branches, influence the interception of photosynthetically active radiation (Stenberg *et al.,* 1994; McCrady and Jokela, 1998).

Hallé *et al* (1978) proposed that tropical trees could be described in terms of 23 architectural models, based on the behaviour of apical meristems in producing branching systems. Subsequent studies have shown that leaf placement and branching angles are highly efficient for light interception in equitable environments of the humid tropics (Chazdon, 1985; Ackerly and Bazzaz, 1995; Pearcy and Yang, 1996), but that crown shape and branch proportions may vary widely within a particular architectural model (Fisher and Hibbs, 1982; Fisher, 1986).

2.3.1.3. Tree phenology

Woody perennials are commonly classified as 'deciduous' or 'evergreen', according to whether or not the canopy is retained or shed (usually seasonally). Evergreen species are sometimes called 'leaf-retainers' as this highlights a wider range of functional consequences (Huxley, 1996). These categories, however, are not distinct and a species may behave in a more deciduous fashion as the aridity of the site increases (Huxley, 1996 citing Richards, 1952 and Longman and Jenik, 1974). It has been pointed out that an increasing proportion of tropical species become deciduous as the intensity of the dry season increases, while both evergreen and deciduous species often produce leaves episodically (Reich, 1995). Citing Lieth (1974), Broadhead et al., (2003b) define phenology as the study of (i) the rhythm of repetitive biological events, (ii) the biotic and abiotic causes of these events, and (iii) the relationship between the periods during which specific phenological events occur (phenophases) for individual or different species. Huxley (1996) has pointed out that the regulatory mechanisms that evoke these phenological responses are poorly understood, although there is probably a simple underlying control that initiates shoot growth phases, and that once a phenophase has started its continuation will depend on the availability of environmental resources.

The most obvious way in which phenological events will have an impact is in determining the trees' ability to capture resources successfully. The time of development and duration of the canopies of taller deciduous trees will clearly affect the environment, and hence the resource capture of lower storey crops in many ways. They can also diminish water loss from the soil surface, which may represent a large fraction of rainfall (Huxley, 1996). Spatial separation of resource use by trees and crops offers the possibility of reducing competition in agroforestry (Broadhead *et al.*, 2003a). The importance of temporal separation of resource capture has been demonstrated for pigeon pea/sorghum mixtures, for which seasonal light interception was greater than in equivalent sole crops due to intrinsic differences in the duration and timing of canopy development (Willey *et al.*, 1986 cited by Broadhead *et al.*, 2003a). Temporal complementarity between trees and crops minimises competition for water and nutrients and increases the utilization of off-season rainfall (Broadhead et al., 2003b).

Despite evidence from intercropping in savannah systems that successful co-existence in mixtures depends on temporal complementarity (Ong and Black, 1994), tree phenology is a neglected aspect of agroforestry research (Broadhead et al., 2003a). Huxley (1996) also noted the paucity of research concerning the importance of tree phenology in agroforestry systems, despite its potential impact on understorey crops, while Broadhead et al., (2003b) emphasised that elucidation of the leafing patterns of trees relative to the prevailing climatic conditions and growth periods of associated crops is essential for a full understanding of the functional aspects of agroforestry, and that detailed information regarding the nature and origins of seasonal changes in leafing patterns would allow experimental results to be extrapolated to other climatic regions and provide criteria for selection of suitable genotypes.

2.3.2. Water and nutrient uptake

While the presence of trees diversifies farm income and provides alternative sources of revenue when crops fail, the trees also tend to compete with crop plants for resources (Deans and Munro, 2004). Agroforestry systems offer the opportunity for spatial and temporal complementarity of water use, resulting in an improved exploitation of available moisture relative to sole crops. However the opportunity for significant complementarity is likely to be limited unless the component species differ appreciably in their rooting patterns as this would permit exploitation of different soil reserves (Ong *et al.,* 1996). Cannell et al., (1996) also argued that agroforestry may increase productivity provided the trees capture resources which are under-utilised by crops.

The vertical uptake and distribution of water and nutrients from soil is an important study topic because soil resources are not equally distributed throughout the soil profile (Lehmann, 2003). Van Noordwijk *et al* (1996) stated that in mixed cropping systems with trees, the knowledge of the vertical distribution of roots is crucial for the optimum utilization of resources, while it has been emphasised that the ability of trees to access subsoil nutrients and water depends on several factors such as tree species, soil physical and chemical properties, tree management and the cropping system (Lehmann, 2003). According to van Noordwijk *et al* (1996), trees with deep roots can potentially intercept nutrients leaching down soil profiles and 'capture' nutrients accumulated in subsoil below the rooting depth of crops.

In annual cropping systems it has been stated that tree roots can extend beyond the rooting depth of the annual crops (e.g. Stone and Kalisz, 1991; Torquebiau and Kwesiga, 1996; Mekonnen *et al.,* 1997). Concluding from a review of literature, Buresh (1995) highlighted that the potential of trees to retrieve subsoil nutrients is generally greatest when (i) trees have deep rooting systems and high demand for nutrients, (ii) water and/or nutrients stress occurs in the surface soil and (iii) considerable reserves of plant-available nutrients or weatherable minerals occur in the subsoil.

Recent studies have shown that considerable amounts of plant-available nutrients and water can be present below the subsoil (more than 10 – 30 cm) or even below 1 m depth, and that these resources may be used by plants (Stone and Comerford, 1994). Numerous studies have also shown that soil moisture can be equal to or higher in the subsoil than in the topsoil. The ratio of subsoil-to-topsoil moisture varies greatly, but is generally higher with larger evaporation and with access to ground water (Lehmann, 2003). Quoting other workers, Lehmann (2003) highlighted that water use and phenology of several multi-purpose trees in tropical dry forest such as *Albizia guachepele, Gliricidia sepium, Cordia alliodora* and *Gmelina arborea* is dependent of subsoil water availability. He concluded that subsoil water use controlled tree crop performance. Less obvious than water availability are the amounts of subsoil nutrients available to plants and their role in tree crop production. Soil organic matter contents are usually higher in the topsoil and are responsible for the retention and release of nutrients. Also, nutrients added to soil by litterfall and fertilization usually accumulate at the topsoil. High precipitation and temperature lead to rapid mineralization leaching, which transports nutrients down in the profile in many regions. These nutrients constitute an important resource for the cropping system but are usually percolation below the root zone of the tree (Lehmann, 2003). According to van Noordwijk *et al* (1996), trees may intercept percolating nutrients and act as 'safety net' against excessive nutrient losses by leaching.

Root distribution is laterally not homogeneous, as roots seek areas where they can grow easily and frequently follow water and nutrients in the soil (Lehmann, 2003). Deep nutrient capture by trees increases the total nutrient availability in the system. Unlike in fallows, however, the nutrients in the tree biomass in tree-crop associations do not necessarily become available to the crops. Nutrients are released from the trees into the soil through prunings, litter and dying roots, or is leached from the crown by throughfall and stemflow (Schroth et al., 2001b). However, the trees compensate these losses through uptake of nutrients to produce new leaves and roots. Therefore, the integration of deep-rooting trees into a system only increases the nutrient availability in the topsoil if the quantity of nutrients taken up from beneath the crop rooting zone is greater than the quantity stored in the tree biomass and in undecomposed tree litter (Willey 1975). Schroth et al., (2001a) point out that this is only most likely to occur in soils with high subsoil fertility (which are rare in the tropics) or if the crops compete efficiently with the trees for nutrients in the topsoil. According to them, competitive crops may force the trees to take up a large part of their nutrients from the subsoil and may then scavenge these from nutrients from the decomposing tree litter.

The total volume of soil explored by a root system is particularly important when considering uptake of mobile resources such as water and nitrogen (N). Horizontal exploration by crop plants is constrained by competition with their neighbours, and so the volume explored can only be effectively increased by increasing rooting depth (Rowe *et al.,* 2001). The benefits of deep rooting derive from acquiring a strongly limiting resource, which is likely to be water in arid environments but may be N in humid environments subject to rapid N leaching (Rowe *et al.,* 2001). A favourable effect of deep nutrient uptake is most likely to occur in the case of leguminous 'service trees', whose nutrient-rich leaf and branch biomass is regularly returned to the soil, and the net nutrient accumulation in the trees is small. For timber and fruit trees, which are not regularly pruned, low competitiveness is particularly important. If these trees are more competitive in the topsoil than the tree (crops), their integration into a cropping system will reduce rather than increase nutrient availability (Schroth et al.,., 2001a).

The most formidable problem in managing simultaneous agroforestry is how to retain the positive effects of tree canopies and roots on soil physical and chemical properties while reducing the negative effects of below-ground competition for limited resources (Ong and Leakey, 1999; Schroth, 1995). A number of workers have stressed that a better knowledge of belowground interactions between trees and crops is needed before the real benefits of agroforestry associations can be fully exploited (Gregory, 1996; Rao *et al* 1998; Sanchez, 1995). Odhiambo *et al* (2001) have also pointed out that the complementarity, either spatial or temporal, in the location of tree and crop root systems is a key issue in agroforestry. It has been suggested that exploiting the different rooting depths of trees and crops could increase resource capture in agroforestry systems without introducing intense below-ground competition (Huxley, 1983). For instance, *Grevillea robusta*, which is a valuable multi purpose agroforestry tree popular with farmers in east Africa, is believed to be deep rooting and to posses few superficial lateral roots (Mwihomeke, 1993). Recent sap flow studies in the roots of this species have shown that its root system is capable of extracting 80% of it water from below the crop rooting zone which suggests good potential for below-ground complementarity (Lott *et al.*, 1996; Howard *et al.*, 1997). Huxley *et al* (1994) discovered that the clumped distributions of trees roots within the soil, as seen in the proteoid roots of *Grevillea robusta*, might also reduce interspecific competition. A number of studies have, however, shown that most tree roots, especially those of fast growing species, exploit the same soil depths as crop roots (Jonsson *et al.*, 1988; Daniel *et al.*, 1991; van Noordwijk *et al.*, 1996). Studies in east Africa and elsewhere also led Ong *et al* (1999) to conclude that in drylands, competition between trees and crops was most serious below ground and was largely for water. In perennial tree crop systems, current studies of root competition between coffee and *Eucalyptus deglupta*, a fast growing timber species, and *Erythrina poeppigiana*, a traditional service tree, are challenging the claim that tree roots generally develop below crop roots and, hence, recycle nutrients to the crop through above-ground litter fall (Somarriba *et al.*, 2001). Quoting other sources, they stated that *E. deglupta* fine roots in coffee plantations are mostly found at 0 – 10 cm depth, while *Coffea Arabica* roots dominate lower depths. Lack of information on below-ground dynamics occurs mainly because it is either too costly or too destructive for the conventional methods (soil cores, ingrowth cores, and trench profiles) of fine root assessment to provide information on root production, mortality and longevity aspects at the necessary high frequency (Heereman and Juma, 1993; Gregory, 1996).

Despite the importance of roots, little is understood about their morphology and architecture. Studies of roots have lagged behind those of the shoot because of the tedious and time-consuming labour involved in quantifying and observing roots in their natural arrangement (Masi and Maranville, 1998). Additionally, traditional methods used to describe root systems, based on root biomass or length distribution in space, have not proven beneficial in quantifying morphology with respect to root branching/architecture and its relation to root function (Fitter and Stickland, 1991). Furthermore, the lack of suitable techniques with which to describe root morphology objectively is another difficulty hampering research efforts in this area (Masi and Maranville, 1998).

2.4. Indigenous knowledge as a tool for technology development

Traditional resource use strategies are often described as not only sustainable, but as an appropriate foundation upon which to develop a modern conservation strategy (Rajasekaran and Warren, 1994). However, this new approach to conservation is based largely on the untested assertion that indigenous people, because of their long association with the land, have developed lifestyles or adaptations that allow them to live in "balance" with their environment (Thomas, 2003). According to this line of reasoning, indigenous people actively manage their lands to maintain environmental equilibrium (Harris, 1974).

In the past, agricultural and natural resource management development projects were often based on top-down transfer of expert knowledge from research institutions to the 'intended beneficiaries', with new farming packages being introduced with a limited notion of farmers' practices, knowledge, needs and constraints, while farmers' reluctance to adapt new technologies was blamed on their ignorance, which could be overcome with a higher input of extension activities. In developing countries where farms are small and many different crops and animals species are reared typically in less than 2ha, improvements in farming outputs have traditionally not benefited from a top-down, researcher-led approach (Goma, *et al.*, 2001). Chambers (1983) also blamed the poor adoption of land evaluation output directives by local communities on the top-down approach often employed by central government agencies. This has made it abundantly apparent that a bottom-up participatory evaluation of farmer practices and constraints and shared monitoring of new approaches to farming based upon the indigenous knowledge of farmers will achieve greater uptake of the identified technologies (Gandah, *et al.*, 2000). Nowadays, it has become clear that local knowledge is a valuable resource for sustainable development and it should play a central role in any development programme.

Over the past two decades there has been a shift in the manner in which agricultural development is researched and implemented towards participatory approaches (Okali *et al.*, 1994). This process of involving farmers in research has been described by Douthwaite *et al* (2002, citing van Veldhuizen *et al.*, 1997) as one by which outside facilitators and rural people interact to enable the target groups to have a greater capacity to adapt a new technology to their conditions and the facilitators to have a better understanding of the traits and characteristics of the local farming systems. Involving farmers in the process is important because as the potential users of new technologies, their knowledge and preferences are critical (Haugerud and Collinson, 1990). Cornwall and Jewkes (1995) stress that local people involvement as participants in research and planning has been shown both to enhance effectiveness and save time and money in the long term. Since the 1980s, non-traditional approaches to planning research, based on the participation of the stakeholders at every stage of the planning process have evolved, and are now being proposed as a viable alternative for resource management (Lanyon, 1994; Ashby *et al.*, 1996). This approach, termed "participatory assistance" (Lanyon, 1994) has been found to promote innovations in farming and research.

In conventional research and extension, inappropriate recommendations have often followed from a failure to take account of local priorities, processes and perspectives (Tumwine, 1989; Agyepong, 1992). In contrast, in participatory research the emphasis is on a 'bottom-up' approach with a focus on locally defined priorities and local perspectives (Rahman, and Fals-Borda, 1991; Chambers, 1992). The importance of taking account of farmers' perspectives in the development process is now increasingly recognised by researchers and development professionals around the world (Chambers *et al.*, 1989; Warren and Cashman, 1988). In the process of technology development, knowledge of the indigenous livelihood system is an indispensable resource which is possessed and can be managed by the community. According to Farrington and Martin (1987), indigenous knowledge is not abstract like scientific knowledge, but is concrete and relies strongly on intuition, historical experiences and directly perceived evidence. The participatory process of technology development based on indigenous knowledge provides the initial self belief and confidence needed to counter the fatalism of poverty and leads to some form of self development (Mcall, 1987).

2.4.1. The importance of indigenous knowledge

Indigenous knowledge has been defined as consisting of facts, experiences, practices, resource management strategies, and production systems developed through trial and error during several millennia in a given community, nation, or region. It is a component of traditions and cultures of people that should be the starting point of science and technology directed at developing more sustainable crop and soil management systems to address changing circumstances of population pressure and problems faced by farmers (Burgesh and Cooper, 1999). Oudwater and Martin (2003) also define indigenous knowledge as the complex of practices and decisions made by local people. It is based on experience passed from one generation to the next, but nevertheless, it changes, adapts and assimilates new ideas. While Joshi, *et al.* (2001) define it as the sum of experience and knowledge of a given ethnic group, that forms the basis for decision-making in the face of familiar and unfamiliar problems and challenges. It can be quite specific to location and may vary between individuals from different social groups according to the differentiating factors such as age, gender, wealth, ethnicity and occupation (Oudwater and Martin, 2003). Ecological knowledge on the other hand is defined as knowledge about organisms, interactions amongst organisms and between them and their environment (Joshi *et al* 2001).

The value of indigenous or local knowledge in agriculture, agroforestry and rural development has become increasingly recognised over the past decade (Walker, *et al.*, 1995). Rural indigenous people are often very knowledgeable about plant and animal species, including their identification and ecology (Redford and Padoch, 1992). The most common approach to collection of indigenous knowledge about biodiversity is through an ethnobotanical survey, which focuses on the traditional uses of given species (Hellier *et al* 1999). A number of participatory tools are now available which may be used to incorporate indigenous knowledge in the resource management process, including semi-structured interviews with key informants, transect walks, preference ranking and participatory mapping (Carter, 1996; David-Case, 1990; Dixon *et al* 2001; Freudenberger, 1994; Martin, 1995). However not much has been done in the assessment of the cocoa agro-ecosystem. Although agroforestry practice is not new to farmers, agroforestry is new as a science. Hence scientific understanding of complex agro-ecosystems such as traditional agroforestry practices is still weak. However it is now known that farmers and local communities who have been managing different traditional agro-ecosystems have gathered a lot of knowledge from their experience and from deliberate experimentation (Joshi *et al* 2001).

Owing to: (i) the need to target research to farmers' needs more effectively to produce technology more appropriate to farmers; (ii) the growing importance of farmer participation in defining research agendas and technology generation and (iii) the realisation that local knowledge is a useful resource which can be complementary to scientific knowledge, recognition of the existence and value of local knowledge, often collected over generations, as well as the need for its effective integration into development, have grown immensely in the last two decades (Walker et al., 1995). There has been a growing consensus among professionals that different farmers have very different types and depths of knowledge. Although some local knowledge may be without clear logic or explanation, there is a large amount of knowledge among farmers about the ecology of the systems they are using, and it is possible to articulate and use this knowledge explicitly in development initiatives (Joshi *et al* 2001).

Three broad approaches for integrating local knowledge and perspectives into development programmes have been identified by Walker et al., (1995), among which is the investigation of local knowledge about ecological functions and processes taking place in the field, and using that knowledge in objective assessment and evaluation and in promoting effective integration with scientific knowledge. This approach requires a much more rigorous analysis of indigenous explanations of ecosystem functioning, which also requires that farmers articulate their knowledge in detail. A comprehensive and explicit representation of local knowledge is therefore required (Joshi *et al.*, 2001).

2.4.2. Indigenous knowledge of cocoa shade trees

There is ample literature on studies of indigenous knowledge in relation to vegetation (Berlin *et al* 1974; Warren, 1991; Mathais-Mundy *et al* 1992). Investigating indigenous knowledge about the management and use of farmland tree fodder in the eastern hills of Nepal, Thapa (1994) found that farmers possessed a detailed ecological knowledge of tree-crop interactions, tree fodder quality and management techniques which they used in making decisions concerning fodder management and feeding strategies.

Few studies, however, are found that specifically consider indigenous systems for the management of natural resources in Ghana, and virtually no study has been carried out to specifically investigate indigenous knowledge in relation to cocoa-shade trees in Ghana.

2.5. Description of the shade tree species

2.5.1. *Albizia adianthifolia* (Schumach.) Wight (Leguminosae – Mimosoideae – Ingeae).

2.5.1.1. Morphology and phenology.

Albizia adianthifolia is a medium to large sized deciduous tree characteristic of secondary forest, forest edges, roadsides, etc (Hawthorne, 1995). It is usually short-boled and unbuttressed. Branching is low, and the crown is an inverted cone, flat on top, wide and thin, with a general architectural model conforming to that described by Troll (Taylor, 1960; Hall and Swaine, 1981). It has dark-grey bark which is almost smooth till the tree is old, when it may be slightly rough (Taylor, 1960).

The leaves are alternate, bipinnate, with about 6 pairs of opposite pinnae, but sometimes more, and stipulate. The leaves are about 15 cm long and 10 cm broad, with about 6 – 15 pairs of opposite, close leaflets occurring on each pinna. The leaflet is like a parallelogram in shape, entire, sessile, with a diagonal midrib, and slightly pubescent below. The terminal leaflets are unequally oblong-elliptic, often with small raised glands between the last two pairs of leaflets on the upper side of the secondary rhachis (Taylor, 1960).

The capitate inflorescences are conspicuous because of their long red stamens, about 3 times the length of the small, pubescent perianth (Taylor, 1960).

The pod is straw-coloured, papery, pendulous, about 19 cm long and 2.5 cm wide, and contains from 4 – 12 black seeds on long funicles. Fine veining is visible on the outside of the pods (Taylor, 1960).

Individual trees may be deciduous for short periods, from mid December to early March. Often the flush of new leaves appears before all the old ones have dropped. Flowering occurs from mid February to April and covers the crown of the tree with conspicuous red flowers, with pods maturing between November and March. Pods usually open on the tree and the light half pod with its seed is carried quite a long way with the wind, ensuring efficient dispersal (Taylor, 1960).

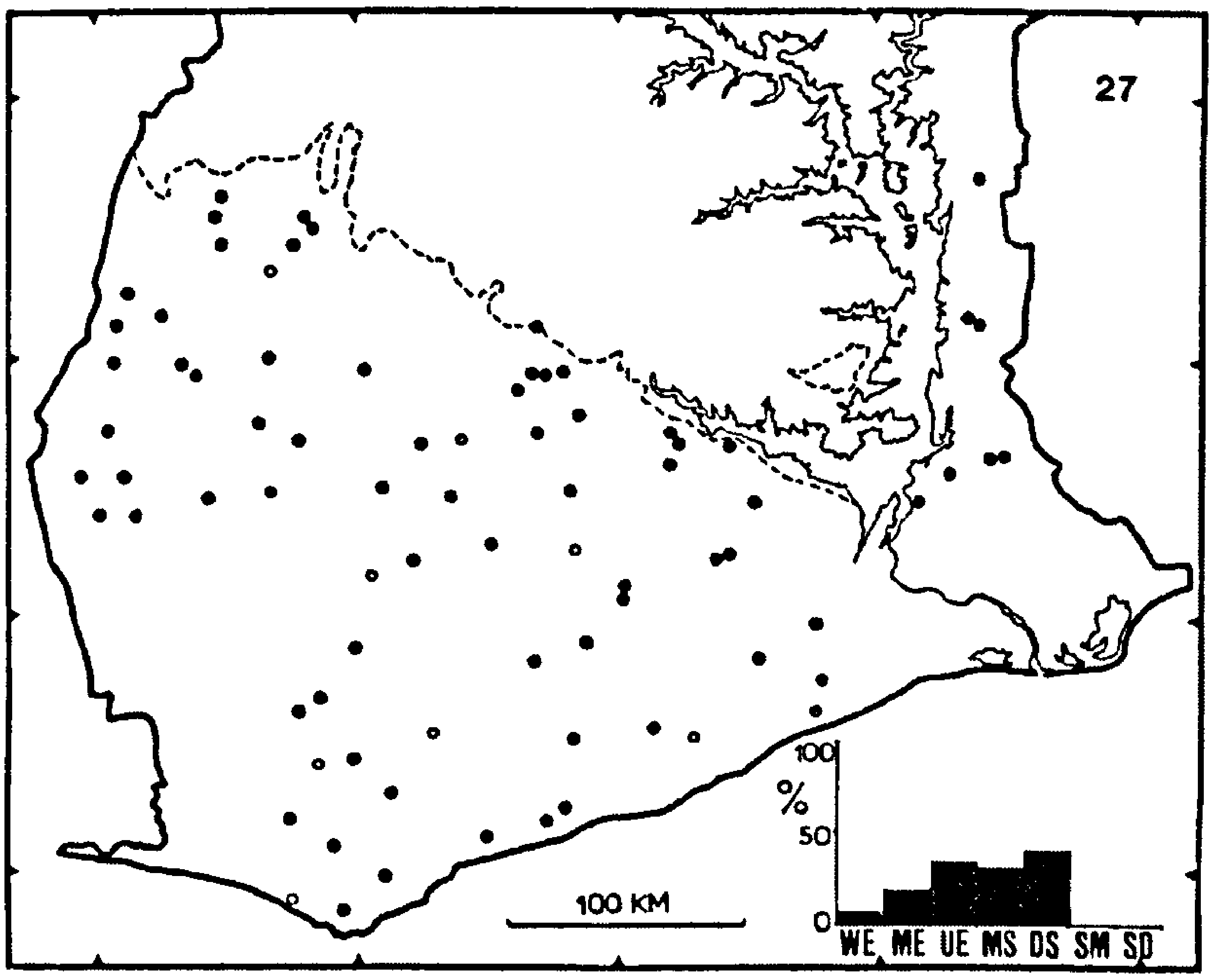
2.5.1.2. Distribution

Albizia adianthifolia is very common in Ghana and widespread in Africa. It is common in secondary forest, abandoned farms, forest edges, etc., and occasionally grows on to become a larger tree in late secondary forest. It is somewhat commoner in dry, infertile sites, which is usual because most dry forest trees favour fertile soils (Hawthorne, 1995). It is indigenous to tropical Africa, with distribution ranging from Senegal to South Africa (Hall and Swaine, 1981). Figure 2.1 shows a detailed map of the population distribution of this species in Ghana, produce by Hall and Swaine (1981).

The species is a chorological transgressor, widespread throughout the forest zone, particularly in secondary forest where it occurs alongside *Albizia glaberrima* and *Albizia zygia*. It is fairly common in good high forest of the *Celtis – Triplochiton* and *Antiaris – Chlorophora* Associations (Taylor, 1960; Hall and Swaine, 1981).

2.5.1.3. Natural regeneration

From March onwards, plentiful regeneration can be seen in any gaps in the High Forest Zone. It is not usually found in the denser parts of the forest. At first, full light is not required, but this condition is necessary for its proper development. Growth is rapid and a height of 1 – 2 m in a year is usual (Taylor, 1960).



(Source: Hall and Swaine, 1981).

Figure 2.1: Population distribution of *Albizia adianthifolia* in Ghana.

2.5.2. *Entandrophragma angolense* (Welw.) DC.

It is a member of the genus *Entandrophragma* (Meliaceace), and is commonly referred to as African mahogany.

2.5.2.1. Morphology and phenology

Entandrophragma angolense is a large deciduous tree with high buttresses (Hall and Swaine, 1981; Hawthorne, 1995) and spreading surface roots (Hall and Swaine, 1981). It is one of the emergent trees in the high forest, with a girth of about 4.6 m above buttresses. The stem is usually not as straight as the other *Entandrophragma* species. The buttresses are thick but not usually above 1.8 m high. Large surface roots run out from the buttresses and may be some 38 cm above ground (Taylor, 1960). The crown is usually not as large as the huge bole might suggest (Hawthorne, 1995), and the general architectural model conforms to that described by Rauh (Hall and Swaine, 1981). It is dark and branches are heavy. The bark has a smooth, grey and brown blotchy appearance cause by the large, irregular, smooth, thin scales, which peel off in large pieces on the older trees. The slash is thick, red, not scented, and bitter to the taste (Taylor, 1960).

The leaves are alternate, exstipulate, paripinnate and up to about 30.5 cm long. There are about 14 pairs of opposite or sub-opposite leaflets. The leaflet is simple, oblong-elliptic, and about 8 cm long and 4 cm broad, entire, apiculate, rounded at the base, dark green and shiny, and with a petiolule about 1 cm long. There are about 7 – 10 pairs of nerves, which are yellow, raised below and looped. The midrib is also raised below. The rhachis and leaflets are glabrous except for some pubescence on the underside of the midrib (Taylor, 1960)

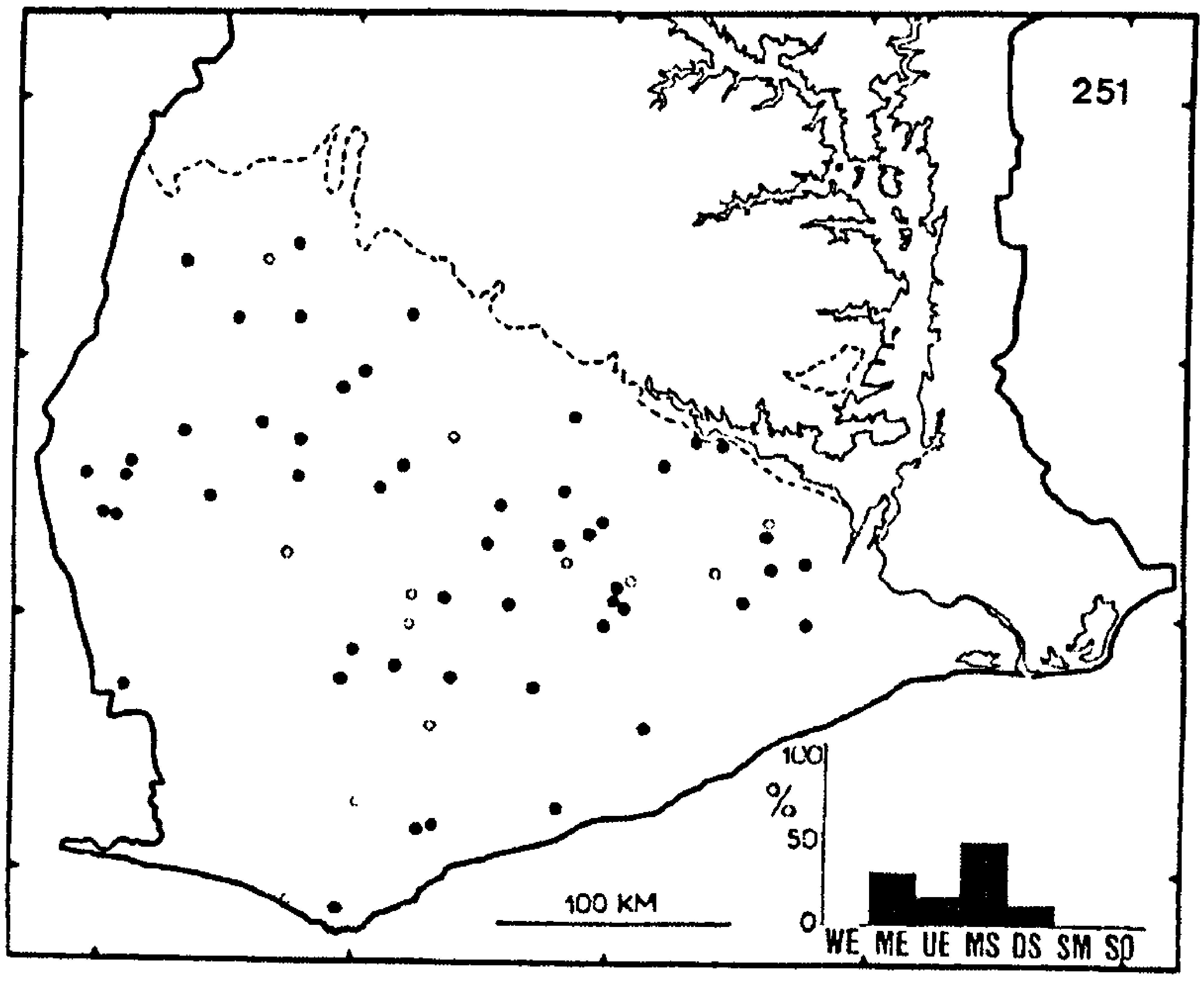
The flowers are in large, lax panicles and are small, scented and greenish-white. There are 5 sepals, 5 petals, 10 stamen inserted on top of a staminal tube and a 5-locular superior ovary with up to 8 ovules in each loculus (Taylor, 1960).

The fruit is a pendulous, elongated, woody capsule about 18 cm long, opening from the base by 5 valves. It is almost black on the outside and smooth, without prominent lenticels, and inside it is brown and flecked with darker brown. There is a central, sessile columella, attenuated at the base, bearing about 6 winged seeds along each of its 5 faces. The seed is almost rectangular, with a prominent hilum and an elongated wing, about 8 cm long and pointed at the farther end. The valves fall off as a unit joined at the apex, and the naked columella is left hanging on the tree for some time (Taylor, 1960).

The deciduous period is from about mid September to November, although individual trees begin to drop their leaves in August (Taylor, 1960). Flushing of new leaves start in December, along with flowering which last until February, although some flowering can be seen after this Taylor 1960; Hawthorne, 1995). The capsules begin to ripen in July and the fruiting season is over in November. In some years, however, fruiting is more or less over in September. Taylor (1960) points out that in such a year almost all the trees flush in October. While the tree is leafless the pendulous, opened fruits are conspicuous. Seed dispersal is by wind (Taylor, 1960; Hall and Swaine, 1981; Hawthorne, 1995), but the seeds do not travel far from the mother trees (Taylor, 1960).

2.5.2.2. Distribution

It is common in Ghana, particularly in better-drained sites, throughout the Moist Semi-deciduous forest zone, but is also found elsewhere (Hawthorne, 1995). Distribution is wide, from Guinea to Angola (Hall and Swaine, 1981). Figure 2.2 shows a detailed map of the natural distribution of the species in Ghana. According to Taylor (1960), this species is rare in secondary forest. In its first year or two the seedling requires shaded conditions, but the shade must not be too dense. Thereafter, overhead light is required for proper development. It prefers reasonably well-drained soils and avoids moist situations where drainage is poor (Taylor, 1960).



(Source: Hall and Swaine, 1981).

Figure 2.2: Population distribution map of *Entandrophragma angolense* in Ghana.

2.5.2.3. Natural regeneration

This is fairly common in good forest where there is sufficiency of mother trees. The seedling is strong and a vigorous grower. This is particularly noticeable in the saplings, which are robust-looking, straight, unbranched and with an annual height increment of often about 0.6 m. it was successfully regenerated under the Tropical Shelterwood System in Ghana. The gradual opening of the canopy is particularly favourable for its regeneration (Taylor, 1960).

Hawthorne (1995) classified this species under the red star conservation status. This implies that although it is presently common in the country's forest, it is under pressure from exploitation. He stresses the need for careful control and some tree by tree and area protection, to ensure successful conservation.

2.5.3. *Entandrophragma utile* (Dawe and Sprague) Sprague.

It belongs to the genus *Entandrophragma* (Meliaceae) and is also commonly referred to as the African mahogany.

2.5.3.1. Morphology and phenology

It is a large tree with straight, cylindrical bole, often bifurcating into two huge branches at the top (Taylor, 1960). It has large buttresses and deeply fissured bark (Hall and Swaine, 1981; Hawthorne, 1995).

The crown consists of large branches and is spreading but not dense, as the leaves are grouped at the ends of the branches and the leaflets droop (Taylor, 1960). The crown architectural model conforms to that described by Rauh (Hall and Swaine, 1981). The bole is characteristic because of its light silver-grey bark and long, regular vertical scales, 2.5 cm or more in width. The slash is brown in the outer layer and then bright pink-red below. It is slightly scented (Taylor, 1960).

It bears highly clustered leaves, borne at the tips of stout twigs (Hawthorne, 1995). The leaves are alternate, paripinnate, exstipulate and about 4o cm long, with about 8 – 12 pairs of sub-opposite leaflets. The leaflet is simple, about 9 cm long and 4 cm wide, oblong-ovate, gradually acuminate, more or less rounded at the base and with unequal sides. The petiole is very short, with the midrib and nerves raised below and pubescent.

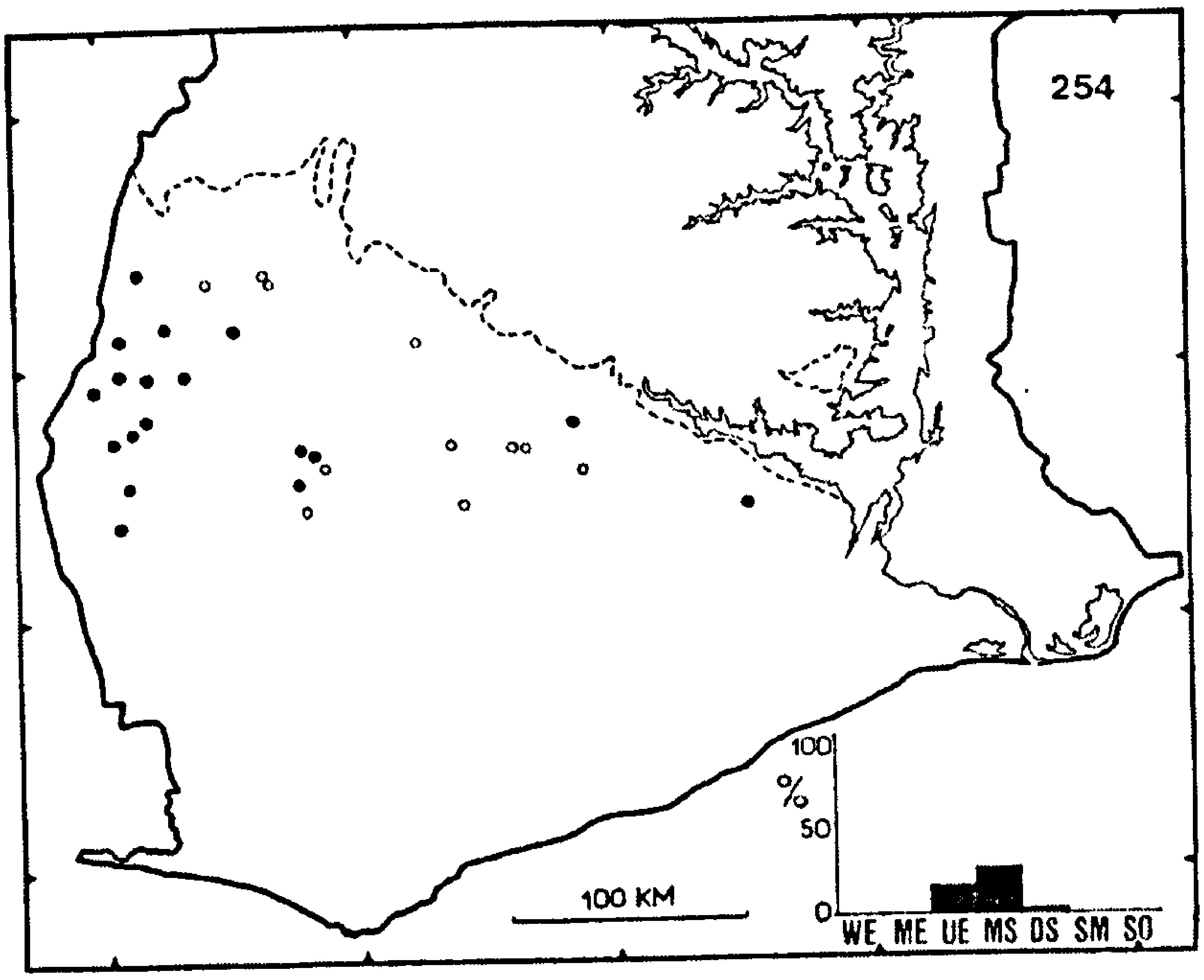
The lamina is dull green on the upper side. Terminal buds are covered with brown tomentose hair (Taylor, 1960).

It bears small white, scented flowers. The fruit is an elongated woody, pendulous capsule, about 20 cm long – the biggest among the *Entandrophragma spp.* It is broadest at the apex and on the outside is dark brown with small warts. The 5 thick valves open at the apex and remain attached to the columella at the base. On the inside they are shiny brown. The columella is sessile and bears about 6 winged seeds on each of its 5 faces. The wing is about 12 cm long and 2.5 cm wide, brown and papery. the seed is not rectangular and is borne towards the straighter side of the wing, near the oblique base (Taylor, 1960).

Individuals are deciduous at various times from November to February. Flowering takes place from about December to March (Taylor, 1960). It bears white, medium sized, monoecious flowers with the young leaves, some time during the dry season (Taylor, 1960; Hall and Swaine, 1981; Hawthorne, 1995). The fruits are woody capsules and take a year to develop, ripening with the flowers (Hall and Swaine, 1981). The species releases wind-dispersed seed, winged seeds in the dry season, a year after flowering (Hawthorne, 1995). Seeds germinate in shade, but development to saplings requires thinning of the canopy (Hall and Swaine, 1981).

2.5.3.2. Distribution

It is common in Ghana and, like the *E. angolense*, is a valuable (class 1) timber tree (Hawthorne, 1995). According to Hawthorne (1995), this species is less widespread than the others, being commonest in the Moist Semi-deciduous, North-West subtype, vegetation zone. It seems to be more drought-tolerant than others in the genus (Hawthorne, 1995). It has a Guineo-Congolian wide distribution, stretching from Sierra Leone to Angola and Uganda (Hall and Swaine, 1981). Figure 2.3 shows the natural distribution of the species in Ghana.



(Source: Hall and Swaine, 1981).

Figure 2.3: Distribution map of *Entandrophragma utile* in Ghana.

2.5.4. *Khaya anthotheca* (Welw.) C. DC., genus *Khaya* (Meliaceae).

2.5.4.1. Morphology and phenology

This species is a large, emergent tree with buttresses (Hall and Swaine, 1981; Hawthorne, 1995). The crown is rounded and the branches are stout (Taylor, 1960), with the general architectural model fitting that described by Rauh (Hall and Swaine, 1981). Quoting Voorhoeve (1965), Hawthorne (1995) points out that the stem of this species is slender with a small crown, until the upper canopy is reached whereupon it diverts much of its energy to lateral growth. The bark is light coloured, almost silvery grey. The slash is red and scented but not as strongly as in *K. ivorensis*. A clear gum exudes from wounds (Taylor, 1960). It is a class 1 timber species (Hall and Swaine, 1981) and the wood is used in making furniture (Taylor, 1960).

The leaves are alternate, paripinnate, exstipulate, and there are 2 – 4 pairs of opposite, glabrous leaflets. The leaflet is thin, elliptic, about 10 cm long and 6 cm wide, entire, broadly apiculate, almost rounded and unequal at the base, and with a slender petiolule about 1 cm long. The fine midrib and very fine nerves are raised below and the venation is reticulate (Taylor, 1960).

It produces small, white, monoecious flowers, but flowering is not clearly seasonal (Hall and Swaine, 1981). The flowers are paniculate and are usually tetramerous – 4 sepals, 4 petals, 8 anthers on a staminal tube and a superior ovary of 4 loculi with many ovules (Taylor, 1960). Its woody capsulated fruits contain very large, winged seeds which are wind dispersed (Hall and Swaine, 1981).

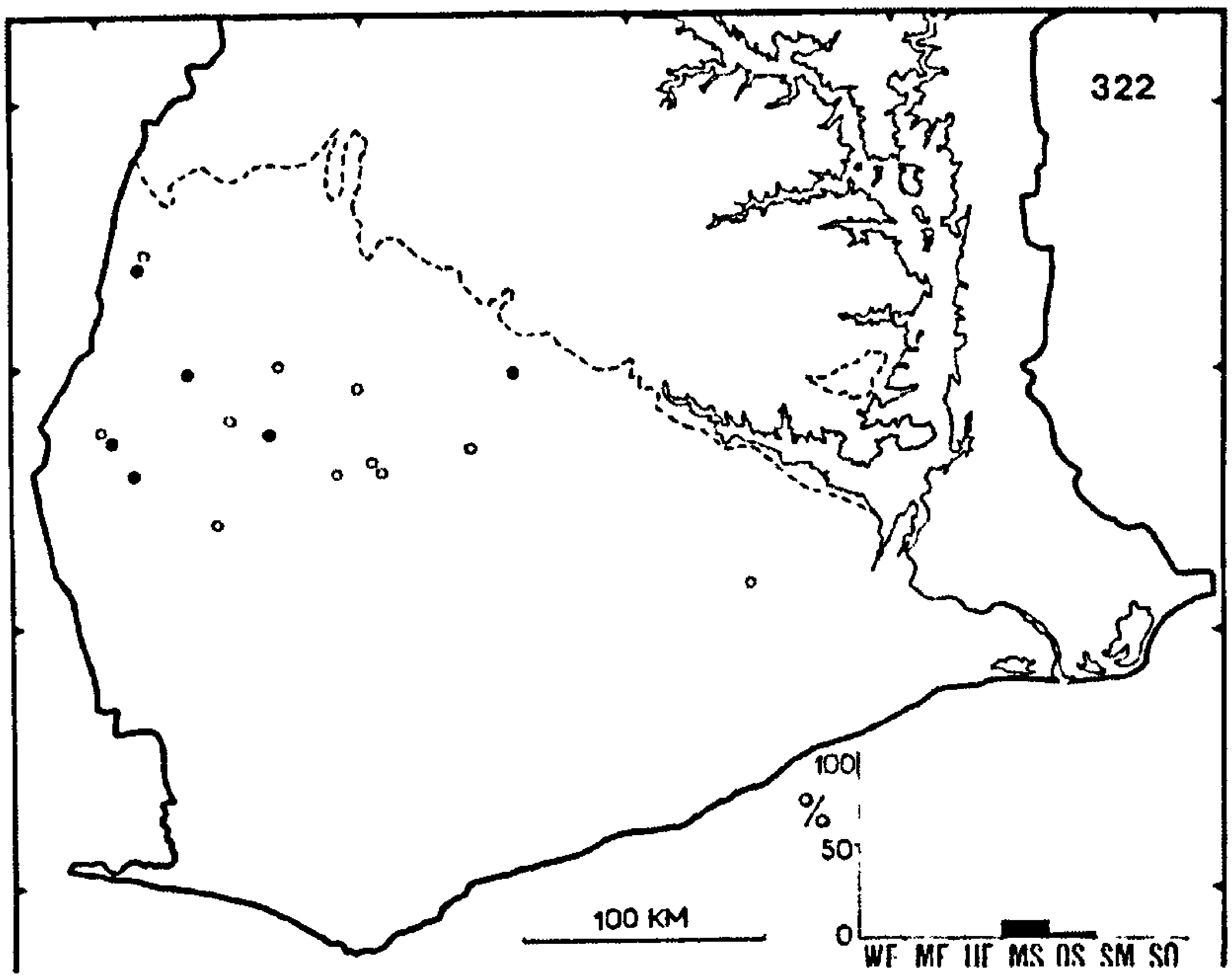
According to Hawthorne (1995), it is evergreen but Hall and Swaine (1981) observe that it is sometimes briefly deciduous. The main period of flowering is from June to July and the ripe fruits are available from December to March. However, there are individuals which flower and fruit out of season (Taylor, 1960)

2.5.4.2. Distribution

It is a common species in Ghana, and has a widespread distribution in Africa, occurring from Sierra Leone to Angola and Uganda (Hall and Swaine, 1981). Taylor (1960) puts the approximate extent of this species in Ghana in an area bounded by latitude 6^0 10' N and 7^0 15' N. and from 1^0 20' W to the western frontier. Quoting Aubréville, he states that *K. anthotheca* requires more light than *K. ivorensis* and also its growth is more rapid at the start. Figure 2.4 shows the natural population distribution map for *K. anthotheca* in Ghana.

The species can regenerate in shade (Hall and Swaine, 1981).

Khaya anthotheca is an important class 1 timber tree, with the trade name of anthotheca (Hall and Swaine, 1981).



(Source: Hall and Swaine, 1981).

Figure 2.4: Population distribution of *Khaya anthotheca* in Ghana.

2.5.5. *Newbouldia laevis* (P. Beauv.) Seeman ex Bureau.

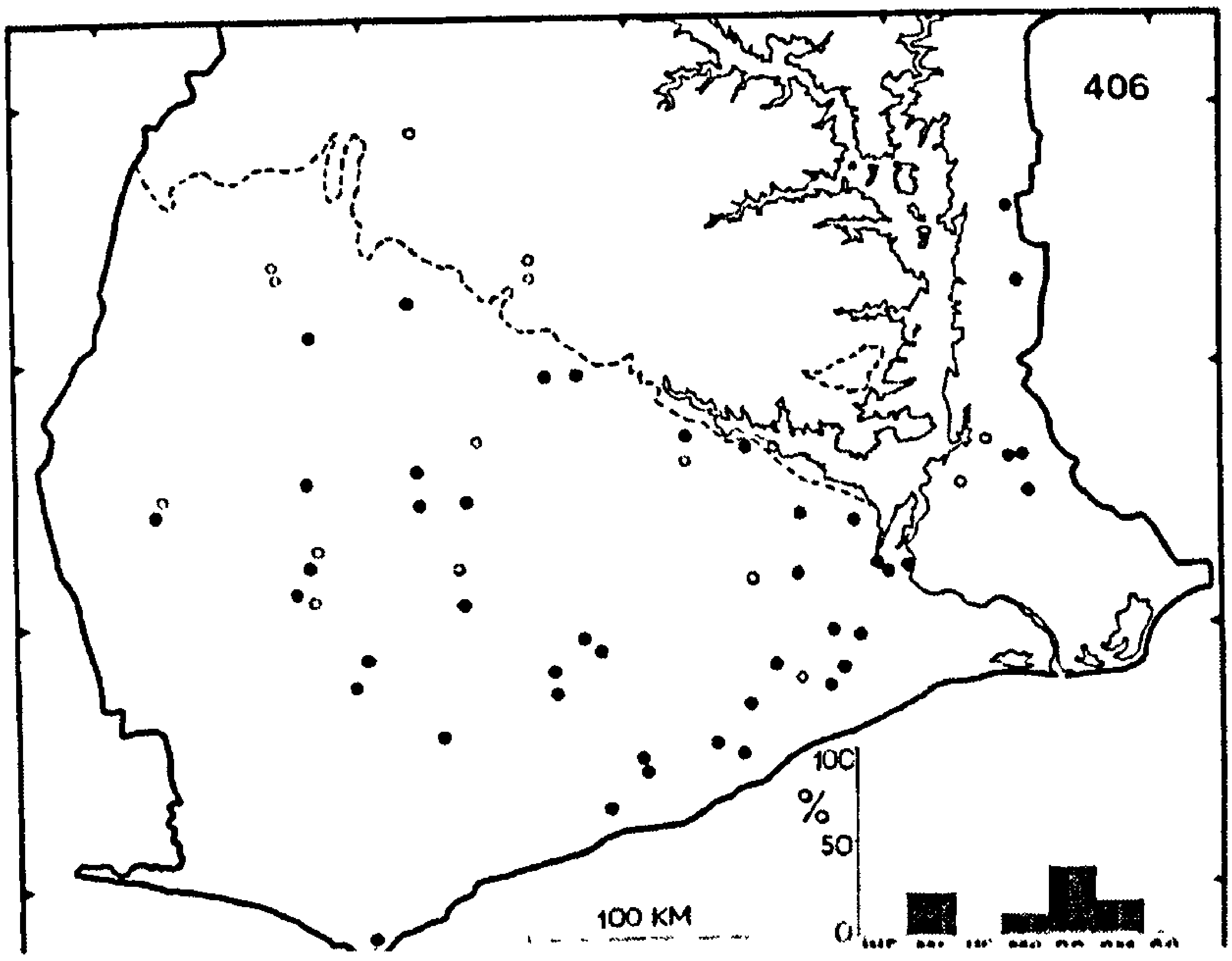
It belongs to the family Bignoniaceae. In Ghana its common name is Sesemasa (Hall and Swaine, 1981; Hawthorne, 1995).

2.5.5.1. Morphology and phenology

It is a medium-sized tree with pinnate leaves. Its crown architecture conforms to the model described by Scarrone. Leaflets are mesophyllous and toothed. The flowers are large, purple and bell-shaped, and produce fruits which are in the form of long capsules. The seeds are large, winged and wind-dispersed (Hall and Swaine, 1981).

2.5.5.2. Distribution

N. laevis belongs to the high forest zone, although it is occasionally found in derived savannah woodland (Taylor, 1960). In Ghana this species is usually left standing on farms, during land cultivation, when other trees are cut down, and is commonly planted in villages. It has a Guinea wide distribution, which stretches from Senegal to Cameroun (Hall and Swaine, 1981). Figure 2.5 shows the natural population distribution of the species in Ghana.



(Source: Hall and Swaine, 1981).

Figure 2.5: Distribution of *Newbouldia laevis* in Ghana.

2.5.6. *Pericopsis elata* (Harms) van Meeuwen.

Synonym: *Afromosia elata* (Harms).

Common name: Kokrodua, Afromosia. It is a member of the family Papilionaceae (Hall and Swaine, 1981; Hawthorne, 1995).

2.5.6.1. Morphology and phenology

P. elata is a large tree, with spreading branches, graceful foliage and a rather flat topped, triangular crown. The bole is characterised by small, red patches. It has high or no buttresses merging into slight flutes (Hawthorne, 1995). The bole is straight and often not exceeding 365 cm girth. The bark is light coloured, but peels off in thin, irregular scales to leave dull rusty blotches which give the bole a diagnostic appearance. The slash is very thick; the outer layer is green and the remainder a pale yellow-brown which soon discolours to dull red (Taylor, 1960).

The leaves are alternate, imparipinnate, about 15 cm long and stipulate. There are about 9 leaflets with fine stipellae. The leaflet is oblong-lanceolate, about 6 cm long and 3 cm wide, entire, light bluish-green below, with a short acumen and usually a rounded base (Taylor, 1960).

The flowers are about 1 – 2 cm wide and in panicles and consist of 5 sepals, pubescent on the exterior, 5 white petals, 10 stamens and a unilocular superior ovary (Taylor, 1960).

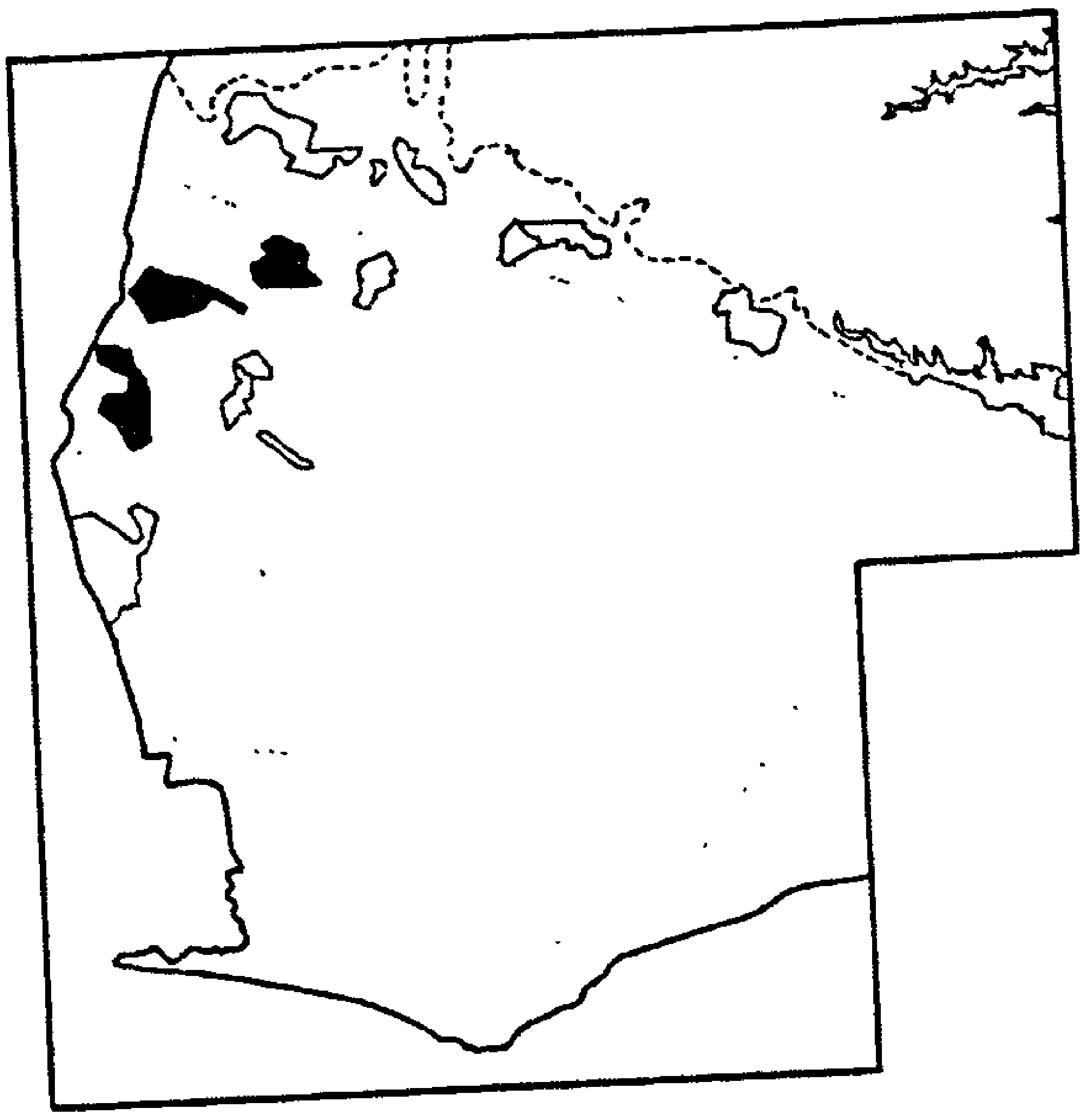
The pod is about 11 cm long and 2.5 cm wide, flat, thin almost papery, light brown, with a marked ridge close to each margin and irregularly reticulate. There 1 – 3 seeds in each fruit. The seed is reddish-brown, almost rectangular, about 1 cm across, with an irregularly notched margin (Taylor, 1960).

The species flowers between April – May but flowering does not appear to be plentiful. The light, pendulous pods are to be seen in May, but are not ripe till August to November (Taylor, 1960).

2.5.6.2. Distribution

It is a timber tree which was once common in the Dry Semi-deciduous and Moist Semi-deciduous, north-west sub-type forest of Ghana (particularly in the Brong Ahafo region), but is now threatened with extinction as a consequence of excessive logging. It also occurs naturally in the Ivory Coast, Cameroun, Nigeria and Zaire (now Democratic Republic of Congo). The species is gregarious in the Moist Semi-deciduous north-west sub-type forest zone, but is widely dispersed in the rest of tropical Africa (Hawthorne, 1995). Figure 2.6 shows the natural of the species in Ghana.

It regenerates mainly in gaps and along roadsides, but also regenerates under light shade (Hall and Swaine, 1981). Seed germination is apparently normal, or rather rapid. Saplings generally have a rather spreading, bushy habit (Hawthorne, 1995).



(Source: Hall and Swaine, 1981).

Figure 2.6: Distribution of *Pericopsis elata* in Ghana.

2.5.7. *Terminalia ivorensis* A. Chev.

This species belongs to the genus *Terminalia* and family Combretaceae.

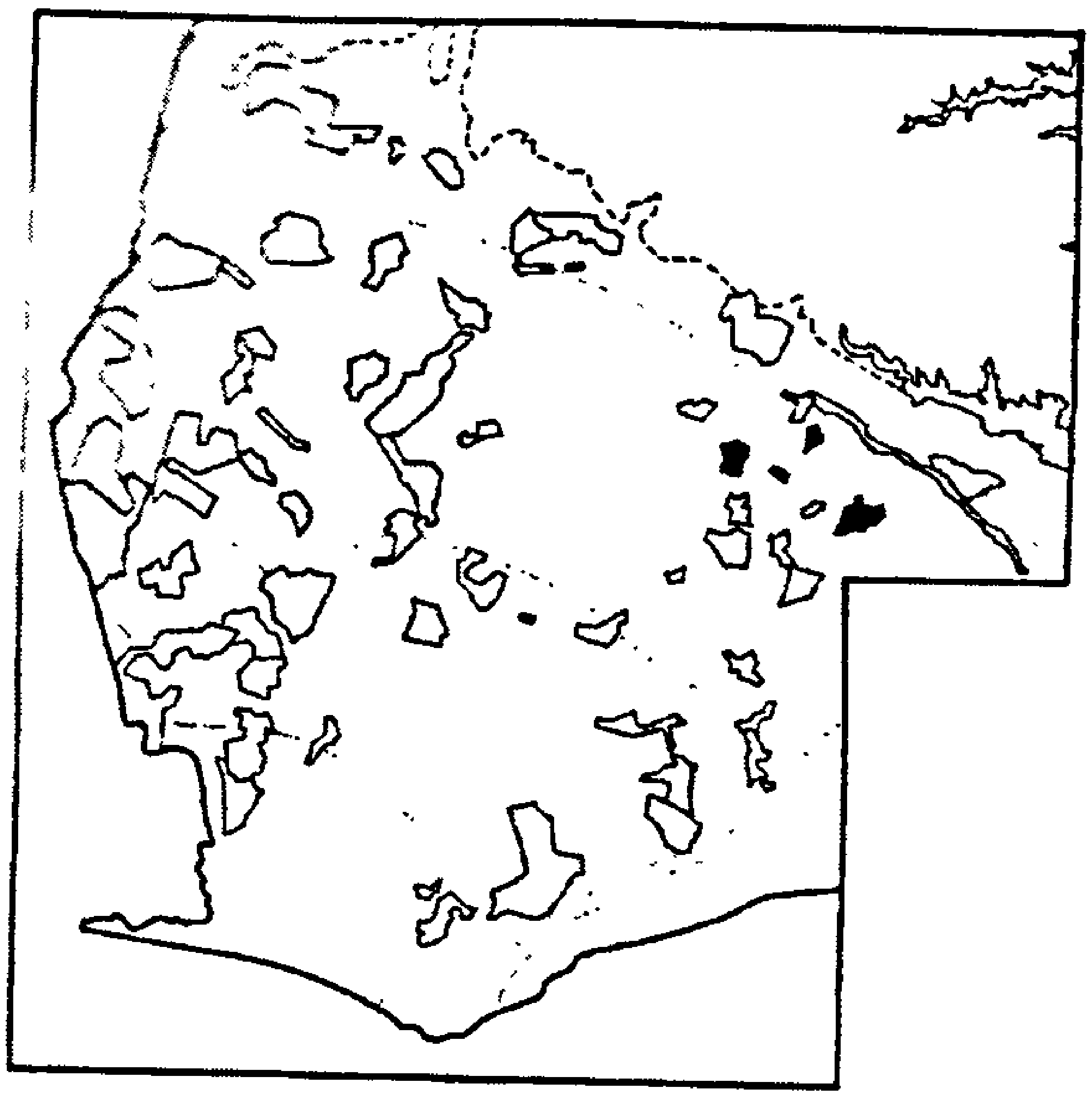
2.5.7.1. Morphology and phenology

It is a large deciduous tree not uncommon in secondary forest, with black bark and graceful, spreading crown of whorled boughs and clustered leaves. Large trees of this species have flat tops, and ascending lower boughs, whereas small trees have horizontal boughs. Lower branches ‘self-clean’, leaving a clear bole even in open conditions. The base of older trees has high, but small buttress, merging into slight flutes (Hawthorne, 1995). The general crown architecture conforms to the model described by Aubréville (Hall and Swaine, 1981).

The leaves are crowded spirally at the ends of the branches. The leaf is obovate, about 8 cm long and 4 cm wide, entire, with a short acuminate apex or acute, cuneate, and with a petiole about 1 cm long. The midrib and nerves are prominent. The petiole and lamina are pubescent but this character disappears in time (Taylor, 1960).

The tree is deciduous towards the end of February and continues in March. The flush of new leaves appears in April and with them come the flowers. Flowering continues until early July. The small yellowish flowers are in upright spikes; petals are absent. The new fruits are not ripe till February and during this month and March they are shed with the leaves. Large quantities of fruits are produced annually. They are wind-dispersed (Taylor, 1960).

2.5.7.2. Distribution



(Source: Hall and Swaine, 1981).

Figure 2.7: Distribution of *Terminalia ivorensis* in Ghana.

It has a Guinea-wide distribution (Guinea to Cameroun) (Hall and Swaine, 1981). The species shows no preference for wet or dry forest (base-poor or base-rich) soils, and is not especially drought-sensitive (Swaine and Veenendaal, 1994 cited by Hawthorne, 1995).

It is found throughout the high forest zone but is not so common in the rain forest as in the moist semi-deciduous forest. The species is a strong light demander and must have overhead light (Taylor, 1960).

2.5.8. *Tetrapleura tetraptera* (Schum. and Thonn.) Taub.

It is a member of the family Mimosaceae.

2.5.8.1. Morphology and phenology

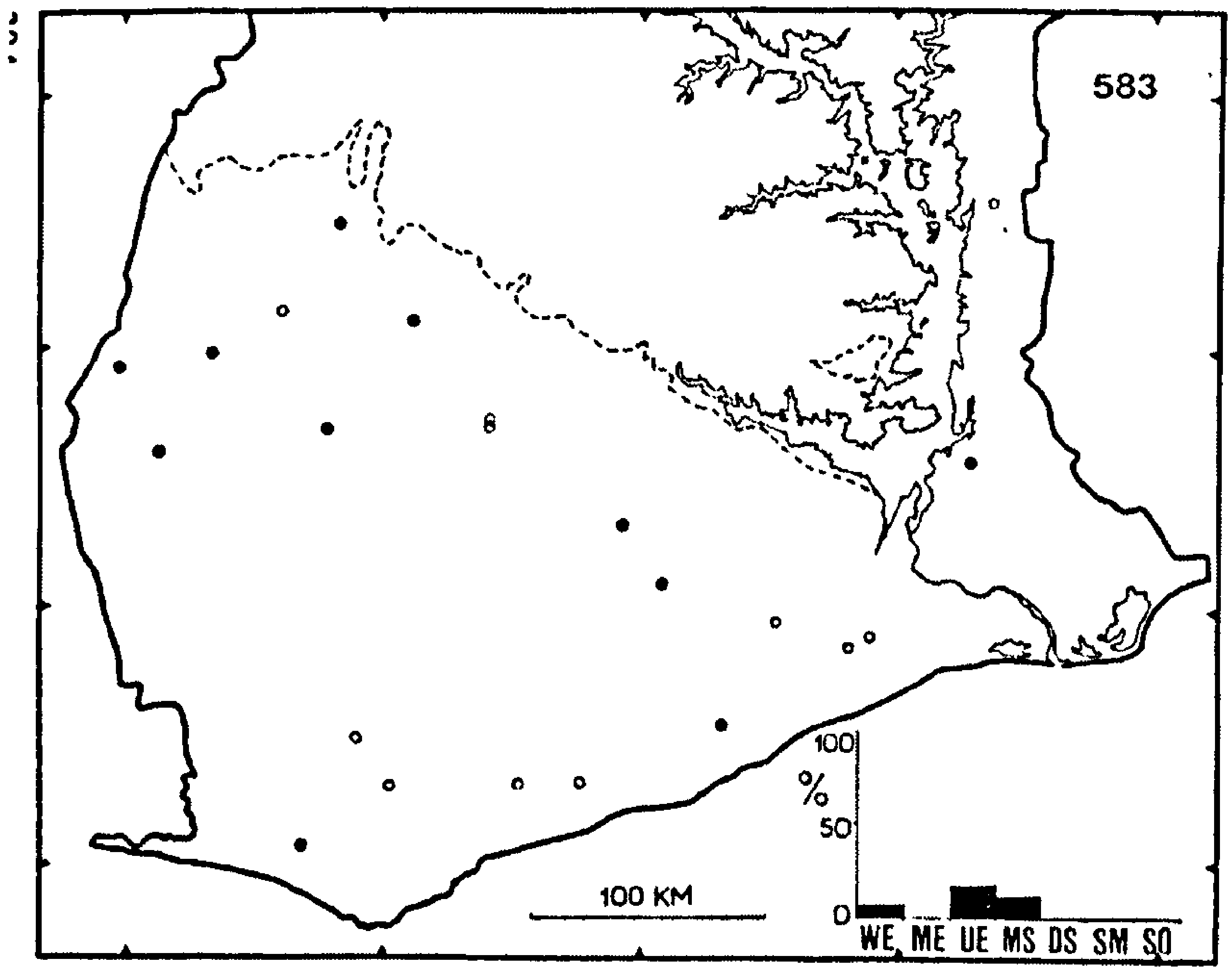
It is a medium-sized, deciduous tree of secondary forest with feathery foliage (Hawthorne, 1995) which are bipinnate, with nanophyll leaflets (Hall and Swaine, 1981). The bole is slender and there are very small, low, sharp buttresses in the older trees. In the forest, the crown is fairly small, thin and rounded, becoming flat when old, but it tends to spread when in the open. The bark is grey-brown and fairly smooth (Taylor, 1960).

The alternate leaves are bipinnate, about 20 cm long, and consist of about 8 pairs of opposite pinnae. There are about 12 pairs of leaflets on each pinna (Taylor, 1960).

It bears small, yellowish, brush-like flowers, crowded in spikes (Hall and Swaine, 1981). Winged, fleshy indehiscent fruits with a strong, caramel smell are produced around the beginning of the dry season. The fruits have recently attracted scientific interest for their medicinal properties. Seeds are large and appear to show erratic germination, with little or no germination without special treatment (Hawthorne, 1995).

2.5.8.2. Distribution

It is common in Ghana, and throughout tropical Africa (Hawthorne, 1995). Distribution is Guineo-Congolian wide, stretching from Senegal to Zaire and Uganda (Hall and Swaine, 1981). Figure 2.8 shows the natural distribution of *T. tetraptera* in Ghana.



(Source: Hall and Swaine, 1981).

Figure 2.8: Distribution of *Tetrapleura tetraptera* in Ghana.

It is at its best in the rain forest and the Lophira – Triplochiton association (Taylor, 1960).

2.6. Seed germination and vegetative propagation of trees.

2.6.1. Seed germination

Seed germination is the most critical part in the life cycle of seed bearing plants (Foley and Fennimore, 1998). Seeds of most horticultural crops have been genetically selected to germinate immediately after sowing. This is not the case for many forest species, however, whose seeds become dormant after they mature (Forest Nursery Notes, 2004). Seed dormancy has been defined variously as the temporary failure of a viable seed to germinate, after a specified length of time, in a particular set of environmental conditions that later evoke germination when the restrictive state has been terminated by either natural or artificial means (Simpson, 1990). Leadem (1988) also defines it as the physical or physiological condition of a viable seed that prevents germination even in the presence of otherwise favourable germination conditions. Alternatively, he defines seed dormancy as "a seed characteristic, the degree of which defines what conditions should be met to make the seed germinate" and points out that this definition may be more useful in understanding dormancy because it suggests that dormancy is variable, rather than constant, which is the situation that is generally encountered in the native populations of many species.

Seed dormancy is a biological mechanism to ensure that seed will germinate at a time and under conditions that will optimize the chances for the growth and survival of the next generation. Dormancy is the inability of the embryo axis to overcome the constraints acting against it. These constraints may originate from within the embryo (endogenous or embryo dormancy) or from the tissues surrounding the embryo (exogenous or coat-imposed dormancy). Understanding whether dormancy originates from within or outside of the seed helps to determine the most appropriate dormancy treatment (Leadem, 1988).

The seeds of many tree species have hard, cutinised seed coats which are impervious to water and sometimes also to the exchange of gasses. Physical seed coat dormancy of this kind occurs most frequently in species adapted to alternating dry and wet seasons. To allow imbibition and initiation of germination processes, hard seed coats must be degraded or broken down. This can be by: (1) letting the seeds fall from the plant and letting nature (microbial, physical and chemical weathering) take its course; (2) mechanical means such as a file or abrasive wheel; (3) hot water soaking; (4) chemical treatment involving digestion of the seed coat with concentrated sulphuric acid or nitric acid; and (5) microwave energy treatment (Doran *et al* 1983; Dirr and Heuser, 1987).

Many species within the legume family, including *Tetrapleura tetraptera*, have hard seed coats that are impermeable to water and gases and widely exhibit coat-imposed dormancy (Dirr and Heuser, 1987; Leadem, 1988). The effectiveness of concentrated sulphuric acid scarification over other forms of pre-treatment in breaking seed dormancy has been reported (Doran *et al.,* 1983; Vora, 1989; Hashim, 1990; Ieadem, 1988). However, it is worthwhile exploring different methods of seed pre-treatment and germination, especially for *Tetrapleura tetraptera* in order to come up with a one that is effective and adoptable for farmers.

2.6.2. Vegetative propagation

Vegetative propagation of trees is a means of producing plants for those species whose seeds do not germinate easily or readily. It is also a means for the conservation of indigenous germplasm (Leakey, 1987; Longman, 1993). Parts of plants such as stems, roots, bulbs, leaves and tissues have been used for many years in multiplying plant species (Leakey, 1981; Hartmann and Kester, 1997). Vegetative propagation techniques employed include the use of cuttings, grafting, buddung, air layering and specialised stems (Longman, 1981; Leakey, 1985; Lamb *et al.,* 1998). A number of workers have highlighted the advantages of vegetative propagation. These include:

i. multiplication of plants that produce seeds which are difficult to germinate but can be propagated more economically by vegetative parts;
ii. propagation of plants that produce seedless fruits or non-viable seeds such as is the case with some orange varieties and fig;
iii. avoidance of long juvenile period which may tie up the nursery space unnecessarily
iv. production of uniform stock plants which are desirable in some characteristics such as resistance to diseases and parasites, drought, cold control of growth form (Longman, 1976; Hartmann and Kester, 1997; Kantari, 1993).

There is current interest in the diversification and domestication of species grown throughout the tropics (Leakey *et al.,* 1982), and vegetative propagation offers a means to greatly enhance the yield of and quality of forest products from commercial plantings in the tropics (Leakey, 1987).

Kantari (1993) has pointed out that in comparison with other methods of vegetative propagation such as budding, grafting, and tissue culture, which are rather difficult and require special technical knowledge, the use of cuttings is the simplest, easiest and cheapest method. In forestry the most widely used type of cutting is the stem. These are easy to prepare and are not readily perishable, making them easier to transport over relatively longer distances. In addition, they require little or no special equipment during rooting of the cuttings (Kantari, 1993; Hartmann and Kester, 1997).

However, to be successful in the use of cuttings, formation of roots is the critical factor. Rooting ability varies among species. And within a species, several factors have been found to influence the success of root formation. The most important of these include:

i. age of the stock – juvenility factor;
ii. state of the material to be used – physiology of the donor;
iii. position of the stem from which the cuttings are made;
iv. time of year at which cuttings are collected;
v. treatment of cuttings
vi. control of environmental conditions of moisture/humidity, light, temperature;
vii. type of rooting media (Leakey, 1983; Kantari, 1993; Longman, 1993; Hartmann and Kester, 1997).

Cuttings from juvenile stock material are reported to have a higher success rate of rooting as compared to those taken from mature stock (Dirr and Heuser, 1987; Kantari, 1993; Hartmann and Kester, 1997). This phenomenon has been observed in *Acacia mangium* (Darus, 1990), *Dalbergia sissoo* (Gupta *et al.*, 1993) and *Parkia biglobosa* (Teklehaimanot *et al.*, 1996; 2000). This has been explained as being possibly due to factors such as the presence of anatomical features such as sclerenchyma, which obstructs adventitious root formation; lowering phenolic levels with age, which are believed to act as auxin co-factors or synergists in root initiation (Darus 1993).

The presence of leaves on cuttings has also been found to affect the formation of adventitious roots in stem cuttings (Hartmann and Kester, 1997), as this may be related to the production of reflux-soluble carbohydrate, apparently derived from current photosynthesis, while the cuttings are in the propagation unit (Leakey, 1990). He states that it seems the ability to produce these carbohydrates is related to the pre-severance light environment and nutrient status. Both the total irradiance and light quality are important components of the pre-severance light environment and these factors interact with nutrient availability to influence the rate of net photosynthesis and rooting. However, the amount of leaves to be left need to be considered carefully, as excessive leaves may lead to excessive transpiration and consequent death of the cuttings before roots are formed to support it (Darus, 1993; Longman, 1993). For some species such as *T. scleroxylon* and *Khaya ivorensis*, an optimum leaf area has been determined for rooting cuttings (Leakey *et al.*, 1982). However, other species such as *Nauclea diderrichii* and *Terminalia spinosa* display no such tendency towards an optimum leaf area (Leakey, 1990; Newton *et al.*, 1992).

Auxins greatly increase the capacity of cuttings to produce roots in most plant species. They are used alone or in combination with other chemicals, as an aid to propagation in horticulture and forestry. Idole-3-butyric acid (IBA) is the most commonly used auxin because of its fair persistence at the site of application and effectiveness in stimulating rooting (Longman, 1993; Hartmann and Kester, 1997). This hormone is used either alone or in combination with α-napthalene (NAA) (Longman, 1993).

Cuttings of different species have slightly different requirements for rooting with respect to auxin concentration (Leakey, 1990). Longman (1993) has pointed out that the best auxin and concentration varies from one tree species to another. He suggested auxin concentrations of 2 g/l IBA for *T scleroxylon*; 0.5 – 4.0 g/l for *Albizia guachapele*; 4 g/l for *Cordia alliodora* and 10 g/l IBA for *Khaya ivorensis*.

However, no work appears to have been carried out on vegetative propagation of *Tetrapleura tetraptera*, and there is therefore the need to assess the rooting ability of juvenile cuttings of this species, to enhance its domestication.

CHAPTER 3

FARMERS' ECOLOGICAL KNOWLEDGE OF THE COCOA AGROECOSYSTEM AND IDENTIFICATION OF INDIGENOUS FOREST TREES USED AS SHADE FOR COCOA IN GHANA.

3.1. Introduction

Agriculture is the mainstay of the economy of Ghana, with over 70% of the population currently engaged in the sub-sector producing food and cash crops. Cocoa is the main export crop and plays a very important role in the national economy, contributing the largest source of revenue for government and constituting the main source of wealth to the people of the forest regions of Ghana (Anim-Kwapong, 1994).

Cocoa has been cultivated in Ghana for decades and its cultivation has undergone transformation over the years both in terms of variety used and mode of cultivation. Though much of it is still grown under the shade of other trees, it is increasingly being grown in full sun. This can be attributed to two main factors: the emergence of the new hybrid varieties developed to thrive without or with little shade; and the absence of forest land to provide the required shade, due to increasing deforestation and land degradation. Smallholders produce the bulk of Ghana's cocoa, under management systems which need to be properly understood in any attempts to develop and formulate technologies aimed at improving cocoa production and management.

Little is known about how farmers manage their production systems with regards to shade trees – how they manage and perceive shade trees – and the value of these trees to them. This study thus sets out to describe farmers' knowledge of the cocoa production system, focusing on shade trees in relation to management of cocoa, but also looking at general system attributes and processes – land/soil suitability, production, weeds, etc. The ultimate aim of the study was to identify criteria used by farmers in deciding the suitability and maintenance of indigenous forest trees as shade for cocoa cultivation, with the view to selecting some of them for field trials.

3.2. Farmers' ecological knowledge

It is widely acknowledged that many of the technological solutions that have been proposed to address problems in rural communities have been compromised by a failure to take into account local knowledge, perspectives and practice of the people (Warren and Cashman, 1988; Chambers *et al.*, 1989; Haverkort *et al.*, 1991; Dudley, 1993; Scoones and Thompson, 1994). In participatory development change is brought about through 'new' knowledge, which is treated not merely as a product to help decision-makers, but as a process of empowerment where local communities take over their own development. This has two important implications for researchers: development can involve the creation of knowledge; but conversely research where the learning processes are only one-way can enforce power structures which block participatory development (Lawrence, 2000). Farmer participatory research rests on the assumption that the farmers' capacities and priorities offer much of the solution to the process of generating and transferring technology. If scientists are to collaborate with farmers they need to understand what farmers know about their agroecosystem. Understanding how farmers generate knowledge provides a deeper insight into farmers' decision making processes (Frost, 2001).

It has been argued that success in development is more likely to be achieved when local people are involved in the planning and implementation of development projects, and that project officials who are familiar with indigenous knowledge are better equipped to facilitate participation by the local people (Brokensha and Riley, 1980; Chambers, 1983; Warren and Cashman, 1988; Scoones and Thompson, 1994). In most developing countries indigenous knowledge is fundamental to the development of agriculture and the management of small farms. Such knowledge reflects experience gained from the past generations, which can be applied to today's ecological and cultural environment, alongside mainstream development strategies (Obua and Muhanguzi, 1998).

Experimental research, although an important means of improving the information upon which farmers make decisions, cannot be solely relied upon to address the pertinent issues over the next decade, and it is worth considering whether relying on experimental scientific methodology alone is the most expedient, effective and efficient way to fill gaps in current understanding about the functioning of agroforestry systems

(Walker et al., 1995). Walker et al., (1995) pointed out that it is particularly worth seeking approaches that could complement experimental investigation, leading to a more rapid understanding of the functioning of agroforestry systems. One approach to filling the gap between what is desirable to know about agroforestry practices in addressing development needs and what knowledge is currently held by research and extension staff is to mobilise and synthesise currently available knowledge from all sources more effectively. It has been proposed that one of the richest but least utilised sources of knowledge available to the development professional is the indigenous knowledge of farmers who practice agroforestry (Walker et al., 1995).

Sinclair and Walker (1998) have indicated that there has been much recent scientific interest in the use of complex agroecosystems, especially those involving trees, as alternatives to green revolution technologies in circumstances where more intensive use of support energy is not appropriate. Such circumstances occur, for example, where capital is more scarce than labour or there is a premium on biodiversity. Harnessing available knowledge in contributing to the development and management of these complex agroecosystems poses interesting challenges for researchers and decision makers. They argued that as these agroecosystems involve diverse mixtures of plants and animals, knowledge is required from across scientific disciplines that have traditionally developed separately – forestry, agriculture and ecology, for example – and that more effective approaches to interdisciplinary research are required. According to them, farmers who have been operating such systems for far longer than there has been scientific interest, may be expected to have developed an understanding of their ecological functioning. This knowledge can be expected to be a key resource for planning and implementing research and development programmes in relation to complex agroecosystems, both because it provides an informed basis from which to proceed (Chambers and Ghildyal, 1985 cited by Sinclair and Walker, 1998) and because relevant programmes are more likely to be achieved where planned with due regard for the farmers' perspective on needs and priorities (Rocheleau, 1987). However, analysis, synthesis and interpretation of the qualitative knowledge held by farmers and professionals across a range of disciplines are conceptually and practically challenging (Sinclair and Walker, 1998).

These issues are particularly acute in agroecosystems that comprise a complex polyculture of species where universal laws are much less likely to be available and applicable than in simplified cropping systems and where there is less scope to ameliorate the resource base using a standardised recipe of inputs. This reflects both the partial understanding of the ecology of such systems by scientists and their extreme heterogeneity over short distances (Sinclair and Walker, 1998). Practical, contextual knowledge of how the environment varies in a particular instance becomes important in determining appropriate action, and farmers are often particularly knowledgeable at this scale of operation (Richards, 1994). Although some local knowledge may be without clear logic, there is a large amount of knowledge among farmers about the ecology of the systems they are using, and it is possible to articulate and use this knowledge explicitly in development initiatives. It is now agreed that farmer knowledge, often based on observations and deliberate experimentation, has a critical role in development initiatives (Joshi *et al.*, 2001).

Sinclair and Joshi (2001) have suggested that the local knowledge of tree-crop interactions has two implications. Firstly, the mechanistic understanding of interactions mediated by the environment makes process-based research on tree-crop interactions directly relevant to and interpretable by farmers. Conventionally, adaptive research may be seen as more relevant to rural people than more fundamental research. But, when we know that farmers themselves understand interactions then research on fundamental processes such as root competition can be formulated with farmers and the results communicated to them. This inverts conventional views on how to make research relevant to farmers. Farmers are often better able to do adaptive research themselves (Veldhuizen *et al.*, 1997; Sinclair and Joshi, 2001), whereas they can learn from fundamental research, providing that it is targeted at processes they need to understand to improve their systems (Sinclair and Joshi, 2001). There is then a role for researchers in doing research that farmers will find difficult to conduct themselves because the disturbance required is beyond their resources, or the methods of observation required are beyond the tools that they have available. When new knowledge is generated from this research, farmers are best placed to integrate it into their system. This requires common understanding of external researchers and farmers, and effective communication which in turn implies a need for formal acquisition of local knowledge (Sinclair and Joshi, 2001).

The second implication is that the generality of local understanding of plant interactions suggests that research with a wide dissemination domain may be derived from analysis of local knowledge. This suggests that analysis of local knowledge can realistically drive on-station and laboratory research as well as more locally situated activity (Sinclair and Joshi, 2001).

Walker et al., (1995) indicated that indigenous knowledge and perspective can impact on agroforestry development at multiple levels and stages. They went on to point out that the active synthesis of indigenous ecological knowledge with scientific knowledge has a potentially important role to play but has received inadequate attention.

3.3. Approaches to indigenous knowledge acquisition

Developing a conceptual model of a complex agroecosystem on the basis of a synthesis of knowledge from a range of sources clearly requires efficient and effective collection and collation of knowledge from many farmers, development workers and researchers (Sinclair and Walker, 1998). Three broad categories of approach to incorporating indigenous knowledge and perspective into development have been distinguished by Walker et al., (1995) as follows:

- approaches based on the active participation of local experts in development activities in which no understanding, per se, of indigenous knowledge is required to be sought by development professionals;
- interactions with local people to generate descriptions of actual practice and constraints on the system in order to improve development professionals' understanding of the target communities' needs; and
- interaction with local people to investigate indigenous explanation of the ecological functioning of the system, in order to facilitate the integration of local and scientific knowledge and produce a more complete and useful resource base for use by professionals or local people in the incremental improvement of land-use systems.

To a large extent, farmers have long been participants in the externally driven research and development process in that they adapt extension recommendations according to detailed knowledge of interactions between crops, pests and soil under local climatic and edaphic conditions (Walker et al., 1995). There is ample literature highlighting the advantages in the use of the first approach (e.g. Drinkwater, 1994; Millar, 1994; Richards, 1994). Effective participation provides not only a means of integrating indigenous knowledge and perspective into the development process but also an environment that encourages better understanding through dialogue. Walker et al., (1995), however, point out that without an independent record of the indigenous knowledge systems, each new interaction with a local community effectively starts with a similar level of ignorance on the part of the professionals, and only those professionals who actively participate may learn what people know and be forced to re-evaluate their scientific knowledge accordingly. Much of the process of incorporating indigenous knowledge remains implicit, occurring because the balance of power shifts from imposing the perspective of the researcher to enabling the farmer to realise his or her objectives (Chambers, 1992). Thus, while participation may empower farmers to pursue their own research, and make the activity of individual research and extension workers more relevant to farmer circumstances, it does not necessarily imply, nor result in, a sufficiently detailed and explicit evaluation of indigenous knowledge for this knowledge itself to be used as a basis for planning research and extension strategies (Walker et al., 1995a).

Traditionally, communication in the development process has been one-way, from the researcher to the farmer. While this approach has had spectacular success, it has frequently resulted in very limited adoption. Success may be more likely in circumstances where a relatively simple technology or new input can be fitted into relatively simple production systems in relatively homogenous ecological zones to produce a high return. As a result, traditional extension has been increasingly recognised as being of limited utility within development programmes (Walker et al., 1995a), and this has led to the developments in approaches to farming systems research (Biggs, 1985; Simmonds, 1985; Hildebrand, 1990), the development of Rapid Rural Appraisal methodologies (Carruthers and Chambers, 1987), and more specifically in agroforestry to the development of the Diagnosis and Design methodology (Raintree, 1987). Approaches to Rapid Rural Appraisal (RRA) are essentially qualitative survey methodologies and are primarily aimed at better understanding the needs of farming communities and the constraints which they operate. These techniques are concerned with participation by the target communities in development activities, however, participation is essentially passive (i.e. responding to request for information) rather than active, and the emergence of Participatory Rural Appraisal (PRA) has gone some way towards blurring this distinction (Walker et al., 1995). PRA is defined as an "intensive, systematic but semi-structured learning experience carried out in a community by a multidisciplinary team which includes community members" (Theis and Grady, 1991), and has become an established procedure for investigating indigenous resource management systems (Webber and Ison, 1994). One of the main advantages of PRAs is that they help provide a holistic vision from the perspective of the end-user, and makes use of their experience, which is integrated with that of the researchers, in order to broaden the common knowledge-base (Chambers, 1994).

A need to support farmers in decision making about incorporating trees within their farming systems based on the results of more fundamental ecological research by the scientific community has been identified (Anderson *et al.*, 1993). This recognition of the need to provide support to the farmer in the light of the farmer's role as the decision maker, demands means of assessing the ecological knowledge that farmers use in their decision-making process, and the knowledge that farmers hold about how to make decisions on the basis of that ecological knowledge. Simply describing actual practice and the constraints contributing to actual practice is inadequate: and understanding of knowledge used to generate that practice is also necessary (Walker et al., 1995). Osbahr and Allan (2003) have also emphasised the urgent need for further studies to discover, develop and maximise the benefits of indigenous knowledge, such as is used in 'precision farming' techniques. They argue that this is particularly important where labour and capital are constraining.

Given that farmers have much more intimate experience of their production practices than external professionals, it seems intuitive that they have developed an in-depth understanding about the ecology of those practices. In principle, the knowledge held by farmers can provide a resource for science irrespective of the participation of the farmers in the use of that knowledge. In other words, the ecological understanding developed by one farming community may be relevant to addressing the constraints encountered by other communities. As a result, investigating local knowledge may be a powerful and efficient means of rapidly filling gaps in scientific understanding about agroforestry. Amalgamating specific local knowledge and general scientific knowledge may be more powerful in designing more appropriate landuse practices than the use of either alone (Walker et al., 1995).

The process of explicit representation, analysis and synthesis of indigenous knowledge and scientific knowledge can have a profound impact on development activities. In contrast to local participation in research and the use of survey methods to better understand target communities, these opportunities have not received adequate attention (Walker et al., 1995).

Previous work on indigenous knowledge systems has been undertaken largely by ethnographers. Although their studies are often rich in detail, the descriptive nature of this work renders it difficult to analyse systematically in terms of ecological processes (Walker et al., 1995). Effective integration of local knowledge with scientific knowledge for a combined understanding of ecological processes requires efficient collection and collation of knowledge from local communities (Joshi *et al.*, 2001). One approach to addressing this problem is through explicit representation of knowledge as it is collected. This involves storing the knowledge in a form that permits repeated and variable analysis and interpretation of the knowledge for decision-making processes (Walker et al., 1995). This can be achieved by the application of knowledge-based systems (KBS) techniques for representing knowledge on computers (Walker et al., 1995). To be useful, this knowledge should be in form that can allow its effective storage, access and analysis. In the KBS approach, local ecological knowledge is articulated and represented as unitary statements. Conditional information, where necessary, is also included in the statements. Local terms and their hierarchical relationships can be captured and represented. With the help of computer technology it is possible to process these basic unitary statements to explore and understand farmers' ecological knowledge systems (Joshi *et al.*, 2001).

In the KBS approach, articulation of local knowledge involves extended dialogues with knowledgeable informants about their understanding of the ecosystem components and functions as well as the interaction between these. The result is a description of the individual's interpretation or understanding from their experience and observation of various processes and components within an agro-ecosystem (Joshi *et al.*, 2001). The Agroforestry Knowledge Toolkit (AKT) methodology and software, is based on this

KBS approach to agroforestry research and extension. The methodology provides a means of iteratively creating knowledge bases about the ecology of agroforestry from multiple sources and of applying formal reasoning tools to less formal exploration of the content of the knowledge base to the analysis of the content of the knowledge base (Walker et al., 1995).

Walker et al., (1995) have stressed that the creation of a knowledge base representing the indigenous ecological knowledge of a community of interest can have a significant utility in better understanding that community and thereby, make research and extension activities more relevant to that community. In summing up on the importance of indigenous knowledge, they have pointed that:

- understanding indigenous knowledge is, in conjunction with understanding practice in the context of social, economic, cultural and environmental variables, an important means of understanding the needs and constraints facing farmers;
- understanding indigenous knowledge is an important activity in improving the communication between target communities and development professionals in the development process;
- facilitating active partnership between development professionals and local people in research can help to result in effective and well-targeted research;
- indigenous knowledge provides a useful source of understanding the functioning agroforestry practices that may be complementary to scientific knowledge.

They stress that the explicit representation of knowledge may have an important role to play in enabling:

- more thorough understanding of target farming communities through evaluation of the knowledge that they hold;
- more effective identification and prioritisation of research objectives
- improved dissemination of knowledge to target farming communities; and
- improved monitoring and evaluation of research activities.

3.4. Study objectives

The purpose of this study was to document farmers' ecological knowledge associated with the management of their complex multistrata cocoa systems, then to contrast farmers' knowledge with what is known scientifically to bridge knowledge gaps. More specifically, the study sought to:

i. investigate farmers' knowledge of interactions occurring among the major components of their cocoa systems, and their effects on system sustainability and productivity;
ii. investigate how farmers use this knowledge for decision-making about the management of their cocoa systems;
iii. native forest tree species growing on farmers' cocoa farms.

3.5. Methods used for the study

The fieldwork for this study was undertaken in two villages (Gogoikrom and Kyereyease) in the Atwima district of Ghana, over a period of two years starting from the year 2000 to 2001. The Agroforestry Knowledge Toolkit - AKT5 (version 1.20) knowledge based systems (KBS) methodology (Dixon *et al.*, 2001) was used to elicit and document farmers' ecological knowledge and management of cocoa multistrata systems, together with participatory rural appraisal (PRA) techniques.

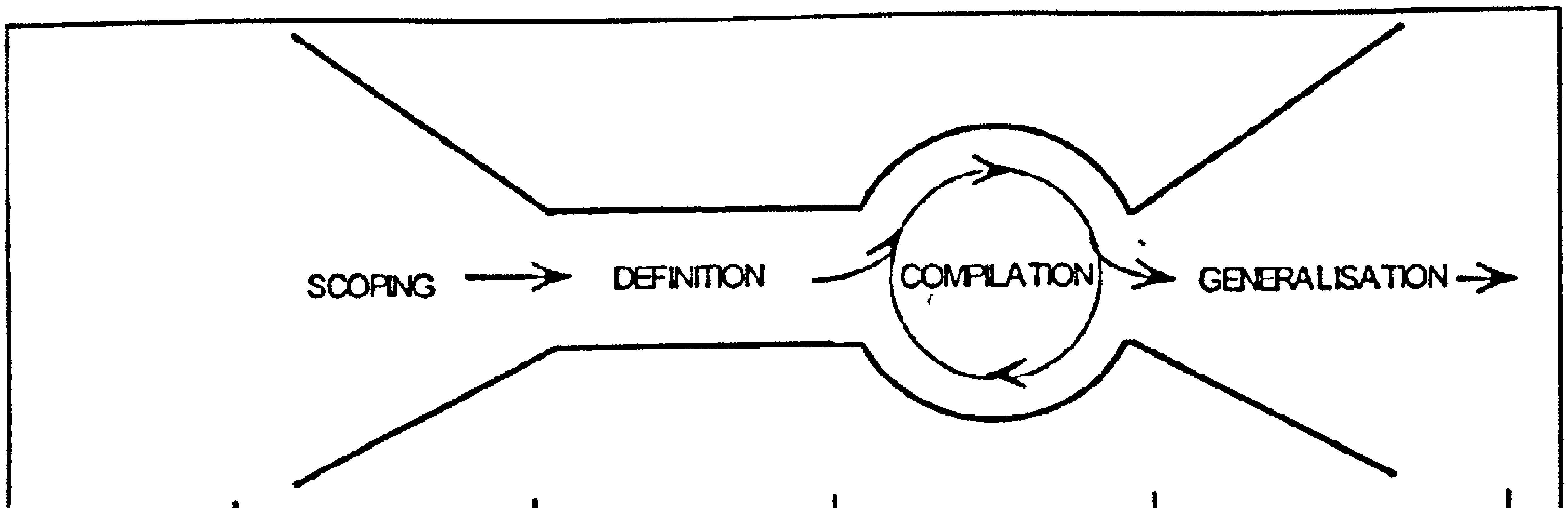
3.5.1. The Agroforestry knowledge Toolkit (AKT)

The AKT is a software that allows qualitative ecological knowledge to be formalised and stored in a computer readable form. Farmers' knowledge on the ecology and management of multistrata cocoa production systems was investigated using the AKT methodology. The AKT allows indigenous knowledge to be analysed systematically through repeated and variable analysis (Walker et al., 1995a). In the application of a KBS approach, local ecological knowledge is articulated and represented as unitary statements. Conditional information, where necessary, is also included in the statements. With the help of computer technology it is possible to process these basic unitary statements to explore and understand farmers' ecological knowledge systems (Joshi *et al.*, 2001).

According to Joshi *et al* (2001), the development of a topical knowledge base consists of four distinct but overlapping stages, namely: scoping, definition, compilation and generalisation. The process is illustrated in figure 3.1.

At the scoping stage, the primary objective is to clarify the purpose of the knowledge gathering. Marking out the domain of interest, understanding local concepts of ecological processes and interactions, and setting definitions for local terms are done in the definition stage. The third stage, compilation, is when actual knowledge elicitation is carried out by a small number of purposively selected "knowledgeable" people. This is usually done in semi-structured interviews, either with individual farmers or in small farmer groups. The process is iterative and intensive where several visits to a key informant may be necessary to elucidate and clarify his/her knowledge. Knowledge statements are extracted from discussions and represented using the AKT. After a sufficient amount of information has been gathered and a fairly robust knowledge base developed, subsets of knowledge statements are compiled into a questionnaire and the knowledge distribution is tested across large sample of people from the target community. This constitutes the fourth stage, generalisation (Joshi *et al.*, 2001). This is the approach that was adopted for this study.

In addition to the knowledge based systems approach outlined above, several PRA methods such as participatory group meetings, history profiling of landuse change, cropping calendars, activity charts, participatory mapping and causal diagramming as described by Pretty *et al* (1995), Slocum *et al* (1995), Galpin *et al* (2000) and Joshi *et al* (2001), were employed.



Objective	To refine knowledge acquisition objectives	To generate a broad understanding of domain & define boundaries & terms	To create a coherent and comprehensive knowledge base	To test how representative the knowledge base is of farmers generally
Informants and activities	A broad range of activities across the community	One or two intensive interactions with a small number of purposively selected informants	Iterative cycle: repeated interaction with stratified sample of key informants, knowledge representation and evaluation of emerging knowledge base	A variety of questionnaire-based survey approaches on a sufficiently large and randomly selected sample of informants from the community

(Source: Sinclair and Walker, 1999).

Figure 3.1: The four stages of knowledge acquisition, with explanatory notes beneath each stage.

3.5.2. Study sites

The study was carried out in two villages, Gogoikrom and Kyereyease, in the Atwima district of the Ashanti region of Ghana. Prior to the selection of these sites, ten villages in the district were randomly visited, based on initial briefings from the District Directorate of Agriculture covering the characteristics of the different farming communities in the district, to characterise the area and the two villages selected to represent this sample. Details of the site selection procedure are presented in Obiri (2003) which also reports results of the socioeconomic study of multistrata cocoa agroforestry systems in Atwima. Criteria for village selection included size of the village and distance from the principal road to Kumasi, the Ashanti regional capital. The two villages were at least 6 km from the principal road, as close proximity to the road would affect the livelihood strategies of the village and render them atypical of most villages in the area. A minimum village size of at least 30 households, and no larger than 100 households, was set. This minimum size would assure that a sample of all common farming practices existed, while the maximum size limitation was set because most villages in the district are small and therefore larger villages would not be representative.

3.5.3. Scoping

Participatory rural appraisal methodologies namely, key informant, group and individual interviews and discussions, and transect walks and farm visits were employed in gathering primary and secondary information from the study communities. Key informant interviews were conducted during exploratory visits to select study sites and establish rapport with district and village authorities as well as village people in general for a quick overview of the farming systems in the communities. Group interviews were then used for gathering more detailed information to define the farming and livelihood systems of the communities.

3.5.4. Knowledge elicitation

3.5.4.1. Choice of key informants

To collect detailed ecological knowledge from farmers, the study focused on a limited number of carefully selected individuals referred to as key informants, in each village. Key informants have been defined as a selected group of individuals who are likely to provide information, ideas and insights on a particular topic (Kumar, 1987). A number of researchers have used stratified samples of key informants on the basis of socio-economic factors thought to influence knowledge. For instance, Thapa (1994), working in the eastern hills system of Nepal, selected informants on the basis of gender, ethnicity and altitude while Den Biggelaar and Gold (1995), in a study of farmers agroforestry practices in Rwanda, selected the most knowledgeable farmers on trees and tree cultivation.

In this study a mix of the two approaches was used, with certain modifications. Fifteen key informants were selected from each village on the basis of ethnicity (i.e. natives and settlers), and on the basis of the most knowledgeable farmers in cocoa cultivation and management. Gender was not an issue here.

3.5.4.2. Interviews

Informal interviews were used throughout the knowledge elicitation process. According to Southern (1994) informal interviews are meant to put farmers at ease and gain information through the creation of a friendly atmosphere. They allow natural conversation and discussions to take place unlike questionnaire which, according to Rusten and Gold (1991), are biased culturally and based on the world view of the researcher.

One field assistant was used to assist with interpretation, where necessary, during the interviews. A checklist of informal interviews was prepared, to ensure that important issues were not left out during discussions. Usually individual interviews were organised by making appointments with the farmer the day before. The interviews typically lasted about one hour and were mostly conducted on Tuesdays, as farmers in the study villages do not go to farm on this day. Transect walks and farm visits were then done to validate issues discussed during the various key informant and group discussions.

Before the interview, the researcher had to first state the purpose of the visit and to introduce the topic for discussion.

In addition to the above procedures, scored causal diagramming (Galpin *et al.*, 2000) was used to explore and analyse in detail the causes and effects of problems and to identify the 'root' causes which need to be addressed. The scoring procedure helps the team to analyse the relative importance of the problems and to prioritise them.

In this exercise, a group of farmers were brought together to discuss farming problems. Once a number of problems had been identified the group was encouraged to represent them pictorially, either on the ground or on a large sheet of paper provided by the researcher. These problems and new ones that were identified during the cause of discussions were then linked in a diagram showing how one problem causes another.

Once the group was happy that the diagram represented all problems, including their causes and effects, scoring was suggested to allow them to represent the relative importance of each problem to them. Scoring was carried out by grouping a number of stones at the end problem and then sharing these up the causal chain in proportion to the relative importance of each problem. Once the farmers were happy with the final scoring the exercise was concluded. The farmers often exhibited a lot of enthusiasm and interest in this exercise, as it was a way to analyse their own problems and to clearly communicate this to the researchers. The exercise often took more than two hours to complete.

3.5.5. Knowledge representation

The knowledge base creation involved two stages of knowledge representation; intermediate representation and formal representation. Intermediate representation involved translating farmers' articulated knowledge and recording them as unitary statements in natural language; in this instance English. Natural language is very flexible and expressive so that the meaning of terms may change according to context. To avoid such ambiguity and imprecision, the intermediate statements were coded using the restricted syntax of a formal grammar which was developed specifically for representing farmers' knowledge about agroforestry (appendix 3.1). The formal grammar has five fundamental elements: i) objects, which are physical items e.g. trees; ii) processes, that are changes or fluxes, e.g. decomposition; iii) attributes, which are properties of objects or processes, e.g. tree height; iv) values, which are measurable state of an attribute, e.g. tall, large, etc; and, v) actions, which are special types of processes involving human interference, e.g. lopping (Kendon *et al.,* 1995). These elements may be combined in four ways, each corresponding to a statement type. These statement type, which may be conditional, are: attribute value; causal, comparison; and user specified link. The statements are expressed in simple language, defined by the grammar and an English 'translation' of the formal grammar is available for clarity. Causal statements may be 2 way in which case an increase in x causing an increase in y is automatically equivalent to a decrease in x causing a decrease in y; or 1 way, in which case this equivalence does not necessarily hold (Thapa *et al.,* 1995). A parser checks the syntax of the formal statements, during formalisation, to be sure that they have been formalised correctly, while the object, attribute, process and link keywords are identified and added to the glossary of terms.

In addition to a set of statements associated with information on who articulated them, a computer holds information about the definition and hierarchical arrangement of terms used in the statements, whilst a diagramming facility enables connections between the statements to be explored (Thapa *et al.,* 1995). For a full description of the AKT methodology, see Dixon *et al* (2001).

3.6. Results and discussion

3.6.1. Farming systems in the two villages

The farming systems of Kyereyease and Gogoikrom were investigated and are outlined here. To provide a clear comparison between the two landuse systems for the two villages, landuse diagrams are used. According to Sinclair and Walker (1999), landuse system diagrams allow representation of four levels of organisation. These are:

i. the overall system
ii. different types of land within the system that have different landuse potentials;
iii. practices (discrete groups of components such as trees, animals or crops that are managed together); and
iv. groups of practices in space and time (such as rotations, where one distinct group of components is followed by another).

3.6.1.1. Kyereyease

Three major types of landuses were identified in Kyereyease. These are the village settlement, grassland (locally called Esre – Esre being the local Twi name for *Panicum maximum* which is the predominant vegetation on this type of land), and secondary forest (locally called Nfofoa Kwae).

Livestock is kept at the village settlement and consists mainly of goats, sheep and poultry, while a few scattered shade and fruit trees are also found here. Actual crop cultivation takes place in the land surrounding the village, which is made up of the esre and nfofoa kwae land types (Figure 3.2 and Table 3.1).

The esre land evolved as a consequence of short fallow periods which are generally less than 5 years. Cropping phase here is occupied by short season cash crops such as rice and vegetables, and food crops such as maize, cassava, cocoyam and plantain, grown for subsistence and for sale. Rice and vegetable cultivation is mostly restricted to clay soils (atekye).

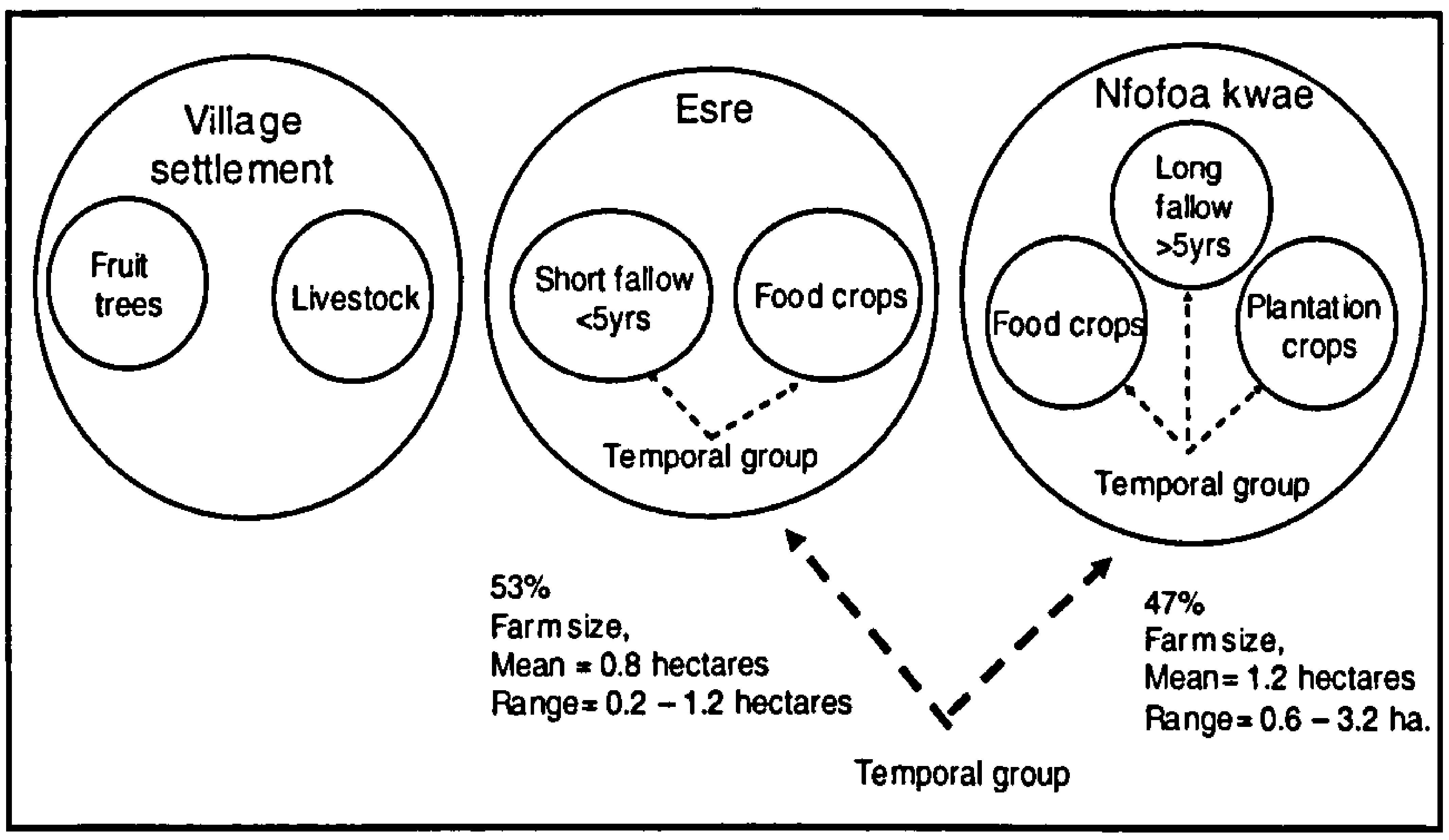


Figure 3.2: Land use diagram for the farming systems of Kyereyease, with arrows showing temporal relationships between different landuse systems.

Nfofoa kwae was defined by the farmers as any forest which has been cleared once, and is distinguished from virgin forest (Kwae) by the size of the trees and vines, the lack of undergrowth and the very thick layer of organic matter found in the latter but which are absent in the nfofoa kwae. The farmers also described various intermediates between esre, nfofoa kwae and kwae. These include nfofoa (thicket), nfofoa acheampong (chromolaena thicket – i.e. land dominated by the *Chromolaena odorata* grass), and kwae pa (very thick forest or true forest). However, apart from secondary forest (nfofoa kwae), there was no true forest (kwae pa) left in this village.

The plantation crop land is temporally linked with long fallows and the cropping phase but only on a long time scale. The main plantation crop here is cocoa, which is the major cash crop of the village. Oil palm, which is a relatively new crop in the area, is also cultivated but on a smaller scale. Old cocoa farms are sometimes abandoned to grow back into nfofoa kwae over a long period and these constitute the long fallow phase of the system, or they may be converted into food crop farms. However, the farmers stated that if cocoa plantations are maintained well and replanted they can stay in production for at least 100 years. Cocoa establishment and the cropping phase are always linked as food crops are relay intercropped with the cocoa during the first three years of cocoa establishment.

Table 3.1: Landuses and their definitions for the village of Kyereyease, Atwima district, Ghana.

Land type	Landuse	Vegetation/ crops	Soils	Land tenure
Nfofoa kwae (Secondary forest)	Long fallow	*Chromolaena odorata* (Achempong) and grass (esre) first, then forest trees regrowth.	Sandy loam White sandy soils Red soils Clayey soils	Individual or family ownership; Rented.
	Plantation crops	Secondary forest growth.		
		Cocoa	Sandy loam, red soil, clayey soil.	Individual or family ownership.
		Oil palm	As above	Individual or family ownership.
	Cropping phase	Rice – maize intercrop;	Sandy loam, clay;	Rented;
		Cassava-maize intercrop;	White sandy soils;	Rented or family land;
		Maize, cassava, cocoyam, plantain, vegetables.	Sandy loam, red soils;	Individual or family;
		Vegetables	Clayey soils, sandy loam.	Rented.
Esre (grassland, guinea savannah)		Dominated by *Panicum maximum* (esre) and *Rotobellia exaltata*, with a few remnant forest trees.		
	Short fallow	*Chromolaena odorata*; *Panicum maximum* (Esre).	Sandy loam, clay, red soils, white sandy soils.	Individual, family and rented.
	Cropping phase	As for nfofoa kwae	As for nfofoa kwae	As nfofoa kwae
Village	Livestock	Fowls; goats and sheep		
	Fruit trees	Citrus, mango, oil palm and gourd tree		

3.6.1.2. Gogoikrom

Much of the land surrounding the village is under cultivation. This forms the farmland, which was initially derived from virgin forest, outside forest reserve, but currently derived mainly from secondary forests. Much of this secondary forest has been derived from old and/or abandoned cocoa farms of 20 or more years old.

Cocoa is the major crop of the village. Oil palm appears to be relatively recent and is preferably established in moist or valley areas. Few pockets of citrus stands may be found near cocoa plantations. Very old cocoa farms (over 50 years and no more productive) may be converted into food farms or new cocoa farms (re-establishment) or may be abandoned to eventually grow into secondary forests (Figure 3.3).

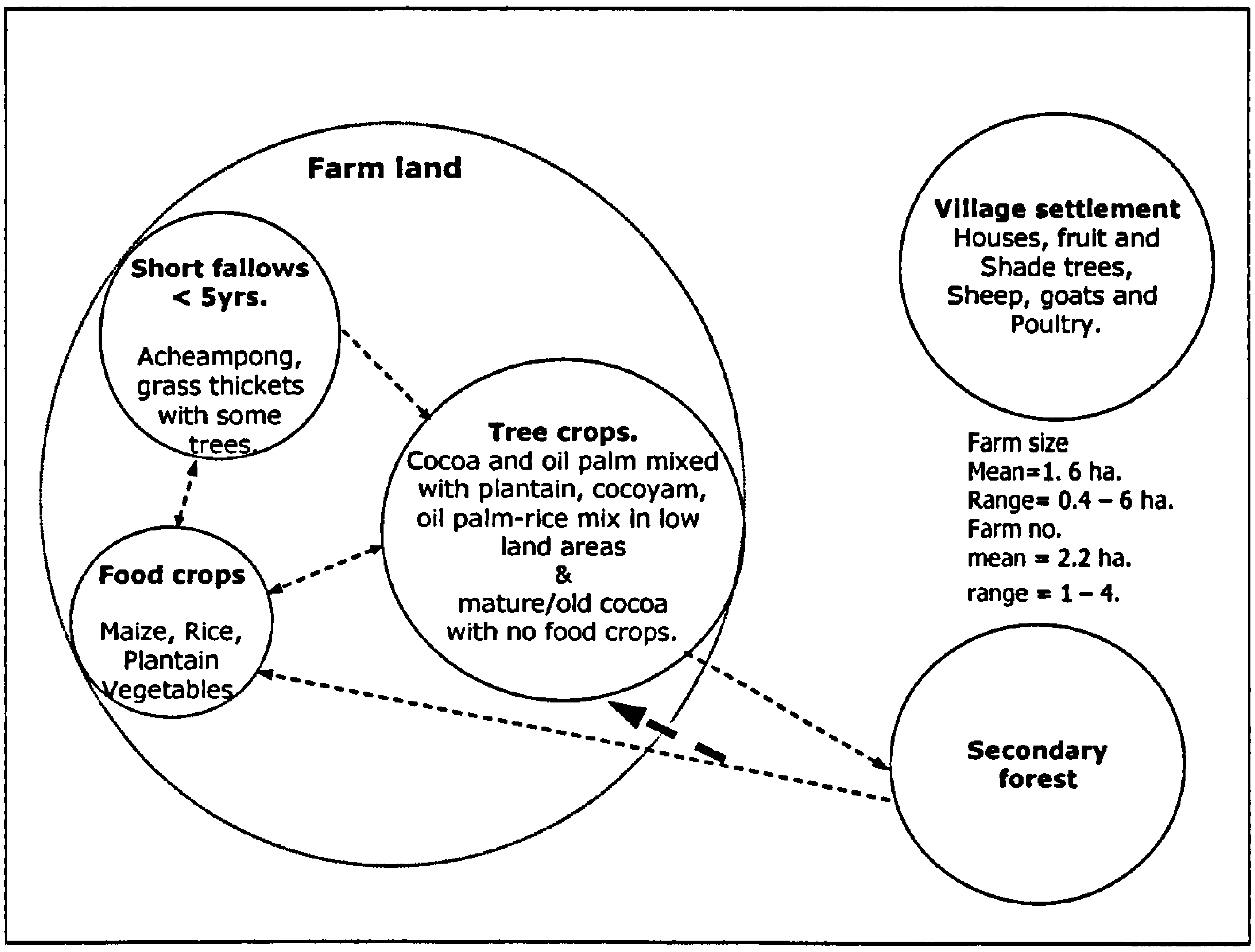


Figure 3.3: Landuse diagram for the farming systems of Gogoikrom, Atwima district. Ghana. Arrows show relationships between different landuse systems; bolder arrow shows major direction of change of the particular landuse.

A smaller proportion of the secondary forest is converted into food crop cultivation for crops such as maize, rice (either sole or intercropped), plantain-cassava-cocoyam and vegetables (pepper, tomatoes, garden eggs, cabbage, okra, etc). Rice, oil palm and vegetables are cultivated in the valley areas. Oil palm is also sometimes intercropped with rice during the establishment phase. Pure food crop farms are left to fallow after a few years of cultivation. The fallow, which is predominantly made up of thickets of *Chromolaena odorata* (acheampong) and mixes of esre, *Pennisetum purpureum* (elephant grass) and other plants like *Centrosema pubescens* and a host of others, may either be converted into food crop or vegetable production, or into cocoa or oil palm farms.

3.6.2. Land tenure

Land tenure is virtually the same for the two villages. Most of the lands available in the village are family and individual lands, however, it was pointed out that land is not scare in both communities. One could acquire land for farming through one's family, individual ownership, and hire/lease and through share cropping. Women, settlers and migrants have easy access to land for the production of any crop (food or tree crops) if agreements under which the land is acquired are maintained (in the case of the landless). The matrilineal inheritance system practiced by the natives in these communities enables women to own land or tree-crop property (cocoa) bequeathed by parents or uncles and other relatives.

3.6.2.1. Family land

This was identified as lands that was obtained by the farmer's parents or grandparents along matrilineal lines through clearance of virgin forest or sharecrop agreements. Such a land is normally held in trust for the farmer's children, nieces and nephews. It may be planted with cocoa, rice, or maize-cassava-cocoyam-plantain mix. The farmer takes all proceeds from the farm in this case. Control over family land is through consultation with other family members with a claim on the land.

3.6.2.2. Individual land

This is land inherited from relative or bought outright. Control of this kind of land is in the hands of the sole owner. Individual land is often planted with plantation crops, mostly cocoa, and has the greatest security of tenure.

3.6.2.3. Rented land

In both villages land may be rented or hired, and the cost of renting varies with the size of the land, the number of years of renting, and the crops to be cultivated. It sometimes also depends on the interpersonal relationship between the tenant and the landlord, or how urgent the landlord needs the money. Renting involves the payment of a cash amount for land and may be rented for just one year or sometimes two years. However, it possible to hire land for longer periods such as 4 – 5 years but the owner is often not keen on it, but may only agree to such a time period if he/she is desperately in need of the money. It was learnt that under such desperate situations some landlords might give out sizeable parcels of land for little cash. One important condition for rented land is that it may only be planted with food crops but not with plantation crops.

A type of rented land defined as different was land belonging to the village chief (Nana), most of which lies along the river Ofin and has clay soils. The clay soils only allows short rotation crops such as rice, maize and vegetables to be grown on it, therefore no one can own it by planting long season crops on it. If rice or maize is grown on the land the chief will accept two buckets of rice or maize as payment, but if dry season vegetables are cultivated using irrigation then the chief takes cash payment. If such a land is returned to a short fallow the chief reclaims it.

3.6.2.4. Sharecropping

Two main types of sharecropping arrangement, *abunu* and *abusa,* as found in many parts of the country, were identified.

3.6.2.4.1. Abunu

The *abunu* share cropping system is practiced for permanent crops like cocoa and oil palm. Under the system, the landlord provides the land and assists the tenant to establish the tree crop, while the tenant intercrops it with food crops in the initial years of establishment. The products from the food crops is solely for the tenant who may give some to the landlord if he so wishes. After the establishment of the tree crop (in 3 – 6 years), the plantation is shared on a 1:1 basis between the landlord and the tenant. The tenant retains ownership of his/her portion of the farm for the entire life of the crop.

Abunu agreements are currently the most common way of acquiring land in Atwima area for replanting cocoa or for other tree crops like oil palm and citrus. The system has become a lucrative means of securing a farm assert by both indigenes and settlers with the main aim of acquiring plantations for future security.

Under the abunu system for replanting cocoa, an initial sum of money is paid to the landowner, which would be at least 300,000 Ghana cedis up to 600,000 cedis (current conversion to pound sterling: 1 GB Pound = 18,000 Ghana Cedis), depending on the quality of the land. This was assumed for a land area that a tenant could clear and farm reasonably. The first few years maize, cassava, cocoyam and plantain would be planted as an intercrop with the cocoa. The plantain acts as a shade tree for the cocoa. The landowner pays for the planting material for the cocoa, be it seeds or seedlings. Depending on the fertility of the soil the cocoa will be mature in 3-6 years. During the first years of food cropping the tenant takes all proceeds from the food crops. Once the cocoa is mature and established the land is divided. The landowner takes 50% of the land area with cocoa and the tenant takes the other 50%.

The tenant's portion is legitimately his, as long as he/she maintains the landuse. If the tenant manages the land well and replants cocoa trees as they lose vigour he/she can keep and farm the land for longer than a 100 years. If the landuse changes the original owner can reclaim the land. An example is the 1983 fires, when the majority of the cocoa was destroyed, if the tenant did not replant the land after a certain period it was reclaimed by the original owner.

In most cases the original landowner is an absentee farmer, living in Kumasi or Accra for example. Under this circumstance he/she will have to make arrangements for his/her share of the abunu land to be catered to after the sharing. This will quite often take the form of employing a caretaker farmer, who will often be the same tenant farmer who established the cocoa.

Other charges still pertaining to the land are an annual payment to the chief and the land commission. Payment made to chief is often in kind such as alcohol during celebrations. The payment to the land commission is called a cocoa tribute, and is often directed through the chief. The chief could reclaim the land if these payments are not made.

3.6.2.4.2. Abusa

The *abusa* agreement is used for food crops such as maize-cassava-cocoyam-plantain mix. In this instance the landowner claims one third ($^{1}/_{3}$) of the crop yield each year the land is cropped whilst the farmer takes the two thirds ($^{2}/_{3}$). After the land is exhausted and left to fallow the land goes back to the owner.

3.6.2.4.3. Caretaker farmer

Caretaker farmers are employed to look after the cocoa. They may not have been involved in establishing the plantation although they have often taken an *abunu* share, and are often employed if the landowner is an absentee farmer. They take 1/3 of the yield of the cocoa farm as payment. The duty of the cocoa caretaker is to maintain the plantation, i.e. weed brush, spray insecticides and fungicides, harvest and process the beans for sale, sometimes in the presence of the landlord. Payment is made by means of a cheque – akuaffo (farmer's) cheque – which is cashed from the bank at Nkawie (District capital) or Kumasi (Regional capital). The landlord then gives a third of the money to the caretaker.

3.6.3. Historical Profile of the Farming System & Environmental Change

The trends of changes in environmental and cropping systems for Gogoikrom and Kyereyease were traced with the elderly men of the two villages (Table 3.2). The numbers in the matrix signify the number of stones used to express the magnitude of a particular parameter of change. Each group was asked to give a rough year of origin of the village and to recount major events that have occurred in the village together with the year of occurrence. The trend of environmental changes and cropping history was then traced.

Both villages were thought to have come into existence in about the 1930s. The major events identified by both groups since the inception of the villages were the earthquake of 1939, the eclipse of the sun in 1947, the 1968 floods and the 1983 bush fires that swept through the country. The main parameters that are related to the cropping system and environment that changed during these time periods were identified to include vegetation cover and crops grown.

Table 3.2: Historical matrix of changes in farming system and the environment drawn by a group of elderly men in Kyereyease and Gogoikrom, Atwima district, Ghana.

A) Kyereyease.

Year/ Parameter	1939 Earthquake	1947 Eclipse of sun	1968 Flood	1984 Drought & fire	1995
Forest cover Kyereyease	10	6	1	0	1
Cocoa Kyereyease	6	6	4	0	1
Plantain Kyereyease	4	4	6	0	11
Cocoyam Kyereyease	4	4	6	0	11
Cassava Kyereyease	1	1	1	0	4
Maize Kyereyease	1	1	1	0	4

B) Gogoikrom

Year/ Parameter	1939 Earthquake	1947 Eclipse of sun	1968 Flood	1984 Drought & fire	1995
Forest cover Gogoikrom	10	10	6	1	1
Cocoa Gogoikrom	10	15	20	10	5
Plantain Gogoikrom	10	15	20	10	15
Cocoyam Gogoikrom	10	15	20	10	15
Cassava Gogoikrom	2	2	6	3	10
Yam Gogoikrom	10	15	20	3	6
Rice Gogoikrom	0	0	1	7	15
Maize Gogoikrom	0	0	4	7	10

Note: The numbers indicate the number of stones used and express the magnitude of that parameter in relation to other periods in time. The number of stones is relative within the same parameter but not across parameters.

3.6.3.1. Vegetation cover

According to the groups, the villages had a thick forest in the 1930s. This kept declining each year due to clearance for agriculture – mainly cocoa cultivation. Even so they felt that up to 1947 the village's forest was still quite intact but had declined by at least 40% in Gogoikrom and 90% in Kyereyease by 1968. However, by 1983, before the wild bush fires, the whole forest had been cleared and used for cocoa cultivation, except in Gogoikrom where a small parcel of forest land – about 1% - was left for the queen mother of Ashanti. That has remained intact to date and is referred to as the queen mother's forest (*ohemaa kwae*). There are however, pockets of secondary forest from old or abandoned cocoa fields.

3.6.3.2. Cropping history

3.6.3.2.1. Cocoa

Unlike Kyereyease, Gogoikrom is mainly a cocoa village. Its inhabitants came to settle there purposely for the cultivation of cocoa. Cocoa production increased from 1937/1939 up to the beginning of 1983. However the 1983 wild fires that swept through the whole country totally destroyed farms especially in most cocoa areas. The farmers did not replant their cocoa immediately after the destruction, as they needed a quick short-term income and the cocoa would take 5 years to start yielding any income.

In Gogoikrom, however, not all the farms were destroyed by the fire. Thus after 1983 there were still some viable cocoa farms in the village, unlike Kyereyease where almost all cocoa farms were wiped out by the fire. However, between 1984 and 1995 Gogoikrom still experienced a declined in cocoa farms due to the fact that some old farms were dying off but were not being replaced immediately. This was mostly due to the fact that many of the farm owners resided in the city (Kumasi) and had lost interest a bit due to the destruction caused by the fire. Presently however, replanting of the burnt and old cocoa farms is taking place actively, due to the introduction of various incentives, by government, including increase in producer price, liberalisation of the produce buying sector which has led to the participation of private cocoa buying companies with a resultant increase in extension services coupled with the provision of loans and other inputs by the competing buying companies.

Three main cocoa varieties are grown, usually in mixtures with food crops and vegetables before canopy closure. The main cocoa varies grown here are the old amazonia and amelonado varieties, locally referred to as *Tetequashie* – after the man who first introduced cocoa into the country. These are low yielding but may remain in production for over 50 years if maintained well. Farmers also reckon that these varieties are hardier, in terms of disease resistance, than the hybrid varieties. The hybrid variety, which is a mixed hybrid developed by the Cocoa Research Institute of Ghana (CRIG) and locally called *akokorabedi* is reckoned to be early maturing and high yielding but has a shorter productive lifespan of about 30 years, compared to the over 50 years for the *Tetequashie*, also depending on how well the plantation is maintained.

Farms under cocoa vary in size from 0.5 – 12 acres or more. Cocoa farms are typically established through a cumulative annual clearing of small areas of farmland. The cropping pattern/calendar for cocoa is presented in Table 3.3.

A cocoa plantation starts as a food-tree crop mix during the first few years of its establishment (3 – 4 years), with the food crop serving as a nurse crop for the cocoa. Most importantly, the food crops also provide much needed cash and food for the household and maintenance of the cocoa until it starts fruiting and or canopy closes.

Establishment begins with land clearing, tree felling, burning and stumping, which are done concurrently, between January and April. Usually land for cocoa would have been under some sort of long fallow of about 10 – 15 years. Planting of food crops in moist lowland areas will usually start in January while drier areas are planted to food crops starting from late February. Harvesting maize planted in lowland areas may start February with the harvesting of some green maize cobs for sale and consumption.

Cocoa is planted between May and August when the rains have normalised and peaked to ensure adequate moisture in the soil for good germination of seeds and survival of seedlings.

The cocoa seedlings would have been established by the second year. Weeding is carried out as and when necessary. Maize and cassava are planted as in the first year. Replacement planting (beating-up) for the cocoa is carried out between April and August. At this stage a few coppice shoots of desirable forest tree species are retained and managed to provide permanent shade for the cocoa in future.

In the third year, the main activities are weeding and harvesting of plantain, cocoyam and cassava throughout the year. The first cocoa harvest of a few pods may be done from September to November on farms planted with the hybrid variety and situated on good fertile soils.

Table 3.3: Cocoa cropping calendar for Gogoikrom, Atwima district, Ghana.

Year 1													
ACTIVITY / MONTH		**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Land clearing		x	x	x	x								
Burning of slash, stumping, tree felling		x	x	x	x								
Planting	Maize	x	x	x	x	x			x	x			
	Cocoyam/cassava/plantain	x	x	x	x	x			x	x	x		
	Cocoa					x	x	x	x				
Weeding (manual)				x	x	x	x		x	x	x	x	
Harvesting	Maize		x	x	x	x	x	x	x	x	x	x	
	Cocoyam/Cassava							x	x	x	x	x	x
Year 2													
Weeding of established cocoa		x	x	x	x	x	x	x	x	x	x	x	x
Replanting of maize/cassava		x	x	x	x	x	x	x	x	x	x		
Replanting dead cocoa (seeds & seedlings)						x	x	x	x				
Harvesting of maize//cassava/plantain		x	x	x	x	x	x	x	x	x	x	x	x
Year 3													
Weeding		x	x	x	x	x	x	x	x	x	x	x	x
Harvesting of plantain/cassava/cocoyam		x	x	x	x	x	x	x	x	x	x	x	x
First harvest of cocoa(minor harvest) – hybrid										x	x	x	
Year 4 – 8 (until canopy closure)													
Weeding		x	x	x	x	x	x	x	x	x	x	x	x
Brushing i.e. removing epiphytes, e.g. mistletoes (nkranpan), etc.							x	x					
Spraying							x	x	x				
Harvesting										x	x	x	x
Processing and sale										x	x	x	x
Year 8 – 10 (when canopy closes fully)													
Weeding							x	x	x				
Brushing, mistletoe removal							x	x					
Spraying							x	x					
Harvesting										x	x	x	x
Processing and sale										x	x	x	x

By the fourth year very few stands of plantain and cocoyam are found on the farm. The main activities from this time on till canopy closes, and after, are maintenance and harvesting. Weeding is carried out when it can be afforded. The plantation is brushed of any epiphytes such as mistletoes, and climbing vines, etc., and other vegetation, annually between June and July. Similarly, spraying with agrochemicals is done between June and August to control insect pests, fungal diseases such as the black pod, etc.

Harvesting and processing of the cocoa pods is done from September to December but much of the produce is sold in November.

3.6.4. Problem causal analysis of farm production

Scored causal diagrams were used to analyse the constraints/problems encountered by the farmers in the two villages. Causal diagrams allow farmers along with researchers to explore and analyse the causes and effects of problems and to identify the 'root' causes that need to be addressed. The scoring procedure helps to identify the relative importance of each problem/constraint and to prioritise them accordingly. Scores (numbers placed under the text in the circle) indicate the perceived magnitude of each problem in the causal chain. The highlighted causes are those scoring highest and therefore regarded as the biggest problems.

3.6.4.1. Kyereyease

Two (2) causal diagrams were constructed in Kyereyease, as outlined by Galpin *et al.*, (2000); one by a group of young women (Figure 3.4) and another by a group of young men (Figure 3.5).

In both instances, weeds were identified as the biggest problem in the village, with the causative factors being short fallows, lack of tree cover and low soil fertility. However, in the case of the young men's group, they outlined a more comprehensive list of causal factors contributing to the high weed problem. The most important of these was inadequate/improper burning during land preparation, as this allows weeds to re-sprout from the cut stumps/stubbles.

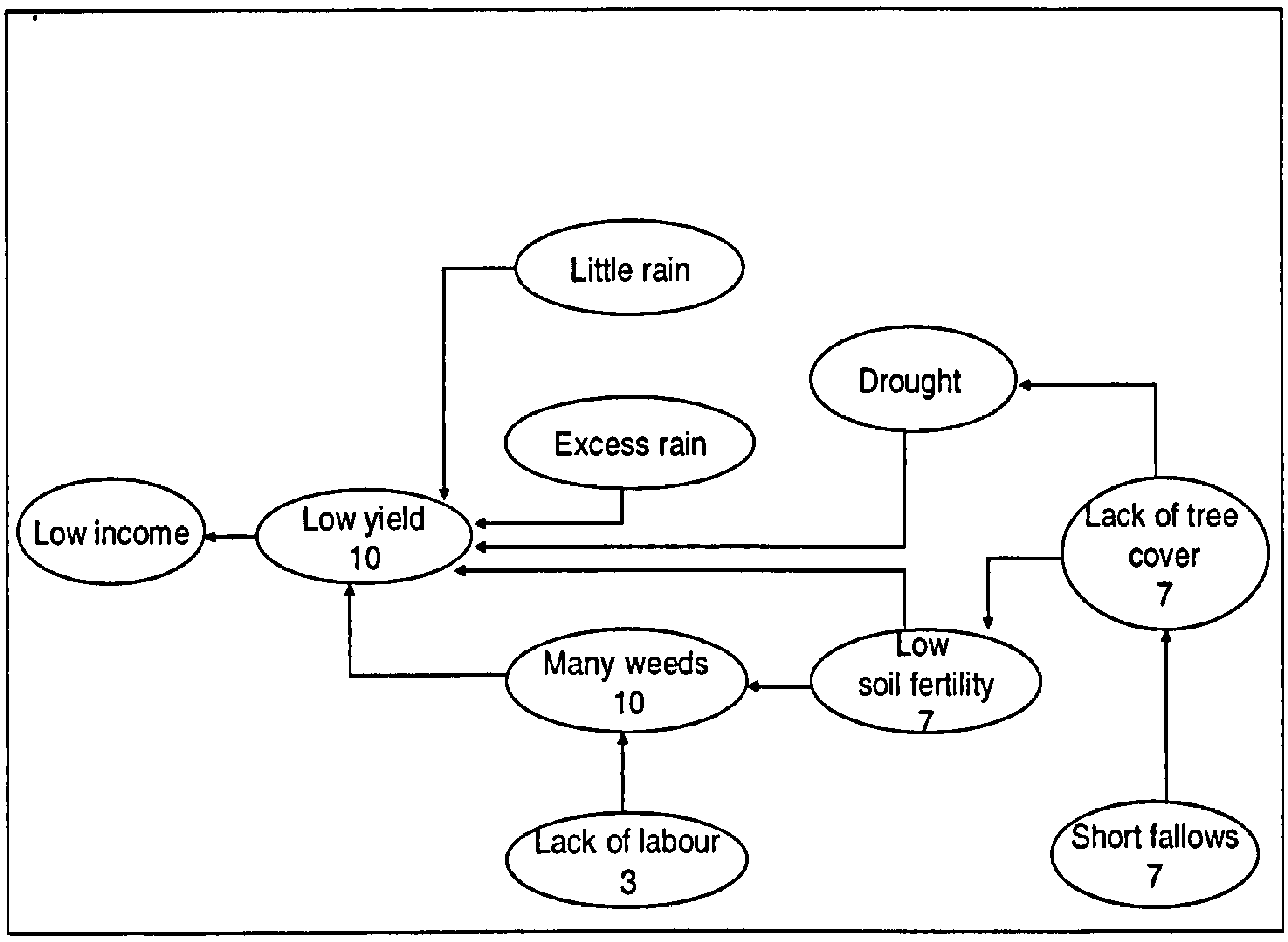


Figure 3.4: Scored causal diagram analysing the farming problems of a group of young (20 – 40 years) women in Kyereyease, Atwima district, Ghana.

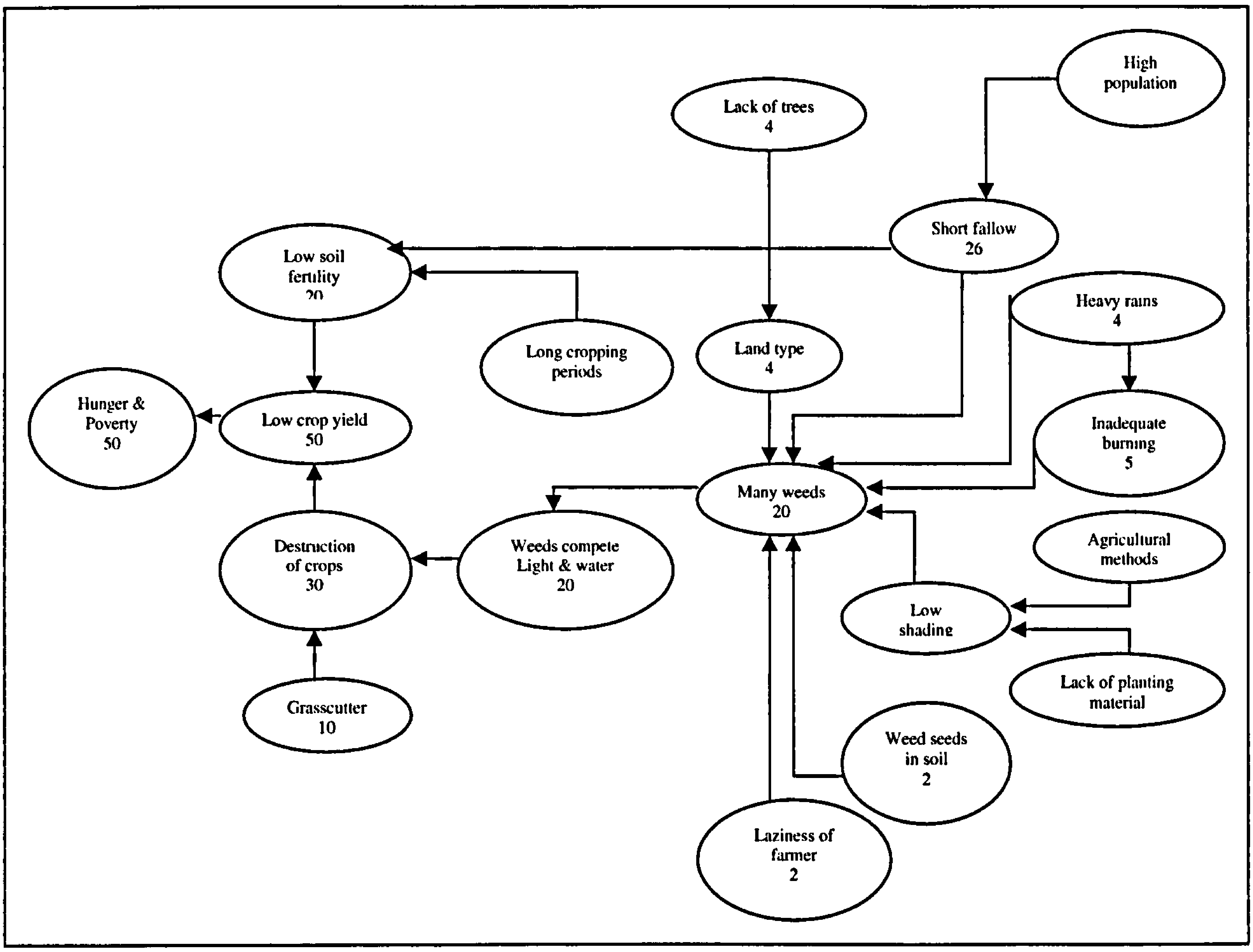


Figure 3.5: Causal diagram analysing farming problems, drawn by a group of young men from Kyereyease, Atwima district, Ghana.

3.6.4.2. Gogoikrom

Two (2) causal diagrams were drawn in Gogoikrom, one by a group of young men (Figure 3.6) and the other by a group of settler men (Figure 3.7). The diagram drawn by the young men (Figure 3.6) highlighted similar pathways to that drawn by the young men in Kyerease, with the difference being that in Gogoikrom weeds were not considered as much of a problem. The reason may be that, being young men, with a good labour resource at their disposal, they did not find weeds to be a major constraint.

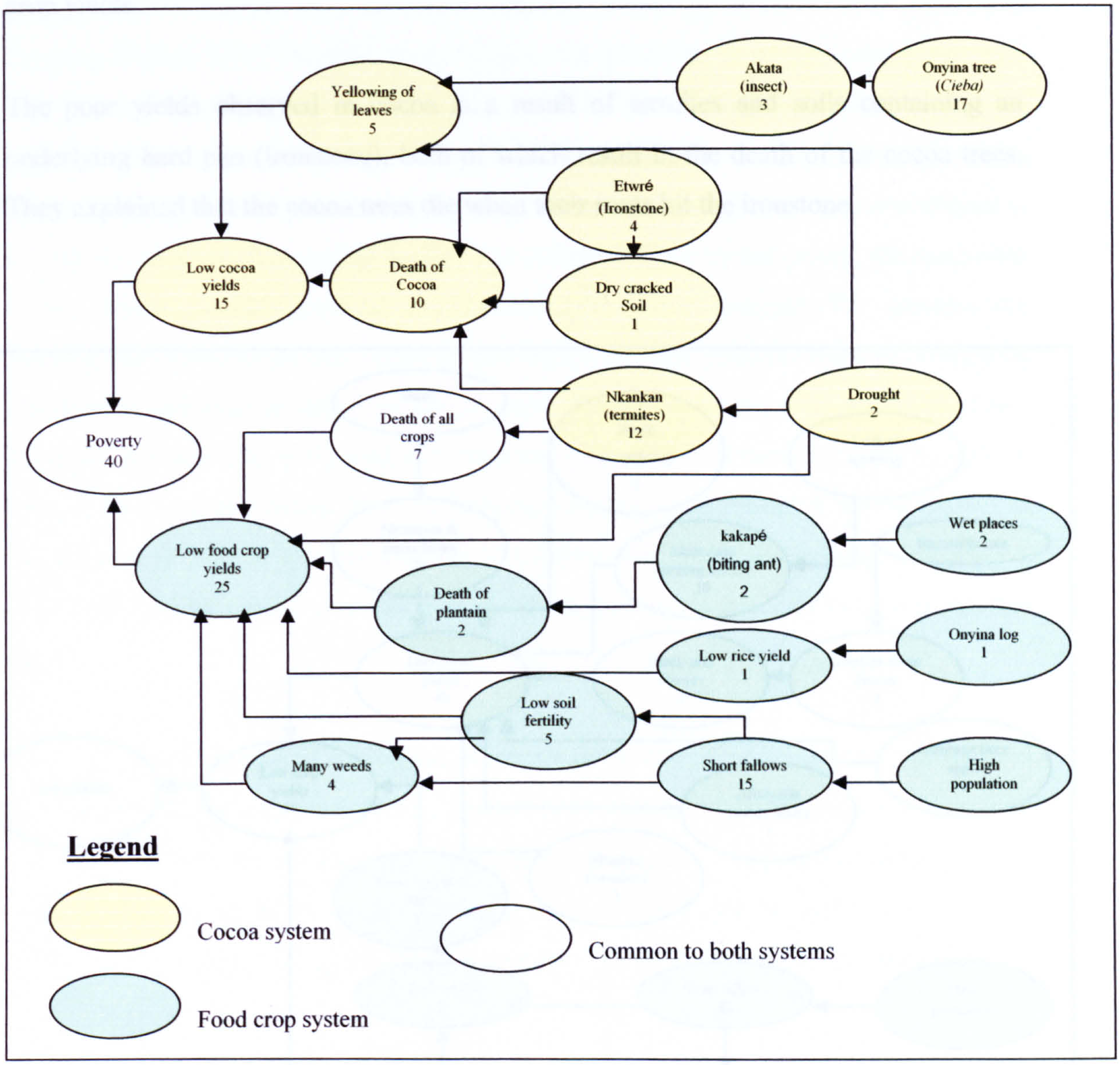


Figure 3.6: Causal diagram analysing farming problems, drawn by a group of young men from Gogoikrom.

The young men recognised poverty to be the ultimate problem with farmers. This, they feel, is caused mainly by low food crop and cocoa yields. Low soil fertility, caused mainly by shortening fallow periods as a result of increasing population pressure, and the emergence of many weeds on farms are the major contributory factors to low food crop yields. Termites (nkankan), under drought conditions, also destroy all food crops whereas ants (kakape) under very wet conditions destroy plantain, all leading to low crop yields.

The poor yields observed in cocoa is a result of termites and soils containing an underlying hard pan (ironstone), both of which result in the death of the cocoa trees. They explained that the cocoa trees die when their roots hit the ironstone.

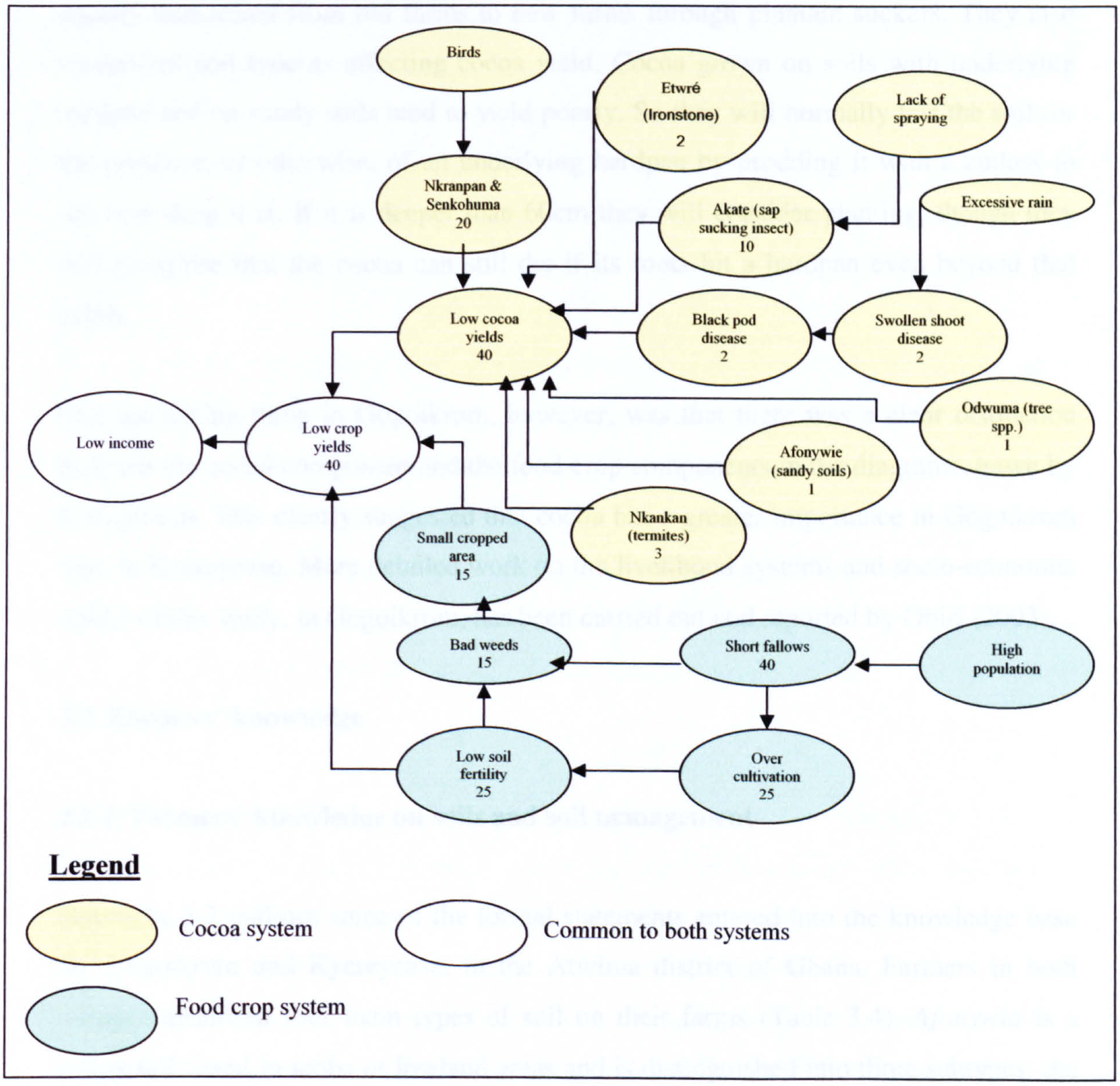


Figure 3.7: Causal diagram analysing farming problems, drawn by a group of settler men from Gogoikrom, Atwima, Ghana.

In the case of the settler men, low farm income was considered the ultimate problem in farming (Figure 3.7). The main causal factor was identified to be low crop yield, with low cocoa yield playing a very significant role. This is quite understandable because, as settlers their main reason for settling there is to generate income, through cocoa farming mostly. Insect pest and diseases as well as parasitic plants were considered to be the main factors responsible for the low yields in cocoa by the group, the main ones being termites, *akate* (capsids) and *anunum* (black pod disease). The termites are usually transferred from old farms to new farms through plantain suckers. They also recognised soil type as affecting cocoa yield. Cocoa grown on soils with underlying hardpan and on sandy soils tend to yield poorly. So they will normally test the soil for the presence, or otherwise, of an underlying hardpan by prodding it with a cutlass to see bow deep it is. If it is deeper than 60cm they will consider planting, though they still recognise that the cocoa can still die if its roots hit a hardpan even beyond that depth.

One interesting thing in Gogoikrom, however, was that there was a clear distinction between the cocoa component and the food crop components in the diagrams drawn by both groups. This clearly suggested that cocoa has a greater importance in Gogoikrom than in Kyereyease. More detailed work on the livelihood systems and socio-economic aspect of this study, in Gogoikrom, has been carried out and reported by Obiri (2003).

3.7. Farmers' knowledge

3.7.1. Farmers' knowledge on soils and soil management

Appendix 3.2 outlines some of the formal statements entered into the knowledge base for Gogoikrom and Kyereyease, in the Atwima district of Ghana. Farmers in both villages identified four main types of soil on their farms (Table 3.4). *Afonywia* is a sandy soil found in moist or lowland areas and is distinguished into three subtypes: the *afonywia tuntum* or black sandy soils; *afonywia fufuo* – white sandy soils; and *afonywia kokoo* – red sandy soils. They reckon that crops, especially cocoa, grow poorly on *afonywia* when rainfall is low or soil moisture content is low. Of course, *afonywia,* being sandy, has poor water holding capacity, which causes moisture stress on crops grown on it when rainfall or moisture is inadequate. They, however, consider it important for the cultivation of rice, oil palm, cassava, vegetables and cocoa, under a good rainfall regime.

Asaase tuntum and *asaase kokoo* are black and red soils respectively, which the farmers described as soils with high fertility levels and high water holding capacities. They, however, recognised *asaase tuntum* as higher in fertility than *asaase kokoo.* In terms of position on the landscape, they pointed out that while *asaase kokoo* can be encountered on uplands, slopes and lowlands, *asaase tuntum* occurs more predominantly on only slopes and lowlands. Both soil types are however used for the same types of crops and are considered the most suitable soils for cocoa cultivation. *Hyire/Ateche* on the other hand was described as clayey soils, occurring mostly in lowland areas and valleys. Being clayey, they easily harden when dry and crops tend to perform poorly on these soils under low moisture conditions.

The farmers in both villages had terminologies they used to describe the fertility status of the soil (Table 3.5). Soil fertility is described in terms of strength/power. Thus a fertile soil is described as one that has strength/power (*ahuoden*) or one that has fat (*sradie*). On the other hand fertility is viewed as a function of maturity. Thus a fertile soil is also referred to as one that is matured (*enyini*), whereas an infertile soil is described as one that has lost its strength (*ahuoden asa*). Farmers also reckoned that coolness is usually a characteristic of a fertile soil, whereas if the soil is hot it could be infertile.

As discovered by Zurayk *et al* (2001), investigating landuse by farmers in Lebanon, local farmers in Atwima categorised their soils in different classes, which reflect their agronomic potential, following a multi-descriptor system such as colour, texture, water holding capacity, and any other existing limitations. They do not carry out any soil investigations for the purpose of determining these descriptors, but learn about them during land preparation and planting operations. Their description of soil type was based on the soil texture, colour and position on the landscape.

Table 3.4: The main soil types and some attributes described by farmers in Gogoikrom and Kyereyease, Atwima district, Ghana.

Soil type	**Description**	**Fertility Scale****	**Location**	**Common Vegetation type**	**Landuse**	**Importance/ characteristics**
Afonywia *Afonywia tuntum* *Afonywia fufuo* *Afonywia kokoo*	Sandy soil Black sandy White sandy Red sandy soil	4	Lowland Valley bottoms.	Esre	Oil palm, very good for : cassava, maize, cocoyam, vegetables	Crop growth is poor with low rainfall or moisture.
Asaasa tuntum	Black loamy soil	1	Slopes Lowlands	Secondary forest; Some esre.	Cocoa, maize, oil palm, cassava, plantain, cocoyam, yam	Has the highest fertility of all the soil types. Also has highest water holding capacity.
Asaase kokoo	Red loamy soil	2	Uplands Slopes Lowlands	Secondary forest.	Cocoa, maize, cassava, plantain, cocoyam, oil palm	Soil fertility is good/high Has a high water holding capacity.
Hyire/ Atekye	Light clayey soil	3		Esre	Oil palm, rice, maize, vegetables	Hard texture with low moisture level. Extensive occurrence on farm causes poor crop growth under low moisture conditions.

**Farmers perception of the fertility of each soil type; the most fertile soil received the least number of scores (stones) and vice versa.

Table 3.5: Terminologies used by farmers in describing soil fertility in Gogoikrom and Kyereyease. (Source: All farmers interviewed).

Local term	**Translation/literal meaning**	**Comments**
Ahuoden	Fertility (literal: power)	
Sradie	Fertility (literal: fat)	
Asaase a enyini	Mature or fertile soil	Occurs after a long fallow
Enyunu	Cool (characteristic of a fertile soil)	
Asaase ahuoden asa	Soil's strength is finished/depleted	
Asaase shesheeshe	Very hot land (not fertile	Caused by absence of tree cover

3.7.2. Farmers' knowledge of trees on farm/cocoa lands

Farmers identified a number of trees found on farms (Appendix 3.3) as well as their respective characteristics, uses and their ecological interactions with cocoa. Trees were classified by farmers as either good or bad on the basis of their compatibility with cocoa as shade trees. Thus a good tree was descried as one that is suitable as shade for cocoa, and vice versa.

Farmers' knowledge on tree diversity on cocoa farms was based on their usefulness. Thus during discussions, three categories emerged from their classification of tree functions on cocoa farms: i) naturally occurring trees that are very useful because of their high timber value, fruit value, medicinal value, soil fertility value, and spiritual value; ii) naturally occurring species of minor economic use, but accepted because of their shade and/or fuelwood value; and iii) naturally occurring trees species that are aggressive or incompatible with cocoa because of factors such as being host to cocoa pest and diseases, incompatible rooting habits, above ground competition, allelopathy, etc.

Generally, farmers' site selection for cocoa cultivation was based on soil type and biological indicators. Their description of soil types was based on soil texture, colour and position on the landscape. In all, four main classes of soil were identified, and their effects on cocoa growth and production described. Trees, shrubs and weeds are used as indicators of soil fertility and, hence, site suitability for cocoa cultivation. The farmers identified over 45 tree species and their interactions with the cocoa crop.

3.7.2.1. Farmers' knowledge about tree-crop interactions

In all fifty two (52) indigenous forest tree species were identified on farmers' fields, of which some thirty eight (38) of them were described as suitable cocoa shade trees (Appendix 3.3). Farmers in the two villages demonstrated a good understanding of the interactions between trees and soil fertility. They articulated considerable knowledge about the effects of tree species on the soil (Figure 3.8 and Table 3.6), and hence cocoa production. A clear link was drawn between tree density and soil fertility and between soil type and tree density. A positive relationship was drawn between tree density and soil fertility, with an increase in tree density said to cause an increase in soil fertility. Their basis for this knowledge was the observed difference between the soils in forest (Kwae), forest fallow – i.e. secondary forests (Nfofoa kwae) and open grasslands (e.g. esre land). They explained this to be the result of decomposition of organic matter contributed by the trees in the form of leaf litter fall. The density of trees was said to be influenced by the soil type. In their view, *asaase tuntum* (black soil), which is the most fertile soil, usually contains the highest density of trees while *afonywea* (sandy soil), which is the least fertile, will normally contain the least tree density. A strong link was also drawn between density of trees, litter production, decomposition and soil nutrient enhancement, as well as between litter production and soil moisture conservation (Figure 3.9 and Table 3.7). Farmers would usually try to influence the density of trees on their fallow lands by leaving regenerating tree seedlings and coppicing shoots in the year prior to leaving the land to fallow.

Trees were said to exert a 'cooling' effect on the soil, and this has a positive effect on soil moisture conservation and on the suitability of particular tree species for use as cocoa shade, as well as affecting the overall lifespan of the cocoa trees on the farm. This knowledge is well supported by scientific evidence that the use of shade trees in the cocoa agroecosystem, as well as diversifying productivity, improves nutrient cycling within the system, and increases the lifespan of the cocoa crop (Beer, 1987; Beer *et al.*, 1998; Johns, 1999; Rice and Greenberg, 2000).

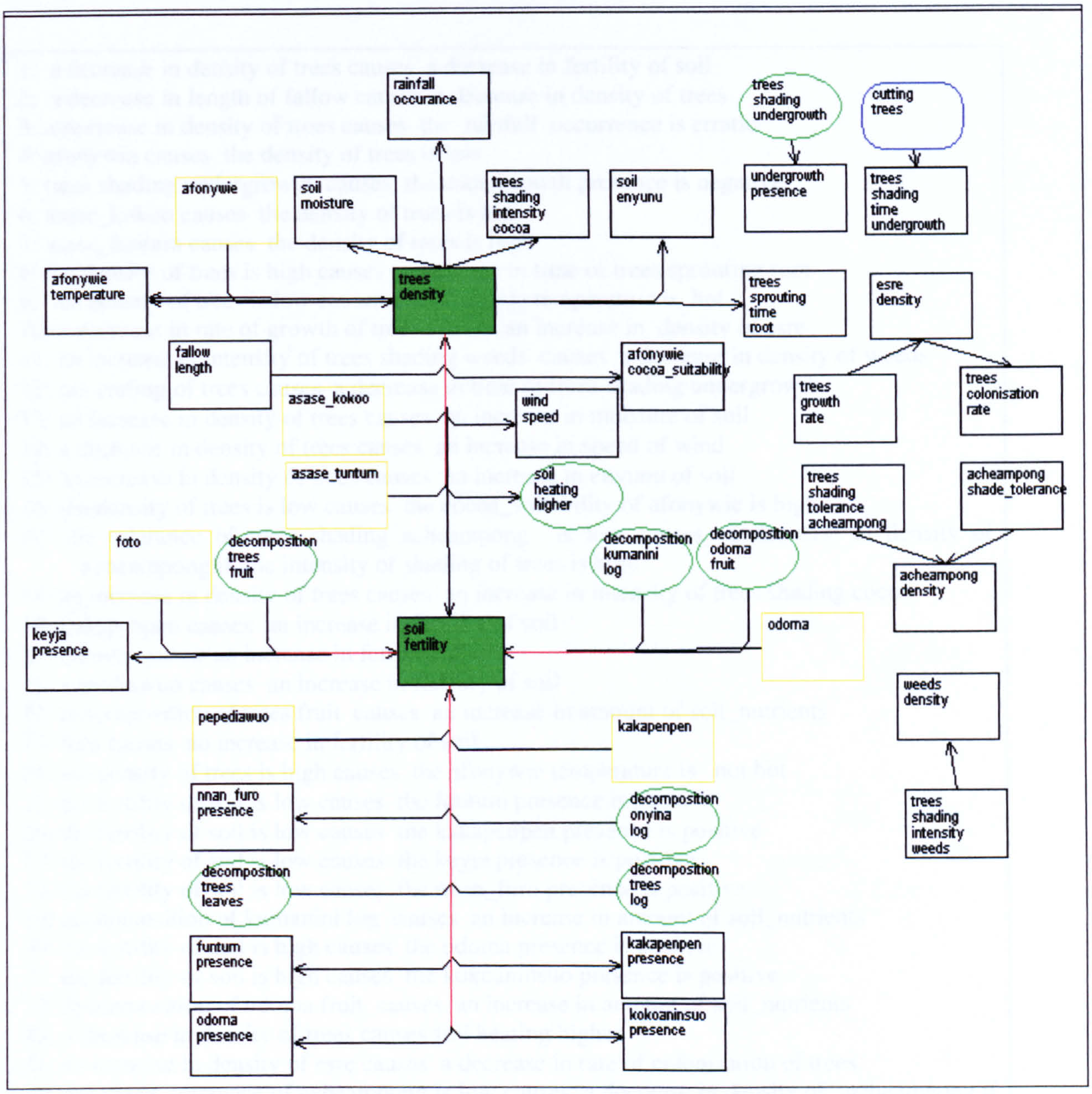


Figure 3.8: Farmers' causal knowledge of the effect of trees on soil fertility and of soil type on tree density in the Atwima district, Ghana (generated by AKT from the knowledge base). Nodes represent attributes of components or the system. Arrows indicate the causal node from which the arrow emanates has an influence on the "effect" node to which arrow points, or indicate an increase or a decrease. Information about the nature of the relationship is also held within the knowledge base. Oval nodes represent processes.

Table 3.6: Extract of farmers' knowledge on trees and soil fertility in Atwima district (extracted from AKT).

1: a decrease in density of trees causes a decrease in fertility of soil
2: a decrease in length of fallow causes a decrease in density of trees
3: a decrease in density of trees causes the rainfall occurrence is erratic
4: afonywia causes the density of trees is low
5: trees shading undergrowth causes the undergrowth presence is negative
6: asase_kokoo causes the density of trees is high
7: asase_tuntum causes the density of trees is high
8: the density of trees is high causes a decrease in time of trees sprouting root
9: the density of trees is low causes the afonywie temperature is hot
10: a decrease in rate of growth of trees causes an increase in density of esre
11: an increase in intensity of trees shading weeds causes a decrease in density of weeds
12: not cutting of trees causes a decrease in time of trees shading undergrowth
13: an increase in density of trees causes an increase in moisture of soil
14: a decrease in density of trees causes an increase in speed of wind
15: an increase in density of trees causes an increase in enyunu of soil
16: the density of trees is low causes the cocoa_suitability of afonywie is high
17: the tolerance of trees shading acheampong is low causes a decrease in density of acheampong if the intensity of shading of trees is high
18: an increase in density of trees causes an increase in intensity of trees shading cocoa
19: kakapenpen causes an increase in fertility of soil
20: odoma causes an increase in fertility of soil
21: pepediawuo causes an increase in fertility of soil
22: decomposition of trees fruit causes an increase in amount of soil_nutrients
23: foto causes an increase in fertility of soil
24: the density of trees is high causes the afonywie temperature is not hot
25: the fertility of soil is low causes the funtum presence is positive
26: the fertility of soil is low causes the kakapenpen presence is positive
27: the fertility of soil is low causes the keyja presence is positive
28: the fertility of soil is low causes the nnan_furo presence is positive
29: decomposition of kumanini log causes an increase in amount of soil_nutrients
30: the fertility of soil is high causes the odoma presence is positive
31: the fertility of soil is high causes the kokoaninsuo presence is positive
32: decomposition of odoma fruit causes an increase in amount of soil_nutrients
33: a decrease in density of trees causes soil heating higher
34: an increase in density of esre causes a decrease in rate of colonisation of trees
35: the shade_tolerance of acheampong is low causes a decrease in density of acheampong if the density of trees is high
36: water transfer soil surface causes an increase in moisture of soil
37: abe causes an increase in moisture of soil
38: cocoa causes a decrease in moisture of soil
39: an increase in amount of soil_nutrients causes an increase in fertility of soil
40: an increase in fertility of soil causes an increase in yield of cocoa

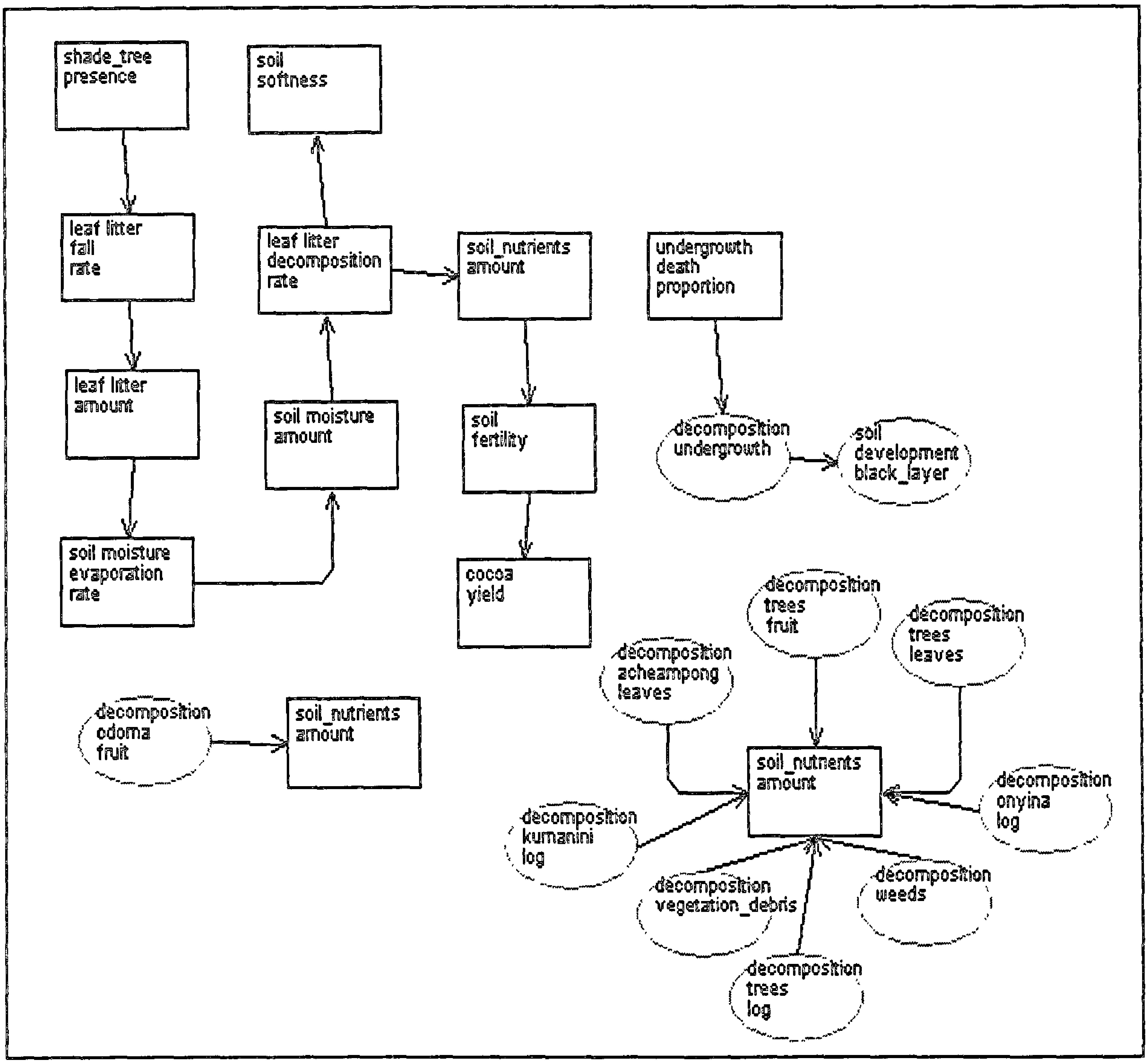


Figure 3.9: Farmers' ecological knowledge on litter production, decomposition and soil nutrients (generated from AKT). Legend as for Figure 3.8.

Table 3.7: Farmers' knowledge on decomposition and soil nutrient status.

1: the death of undergrowth proportion is 100% causes decomposition of undergrowth
2: decomposition of undergrowth causes soil development black_layer
3: decomposition of trees log causes an increase in amount of soil_nutrients
4: decomposition of vegetation_debris causes an increase in amount of soil_nutrients
5: decomposition of weeds causes an increase in amount of soil_nutrients
6: decomposition of onyina log causes an increase in amount of soil_nutrients
7: decomposition of trees leaves causes an increase in amount of soil_nutrients
8: decomposition of trees fruit causes an increase in amount of soil_nutrients
9: decomposition of acheampong leaves causes an increase in amount of soil_nutrients
10: decomposition of kumanini log causes an increase in amount of soil_nutrients
11: decomposition of odoma fruit causes an increase in amount of soil_nutrients
12: the shade_tree presence is positive causes an increase in rate of fall of leaf litter
13: an increase in rate of fall of leaf litter causes an increase in amount of leaf litter
14: an increase in amount of soil moisture causes an increase in rate of decomposition of leaf litter
15: an increase in rate of decomposition of leaf litter causes an increase in softness of soil
16: an increase in rate of decomposition of leaf litter causes an increase in amount of soil_nutrients
17: an increase in amount of leaf litter causes a decrease in rate of evaporation of soil moisture
18: a decrease in rate of evaporation of soil moisture causes an increase in amount of soil moisture
19: an increase in amount of soil_nutrients causes an increase in fertility of soil
20: an increase in fertility of soil causes an increase in yield of cocoa

Farmers articulated a good knowledge of the above-ground interactions between shade trees and the cocoa. Several attributes of the shade trees which influence shading were outlined by the farmers, and these included: the crown size, the number of branches, leaf size, leaf number, and crown density. An increase in any of these attributes was believed to cause an increase in shading intensity. Crown size was described in terms of its diameter, while crown density was described in terms of the number of leaves per unit area. They were of the opinion that trees with large broad crowns and extensive branching habits cast more shade than those with small crowns. Trees with dispersed leaves were said to cast less shade than trees with many and closely spaced leaves. This knowledge is well supported by a number of scholars, who have pointed out that the level of shading or light interception is influenced by the amount of leaf area and the spatial distribution of the leaf area in the vertical and horizontal inclination, as well as general characteristics of tree crowns (Wang and Jarvis, 1990; Stenberg *et al.*, 1994; McCrady and Jokela, 1998; Lott *et al.*, 2000).

It was apparent that farmers strongly linked aboveground interactions to the shade level in their farm. Indeed, they said that plant density, together with the architecture of the aerial parts of the shade tree species concerned, mainly determined the shade level, which in turn influenced the microenvironmental conditions in the field such as the amount of solar radiation getting to the understorey, humidity and air circulation. Amongst the tree species attributes identified as influencing the shade level in the farm, emphasis was put on crown density and shape, tree height and the extent of canopy closure. The crown density principally referred to tree foliage abundance. Bigger leaf size tended to be associated with higher crown density, and vice versa (Table 3.8). Farmers said the crowns were importantly shaped by the spatial development of tree branches; they clearly distinguished between the following shapes:

- Wide crown shape: where tree branches had a pronounced plagiotropic development, with few branches developing on the trunk.
- Narrow crown shape: where tree branches had a pronounced orthotropic development, with few branches in general and few developing on the trunk.
- Intermediate crown shape: where there was a somewhat balanced mixture of both plagiotropic and orthotropic branches, with no predominant development of either type.

The effect of shading level on cocoa yield was well articulated by the farmers. They pointed out that too much shade had a negative effect on cocoa yield, as well as causing an increase in the incidence of diseases especially the black pod disease. In their opinion, dense shade, which is caused by too many shade trees or trees with heavy canopies, makes the farm 'dark' and 'silent'. This, they believe, causes low yields directly by cutting the sun's energy to the cocoa crop underneath, and indirectly by causing disease outbreaks. Height of the shade tree was also considered very important and was linked to below canopy micro-climatic factors such as air circulation and humidity. They were clear in their understanding that short, heavy-crowned trees tend to prevent proper circulation of air beneath them.

This, in their opinion, causes high temperature, as a result of improper ventilation, and high humidity, which in turn encourages the development of the black pod disease (called *anunum* in the local twi language). This is in consonance with the views of Bellow and Nair (2003) who have pointed out that yields of understorey crops grown in areas where soil nutrients and water are not limiting are likely to be reduced due to reduced solar radiation. Monteith (1990) also stated that tree shading affects understorey crops by reducing temperature and the amount of light, thus affecting the amount of photosynthetically active radiation intercepted by the crop canopy and the efficiency with which this radiation is converted into plant matter. Rao *et al* (1998) also found a link between understorey microclimatic conditions and tree species' canopy characteristics and size and density of the trees in the system.

Table 3.8: Examples of farmers' assessment of tree attributes and their effects on the microenvironmental conditions of the multistrata cocoa fields.

Tree species	Attributes				Effects on conditions in farm		
	height	crown density	crown shape	leaf size	shade	solar radiation	humidity
Albizia adianthifolia	medium	sparse	wide	small	light	excessive	low
Entandrophragma angolense	tall	dense	narrow	big	excessive	low	high
Entandrophragma utile	tall	dense	narrow	big	adequate	adequate	medium
Khaya anthotheca	tall	dense	wide	big	excessive	low	high
Newbouldia laevis	short	dense	narrow	big	light	adequate	medium
Terminalia ivorensis	tall	medium	wide	medium	adequate	adequate	medium
Tetrapleura tetraptera	medium	sparse	wide	small	light	adequate	medium
Ficus capensis	tall	dense	wide	medium	excessive	low	high
Milicia excelsa	tall	dense	narrow	medium	excessive	low	high
Baillonella toxisperma	tall	dense	wide	big	adequate	adequate	medium
Alstonia boonei	short	dense	wide	big	excessive	low	high

The farmers exhibited an appreciable level of knowledge about the rooting pattern of shade trees and the complementarity or otherwise of various tree species with the cocoa. They had a good understanding of the effect of shallow and deep rooted trees on the cocoa. They pointed out that deep rooted trees do not compete with the cocoa for soil nutrients and water, whereas shallow rooted trees tend to compete with cocoa for nutrients and water. Among tree species cited as having shallow roots were wawa (*Triplochiton scleroxylon*), emire (*Terminalia ivorensis*), nyankyereni (*Ficus exasperate*), watapuo (*Cola gigantia*), among others. The shallow rooted trees were said to have extensive lateral roots near the soil surface and this results in serious competition for soil moisture and nutrients.

The literature is replete with information on the competitive effect of overstorey tree roots on the understorey crop, especially in alley cropping systems (e.g. Singh *et al.*, 1989; Ong *et al.*, 1991; Rao *et al.*, 1993; Akinnifesi *et al.*, 1998; Jama *et al.*, 1998; Mekonnen *et al.*, 1999). For instance, Akinnifesi *et al* (1998) found that the percentage of fine roots in the top 0 – 30 cm of soil varied from 21% for *Lonchocarpus sericeus* to 84% for *Tetrapleura tetraptera*. Jama *et al* (1998) found that the slope of roots of log L_{TV} (root length density) against depth differed significantly between tree species, indicating that some had deeper root distribution. These studies have concluded that deeper rooting trees are better candidates for use when trees and crops are mixed in fields, since they will compete less with the crops.

With regards to soil moisture dynamics the farmers recognised that while certain tree species were capable of bringing up water from deep down the soil to keep the soil surface beneath them moist and cool, there were others that have the characteristics of making the soil beneath them dry and hard (Figure 3.11 and Table 3.9). They pointed out that trees with deep roots usually bring up water from deep in the soil to keep the soil surface moist. They cited specific trees which, they say, pump up water from the soil depths to the surface to feed the surrounding cocoa seedlings and/or trees. Tree species such as *odoma* (*Ficus capensis*), *kokoaninsuo* (*Spathodea campanulata*), *okro* (*Albizia zygia*) and oil palm were specifically cited as having the quality of keeping the soil around them cool (*enyunu*) and moist, in addition to providing good shade, and hence enhancing the growth of the cocoa around them. Other species like *akata* (*bombax buonopozense*) and (*Ceiba pentandra*) are also mentioned as having the same soil cooling and moistening abilities, however, they are considered as unsuitable shade for cocoa because they harbour insect pest and diseases that affect the cocoa. On the other hand, some tree species were cited as making the soil around them dry and hard. These included, *nyankyereni* (*Ficus exasperate*), *kegya* (*Pterygota macrocarpa*), *wawa* (*Triplochiton scleroxylon*), *watapuo* (*Cola gigantia*) and the cocoa tree itself. This clearly demonstrated a deep understanding of ecological processes going on within tree-crop systems by the farmers, and tallies with the findings of scientific research which has reported the recycling of nutrients from considerable depths in the soil profile by deep rooted trees (e.g. Singh *et al.*, 1989; Rao *et al.*, 1993).

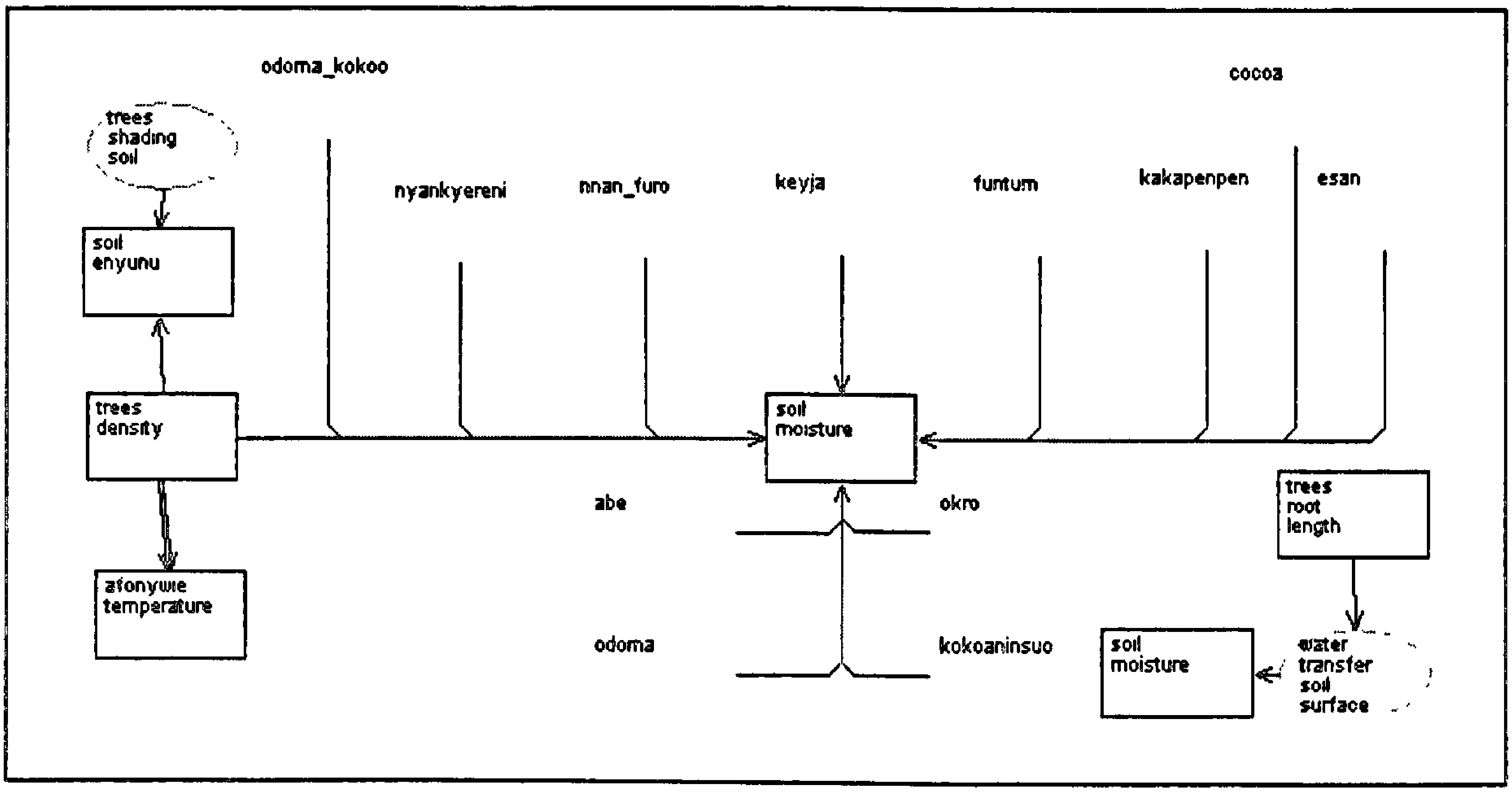


Figure 3.10: Farmers' knowledge of the effect of tree species on soil moisture (generated from AKT). Legend as for Figure 3.8.

Table 3.9: An extract of farmers' knowledge on the effect of trees on soil moisture.

1: the density of trees is low causes the afonywie temperature is hot
2: an increase in density of trees causes an increase in moisture of soil
3: odoma causes an increase in moisture of soil
4: okro causes a decrease in moisture of soil
5: esan causes a decrease in moisture of soil
6: funtum causes a decrease in moisture of soil
7: an increase in density of trees causes an increase in enyunu of soil
8: the trees root length is deep causes water transfer soil surface
9: odoma_kokoo causes a decrease in moisture of soil
10:nyankyereni causes a decrease in moisture of soil
11:kokoaninsuo causes an increase in moisture of soil
12:trees shading soil causes an increase in enyunu of soil
13:the density of trees is high causes the afonywie temperature is not hot
14:kakapenpen causes a decrease in moisture of soil
15:keyja causes a decrease in moisture of soil
16:nnan_furo causes a decrease in moisture of soil
17:water transfer soil surface causes an increase in moisture of soil
18:abe causes an increase in moisture of soil
19:cocoa causes a decrease in moisture of soil

On cocoa diseases, a number of environmental factors were enumerated as having an influence on disease incidence (Figure 3.11). These include too much shade, excessive rainfall, poor ventilation, all of which encourage the incidence of capsids (*anunum*).

What was however not well articulated was the link between shade tree presence/density and pest infestation. This is more likely due to the fact that the interviews did not explore the topic well enough rather than a lack of knowledge on the part of farmers. There is therefore the need to do further knowledge exploration on this and other issues relating to the multi-strata cocoa systems in Ghana.

Trees were shown to be of enormous importance in the farming systems of Gogoikrom and Kyereyease in the Atwima district of Ghana, as it is in other parts of the country. The farmers had a strong belief that the presence of trees on their farms greatly enhances soil fertility. This fertility enhancement, they know, is brought about by increase in soil organic matter through litter fall and accumulation. They eloquently described how the tree leaves formed black layers in the soil and how the percolating rain water takes the rotting leaves into the soil. A number of tree species were identified as indicators of soil fertility.

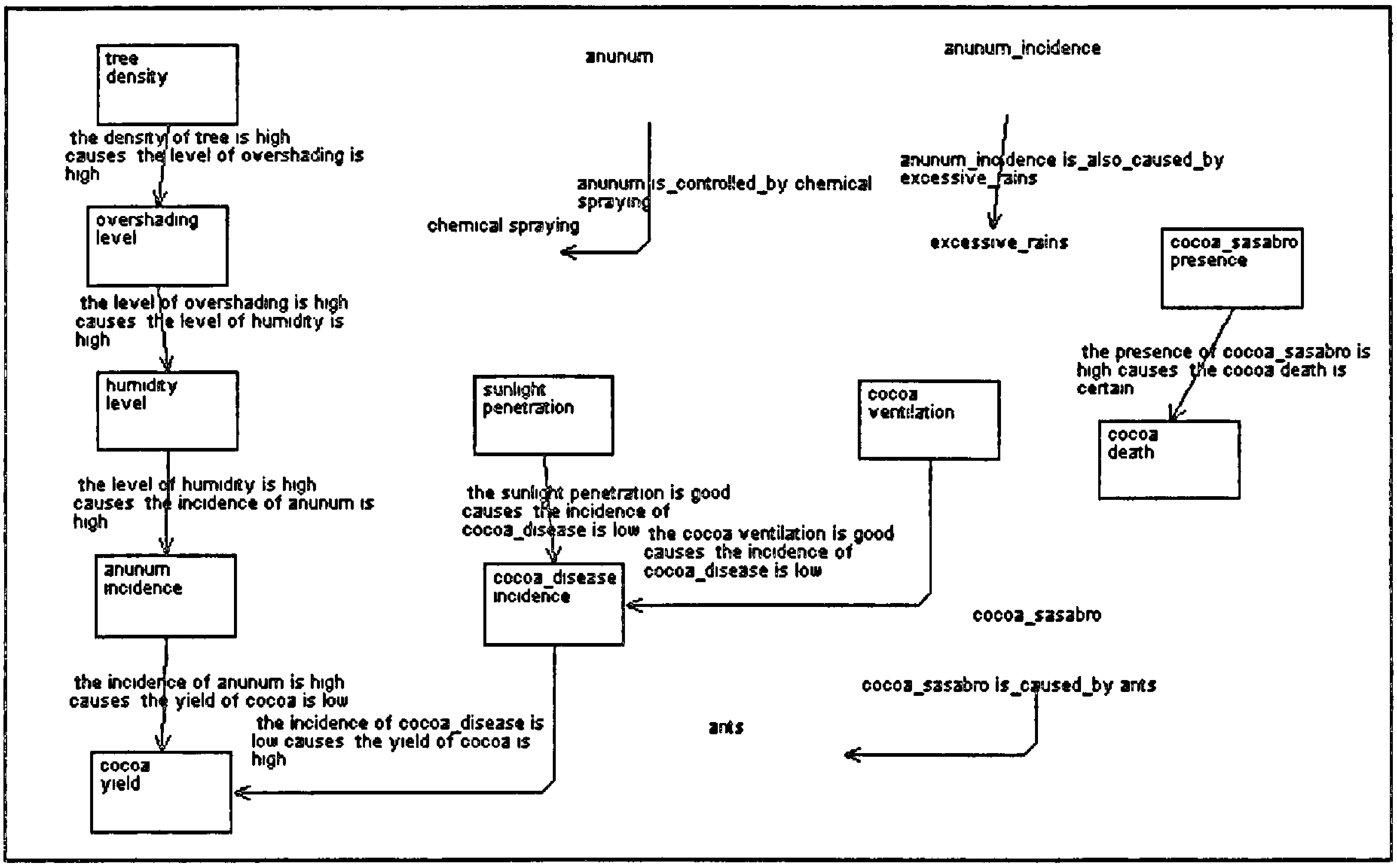


Figure 3.11: Farmers' causal knowledge of environmental factors influencing disease incidence in cocoa (generated from AKT). Legend as for Figure 3.8.

With regards to cocoa shade, the farmers displayed sound knowledge of the attributes of good shade trees and of the above-ground and below-ground interactions between the trees and the cocoa. Certain tree species such as *Celtis mildbraedii*, *Funtumia elastica*, *Ficus exasperate* and a host of others were said to dry out the soil around them and therefore tend to starve the cocoa crop of water, while others like *Spathodea campanulata*, *Albizia zygia*, *Ficus capensis*, and others, kept the soil around them moist and are thus highly desirable. The relationship between shade tree species and shade density on one hand and cocoa disease incidence was well articulated by farmers. Some species like *Alstonia boonei* and *Ficus exasperate* were said to be good habitats for the tree squirrel, which is a serious cocoa pest as it feeds on and destroys the cocoa pods. Other trees such as *Albizia zygia*, *Alstonia boonei*, *Triplochiton scleroxylon*, and others, were said to have brittle branches which tend to break easily and destroy the cocoa crop beneath them, although *Albizia zygia* and *Alstonia boonei* are considered as good cocoa shade trees. Such species are therefore eliminated as the cocoa matures and begin to fruit.

Shade trees were also described according to their socio-economic values. Majority of them however, were valued for their sawn wood (timber) quality, with a few of them maintained for their fruit and/or medicinal value. Others were also retained/desirable either for their soil nutrient/moisture enhancing qualities or purely for the quality of shade they provide. The decision to classify a tree as a good shade tree appeared however, to be greatly influenced by the socio-economic value of the tree, such as its value as a timber species, fruit tree, medicinal properties as well as some other value. Timber trees appeared to be valued the most because of their socioeconomic value; though past forest policies in the country, which vested total right of harvesting such trees in the government through the Forestry Service, served as a great disincentive for retaining/planting such trees on cocoa farms, as such a practice invariably led to the destruction of cocoa farms by commercial timber companies, who were granted timber harvesting rights by the Forestry Service, with little or no payment of compensation for the damaged cocoa crop.

With the change in forest policy which now gives farmers the right of use for trees growing or planted on farms, farmers are now more willing to retain such timber trees which provide quality shade for their cocoa as well as an economic potential for the farmer. This knowledge base was thus to help identify which trees farmers consider as good shade for cocoa, the attributes they look out for in deciding which trees to retain as shade, so as help in the selection of some species for field trials in a bit to encourage farmers to actively integrate shade tree planting into their cocoa production system. This knowledge base was more of a preliminary study of farmers' knowledge and will serve as basis for a more in-depth compilation, analysis and evaluation of a more comprehensive knowledge base on multi-strata cocoa agroforestry systems in the country.

CHAPTER 4

POPULATION STRUCTURE AND REGENERATION STATUS OF THE SELECTED TRIAL SHADE TREE SPECIES.

4.1. Introduction

In the study area, as in other parts of the country where cocoa is cultivated, planting of trees on cocoa farms for the purpose of providing shade for the cocoa is currently not normal practice. However, farmers generally recognise the importance of shade for cocoa establishment/cultivation. Therefore knowledge of the population density and population structure of the individual shade tree species will be of great importance in providing an insight into the natural regeneration potential of the preferred species based on which the species can be manipulated to provide the required products and services.

As with savannah ecosystems (Lykke, 1998), many tropical forest ecosystems have been affected by various human activities. An urgent need has therefore arisen for conservation measures and the adoption of sustainable use methods to avoid further degradation of natural resources (Sayer *et al.,* 1992; Myers, 1994). It has been pointed out that one main goal of forest ecology is to infer past changes and predict future changes in species composition (Hart *et al.,* 1989; Franklin *et al.,* 1993; Read *et al.,* 1995). Ecologists often use size distribution to indicate the health of a population. If there are large numbers of juveniles relative to adults, this is taken to indicate that a population is stable, perhaps growing, but a few juveniles can be seen as warning that the population is in decline (Condit *et al.,* 1998).

In forestry, forest management on a sustained yield basis requires information about diameter increment and growth pattern of individual tree species. However, because of the difficulties in measuring accurately total or even merchantable tree height of tropical trees, diameter at breast height has become the most important variable (da Silver *et al.,* 2002). In the tropics, the use of diameter distributions to project community change has been especially important in Africa (Condit *et al.,* 1998). Unfortunately, there are few studies from which the population dynamics of important species can be estimated (Obiri *et al.*, 2002).

4.1.2. Hypothesis and study objectives

The hypothesis for this study is that there is sufficient natural regeneration of the different shade tree species which could be managed for the rehabilitation of abandoned and degraded cocoa farms in Atwima district.

The main objective of the study, therefore, was to assess the population structure and regeneration status of the selected cocoa shade tree species in cocoa plantations, fallow land and natural forest. This information will provide a basis for an effective management of the species for the rehabilitation of abandoned and degraded cocoa lands and ultimately provide shade trees for re-establishing cocoa on deforested and degraded lands in Ghana.

4.2. Materials and Methods

Forest management on a sustainable yield basis requires information about diameter and growth pattern for individual tree species in addition to those related to forest stand productivity. Because of the difficulties in measuring accurately total or even merchantable tree height of tropical trees, diameter at breast height (DBH) has become the most important variable for allometric equations. Also diameter increment measurements have been used to examine the dynamics of natural forests as well as landuse changes. Besides, DBH is very easy to measure in the field without the risk of introducing non-sampling errors (da Silva *et al.*, 2002).

As pointed out by Campbell (1989), the amount of effort required to conduct an inventory is a function of minimum DBH. Smaller DBH's yield more information per unit area of forest, but usually limit the overall geographical sample size. Larger DBH's sample fewer juvenile trees, but enable a larger area to be sampled. Many ecologists have compromised by using a minimum DBH of 10 cm (Campbell, 1989). He recommended that a minimum DBH of 10 cm be employed in quantitative ecological inventory of tropical forests, as this will ensure the comparability of separate surveys and, given a sample of one or several hectares, will embrace most of the species of trees found in the forest. Hence this minimum DBH (10 cm) was adopted in this study.

A number of methods have been developed over the years for the assessment of plant population structure, some of them involving the use of sample plots and others employing plotless sampling techniques, as reviewed by Bowbow *et al* (1987) and Anderson and Ingram (1993).

However, since the study was not assessing total vegetation, but only looking at a few selected tree species, a 100% enumeration of the selected tree species was carried out on the cocoa farms, fallow land and in the natural forest.

Assessment of population density of the selected shade trees species in the natural forest was carried out in the Jimira forest reserve, near Bontomuruso, in November, 2002. The reserve was created in 1932 and been seriously affected by logging and fire damage; the logging in this reserve was in 1986 (Hawthorne and Abu-Juam, 1995), as at the time of this assessment. At the time of assessment only 91 ha of the reserve was considered not to have been affected by fire (Hawthorne and Abu-Juam, 1995), and it is in this area the the assessment was carried out. The area was stratified between three topographic positions (upland, mid-slope and lowland or lower slope). Three (3) plots of plots of 50 m x 50 m each were demarcated in different sections of each of the upland and mid-slope strata, while four plots were demarcated in the lowland stratum, using a 150 m tape and a compass. This resulted in ten 50 m x 50 m (2500 m^2) or 5 ha assessed. Each of the 50 m x 50 m plots was then divided into 5 m strips to give ten 5 m x 50 m strips. All individuals of the selected tree species with diameter at breast height (DBH) greater than or equal to 10 cm were enumerated by walking along, and measuring the diameters of trees, in each strip. The number of individuals recorded for each species in each 50 m x 50 m plot was used to estimate tree density for the different tree species in the forest.

For density of the selected tree species on fallow lands and cocoa farms, a 100% enumeration was carried out on 100 m x 100 m (one hectare) plots replicated five (5) times. Thus five hectares (5 ha) each of fallow land and cocoa farms were also assessed. The study was carried out in 12 – 14 old fallow land and 12 – 16 years old cocoa farms in and around Bontomuruso in the Atwima district of Ghana. Since fallows and farms of the above age category mostly did not occur contiguously plot location was dependent on the distribution of each of these land types in the area. Also, plot demarcation on cocoa farms tended to cut across a number of farms (at least 2), and not restricted to one farm ownership per plot due to the small nature of individual farm holdings. All the assessments were carried out in November – December 2002, at the end of the rainy season.

Density of the various candidate species with DBH $\geq$ 10 cm was then estimated directly from the total number of individuals of each species enumerated from each land type, and the total area sampled, using the following relationship developed by Curtis and McIntosh (1950):

$$\text{Density} = \frac{\text{Total number of individuals of the species enumerated}}{\text{Total area enumerated}}$$

To estimate regeneration status for each species at each site, the method described by Hett and Loucks (1976) was employed. This involved the random selection of trees of each species with DBH 20 cm. From each of these trees, radial distances of 40 m were circumscribed to produce circular plots. Four plots, representing 4 replicates, were laid out at each site and the numbers of seedlings and saplings around each of the central trees recorded. All trees <10 cm DBH and taller than 1.0m were recorded as saplings, while all plants with height not exceeding 1.0 m were recorded as seedlings. The densities of seedlings and saplings in each site were estimated from the total number of individuals of the species found and the total area examined (Curtis and McIntosh, 1950).

4.2.1. Data analysis

Data on the population distribution of the tree species in the different landuse systems was tested for normality, using the Kolmogorov-Smirnoff test in the Minitab Statistical package (Minitab 13). As the normality test showed that population distribution was normal for all the species, the mean population distribution of the species in the different landuse systems was analysed using the two-way ANOVA. Mean DBH distribution of the species species in the different landuse systems was also analysed, while regression analysis of the size class distribution (SCD) of all trees with DBH ≥10 cm was also performed to identify trends in SCD of the different shade tree species in the different landuse systems.

4.3. Results

4.3.1. Population distribution of mature shade tree species

Table 4.1 and Figures 4.1 to 4.7 show the size class distribution of all the shade tree species with DBH ≥10 cm in three (3) different landuse systems – mature cocoa farms, fallow land and natural forest.

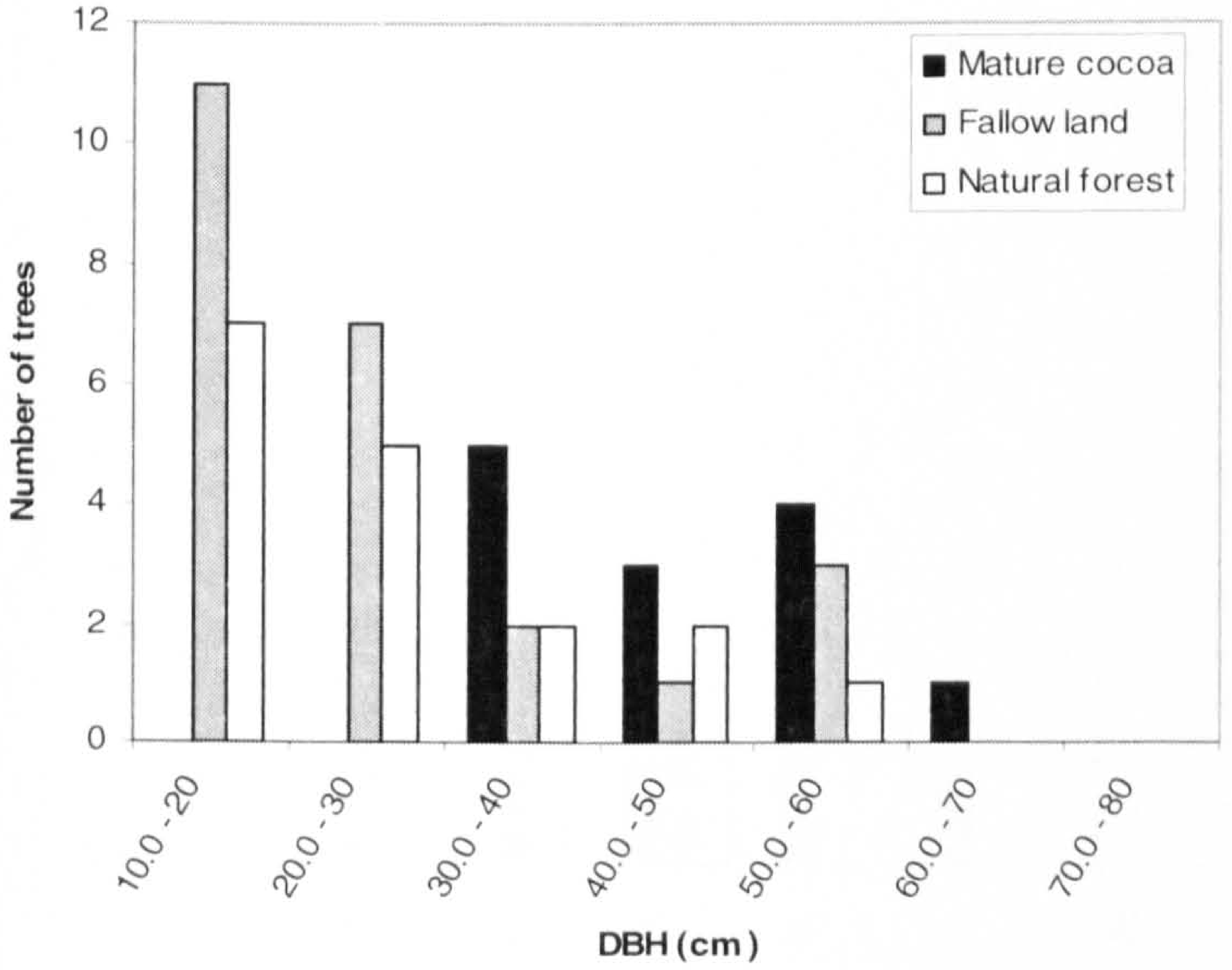


Figure 4.1: Size class distribution of *Albizia adianthifolia* trees in different landuse systems in Atwima: y-axis indicates number of trees in 5 ha sampling area (DBH≥10 cm).

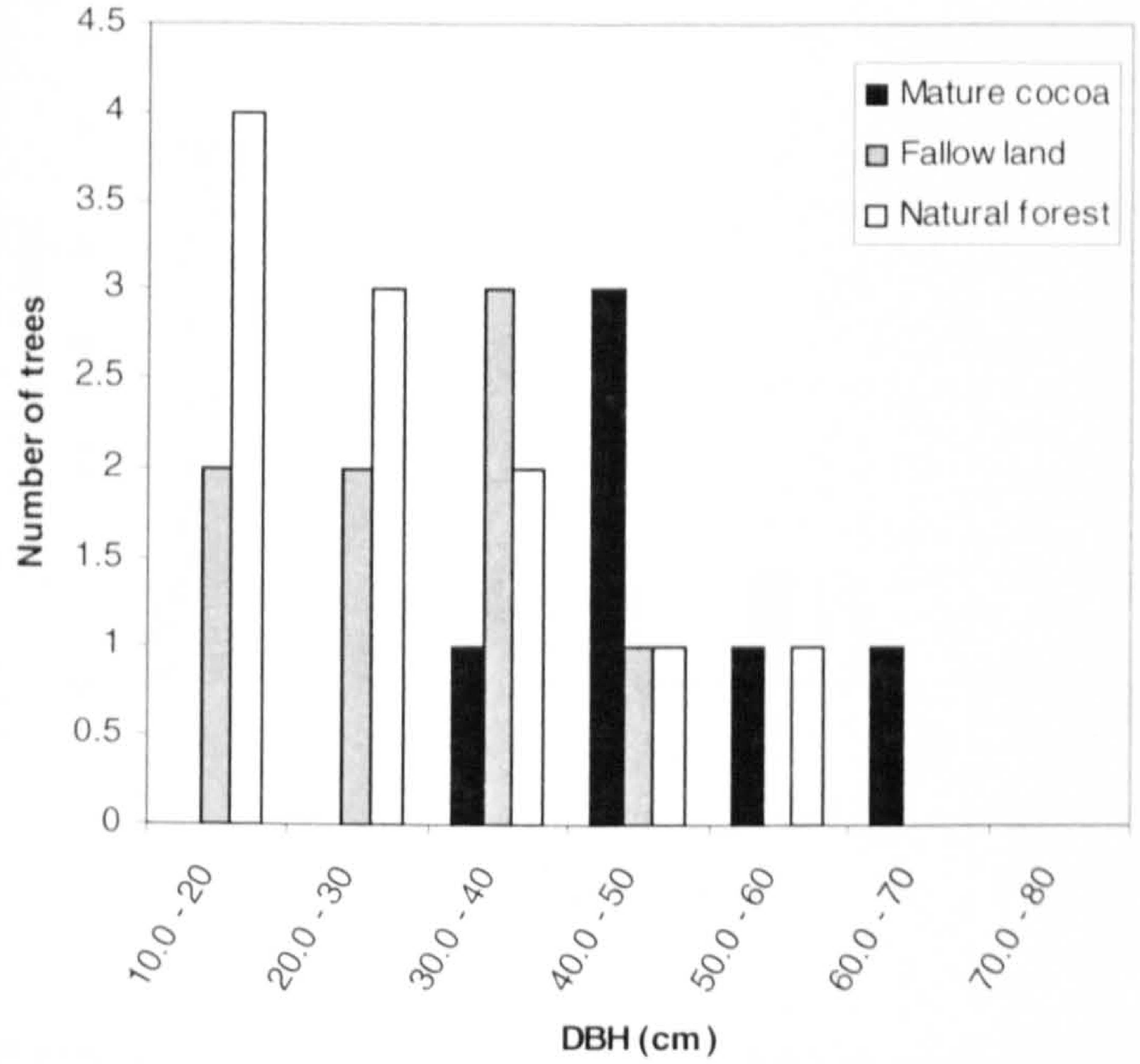


Figure 4.2: Size class distribution of *Entandrophragma angolense* trees (DBH≥10 cm) in different landuse systems in Atwima: y-axis indicates number of trees in 5 ha sampling area.

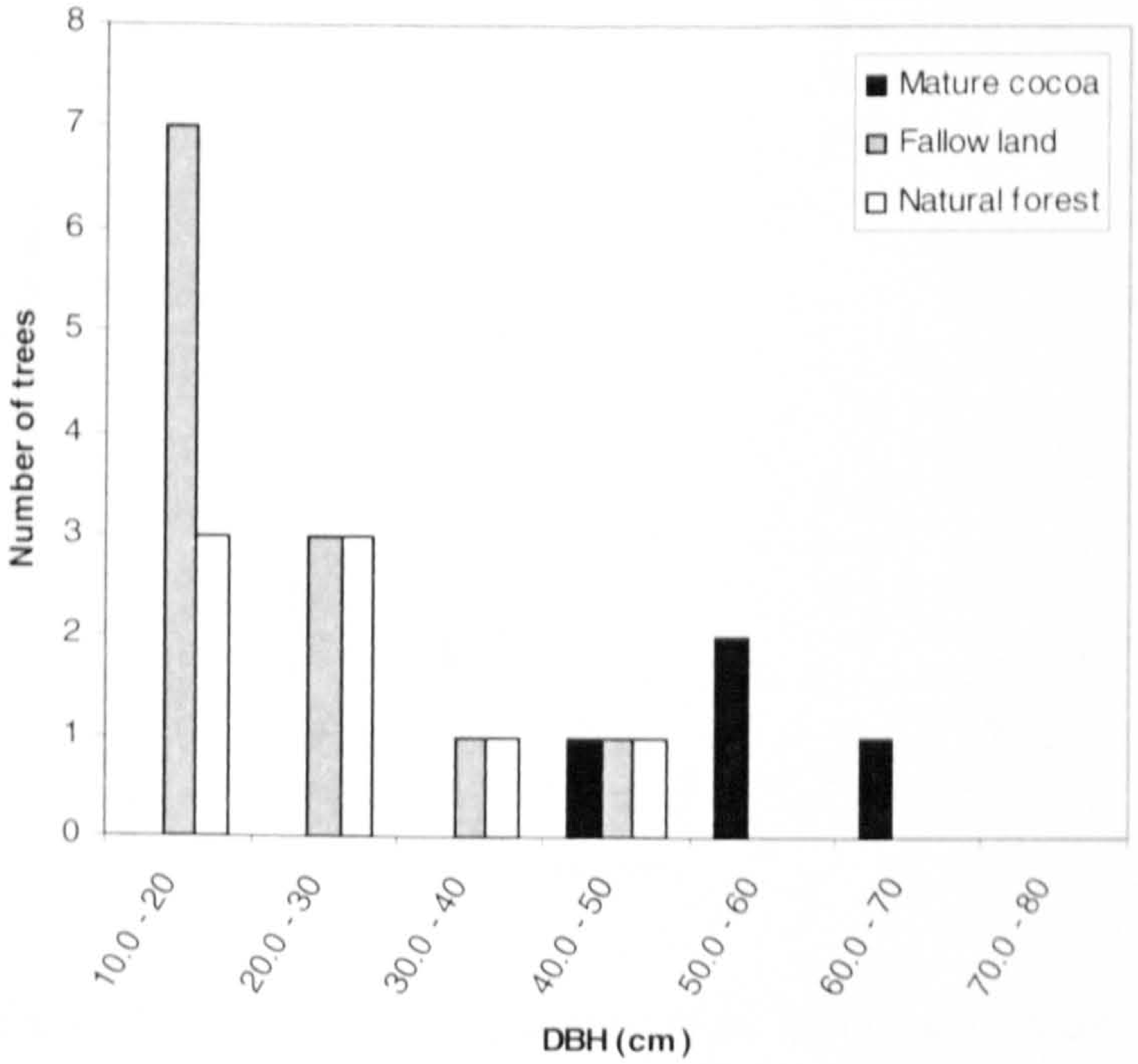


Figure 4.3: Size class distribution of *Entandrophragma utile* trees (DBH≥10 cm) in different landuse systems in Atwima: y-axis indicates number of trees in 5 ha sampling area.

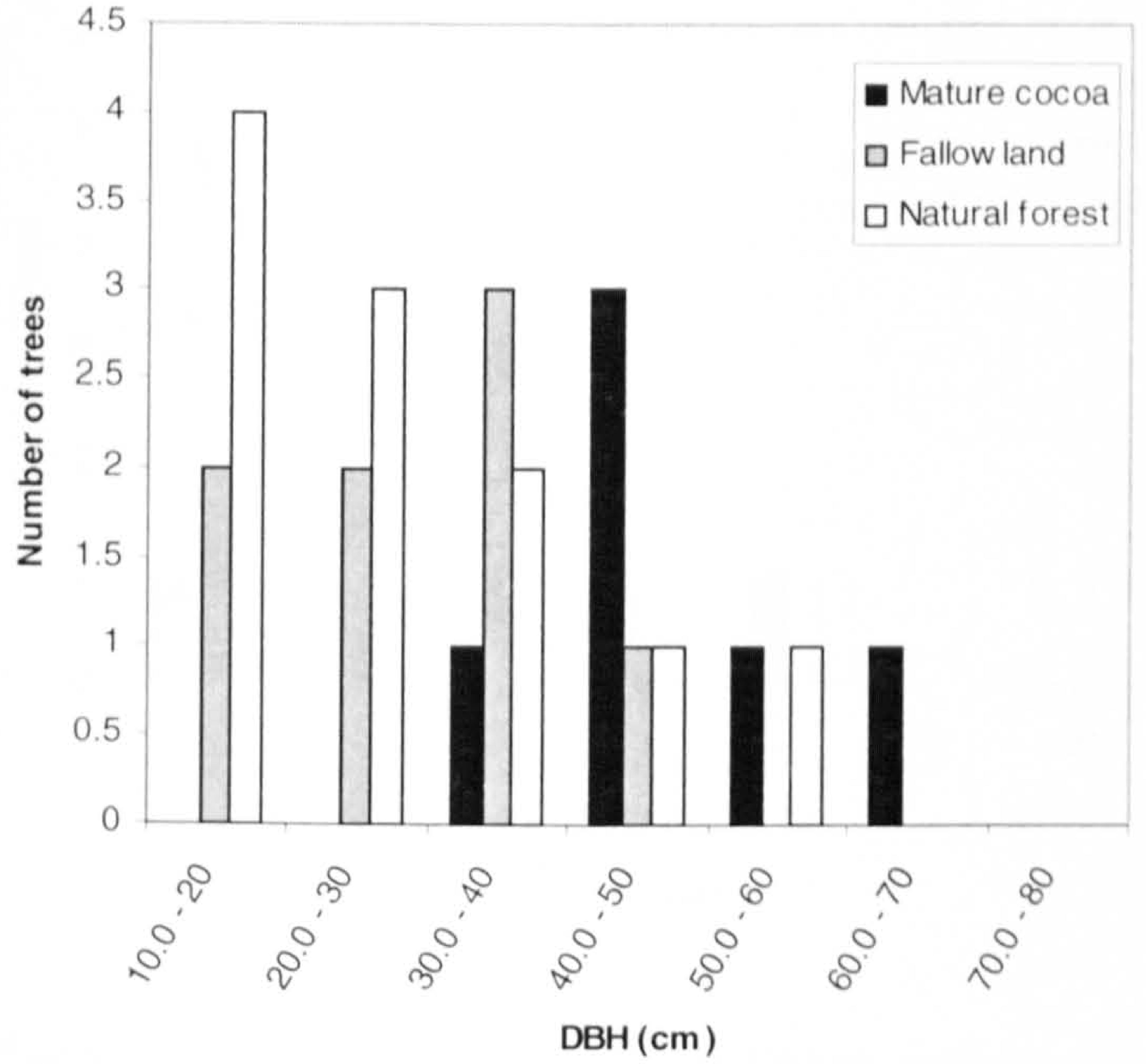


Figure 4.2: Size class distribution of *Entandrophragma angolense* trees (DBH≥10 cm) in different landuse systems in Atwima: y-axis indicates number of trees in 5 ha sampling area.

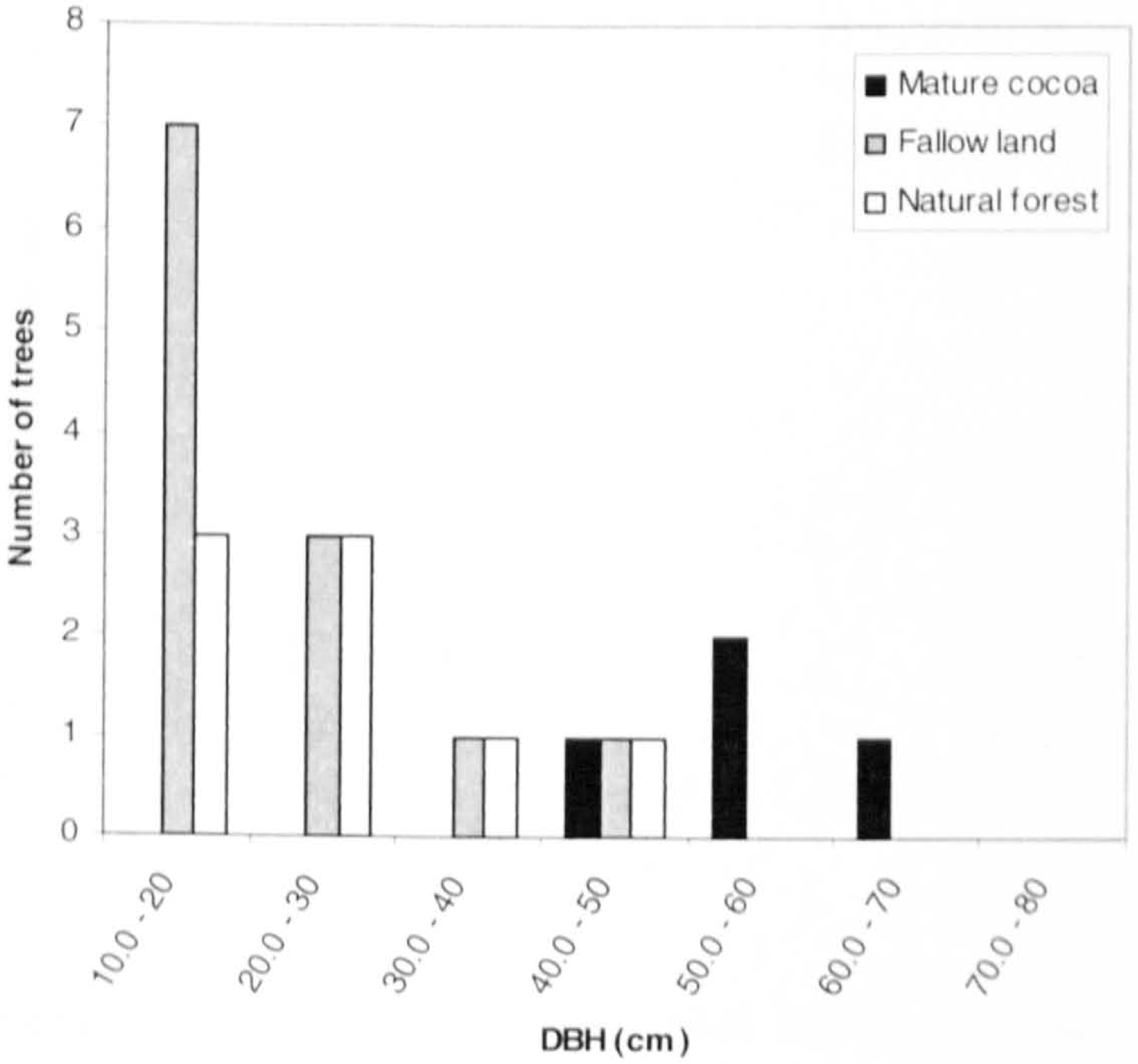


Figure 4.3: Size class distribution of *Entandrophragma utile* trees (DBH≥10 cm) in different landuse systems in Atwima: y-axis indicates number of trees in 5 ha sampling area.

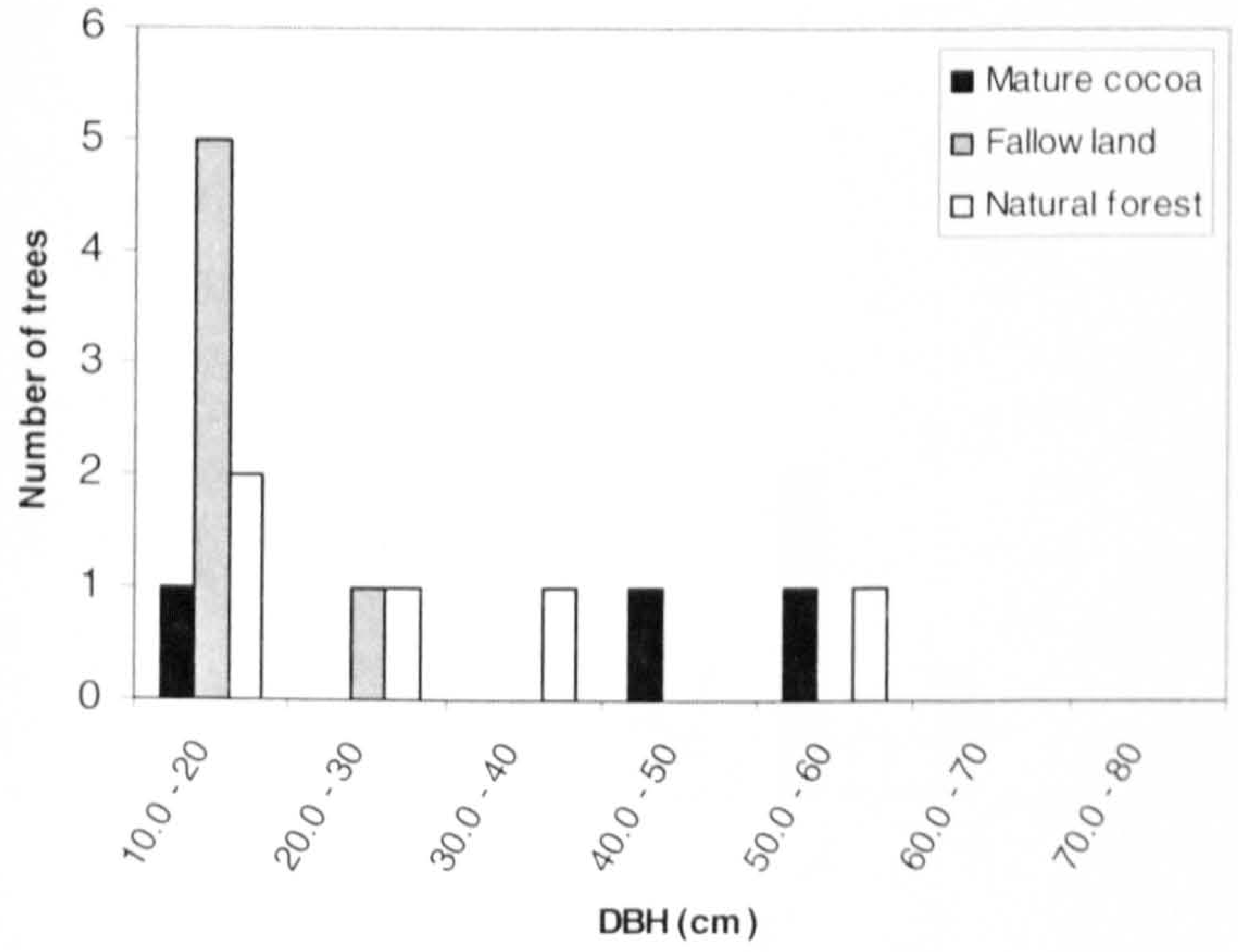


Figure 4.4: Size class distribution of *Khaya anthotheca* trees (DBH≥10 cm) in different landuse systems in Atwima: y-axis indicates number of trees in 5 ha sampling area.

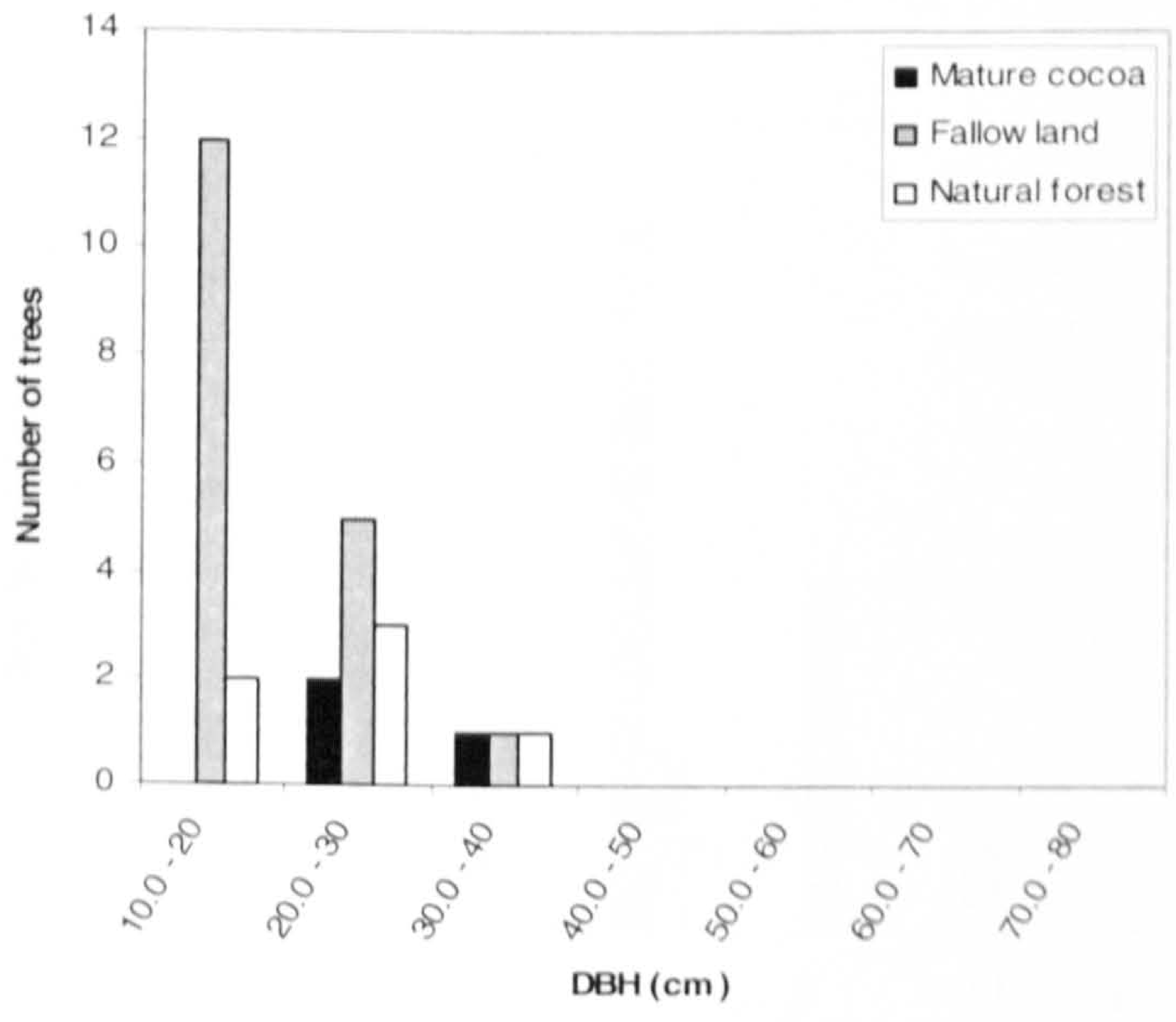


Figure 4.5: Size class distribution of *N. laevis* trees (DBH≥10 cm) in different landuse systems in Atwima: y-axis indicates number of trees in 5 ha sampling area.

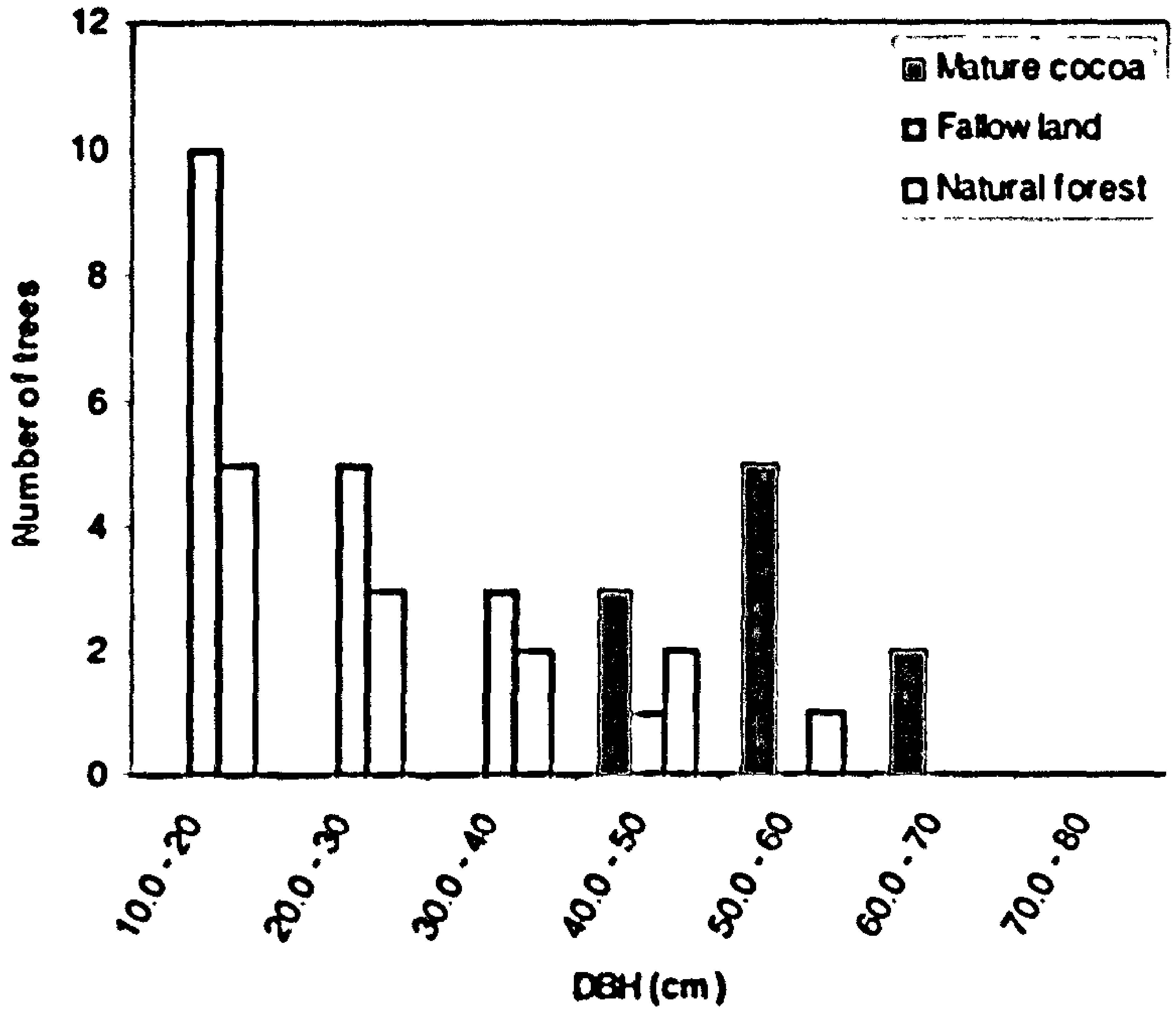


Figure 4.6: Size class distribution of *Terminalia ivorensis* trees (DBH≥10 cm) in different landuse systems in Atwima: y-axis indicates number of trees in 5 ha sampling area.

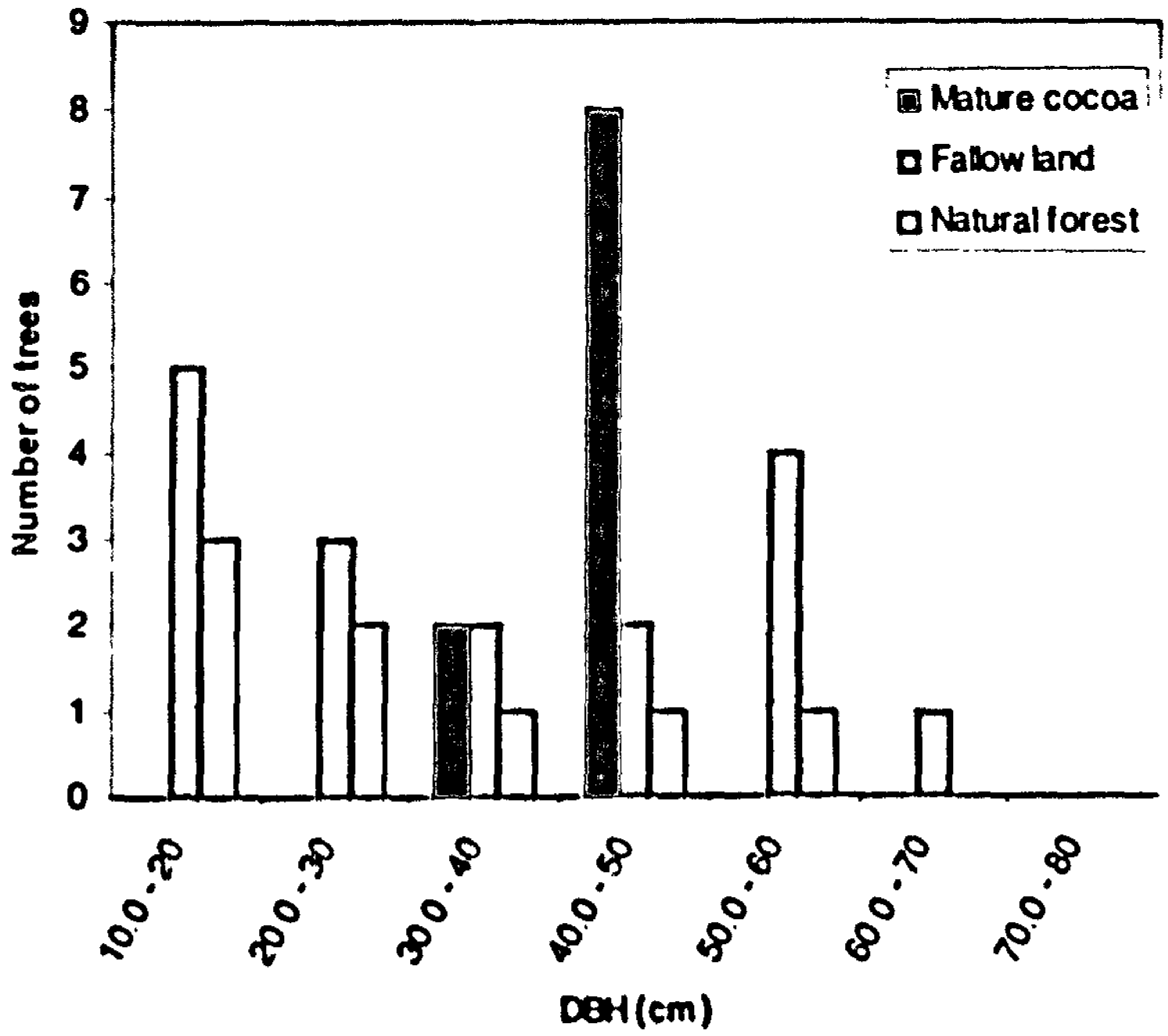


Figure 4.7: Size class distribution of *Tetrapleura tetraptera* trees (DBH ≥ 10 cm) in different landuse systems in Atwima: y-axis indicates number of trees in 5 ha sampling area.

The results show that a greater proportion of individuals in the higher diameter size classes of each species dominated the mature cocoa farms, with mean DBH of 45.40, 49.12, 55.75, 37.00, 26.63, 57.49 and 42.27 cm for *A. adianthifolia, E. angolense, E. utile, K. anthotheca, N. laevis, T. ivorensis* and *T. tetraptera* respectively. The fallow land on the other hand was dominated by trees in the lower diameter size classes, with mean DBH values of 26.08, 25.05, 19.02, 15.02, 18.78, 21.79 and 32.98 cm respectively, while intermediate size classes dominated the natural forest where the mean DBH for the seven species was 25.52, 27.68, 23.60, 29.32, 23.58, 28.55 and 29.00 cm respectively (Table 4.1). In all the three landuse systems, analysis of variance for mean DBH distribution showed that the cocoa farms contained significantly bigger trees than those found in the other two systems, while trees in the fallows were significantly smaller in size (P = 0.000) (Appendix 4.1). The exception was for *K. anthotheca, N. laevis* and *T. tetraptera* for which mean DBH distribution in the three systems was similar. Over the 5 ha area sampled in the study analysis of variance showed that mean population density of all the species was similar in the three landuse systems (Table 4.2), though all the species showed their highest density in the fallow lands with total densities of 24, 12, 6, 18, 19 and 17 trees for *A. adianthifolia, E. utile, K. anthotheca, N. laevis, T. ivorensis* and *T. Tetrapleura* respectively. The mature cocoa farms had the lowest density while intermediate densities of 17, 9, 5, 6, and 13 respectively for *A. adianthifolia, E. utile, K. anthotheca, N. laevis* and *T. ivorensis* were encountered in the natural forest.

In terms of mean densities/ha, *A. adianthifolia* appeared to be the most abundant species, with a mean density of 2.6, 4.8 and 3.4 trees/ha (i.e. 3, 5 and 4 trees/ha) respectively in the mature cocoa, fallow land and natural forest. *T. ivorensis, T. tetraptera* and *E. angolense* showed mean densities of 2, 4 and 3 trees/ha; 2, 3 and 2 trees/ha and 1, 1 and 2 trees/ha respectively in the mature cocoa, fallow land and natural forest. *E. utile* and *N. laevis* on the other hand had mean densities of 1, 2 and 1 trees/ha and 1, 4 and 1 trees/ha in mature cocoa, fallow land and natural forest respectively, while *K. anthotheca* had a mean density of 1tree/ha in all three landuse systems. All the species posted their highest densities in the fallow land, with the exception of *E. angolense* which showed highest mean density in the natural forest (Tables 4.1; and Figure 4.8).

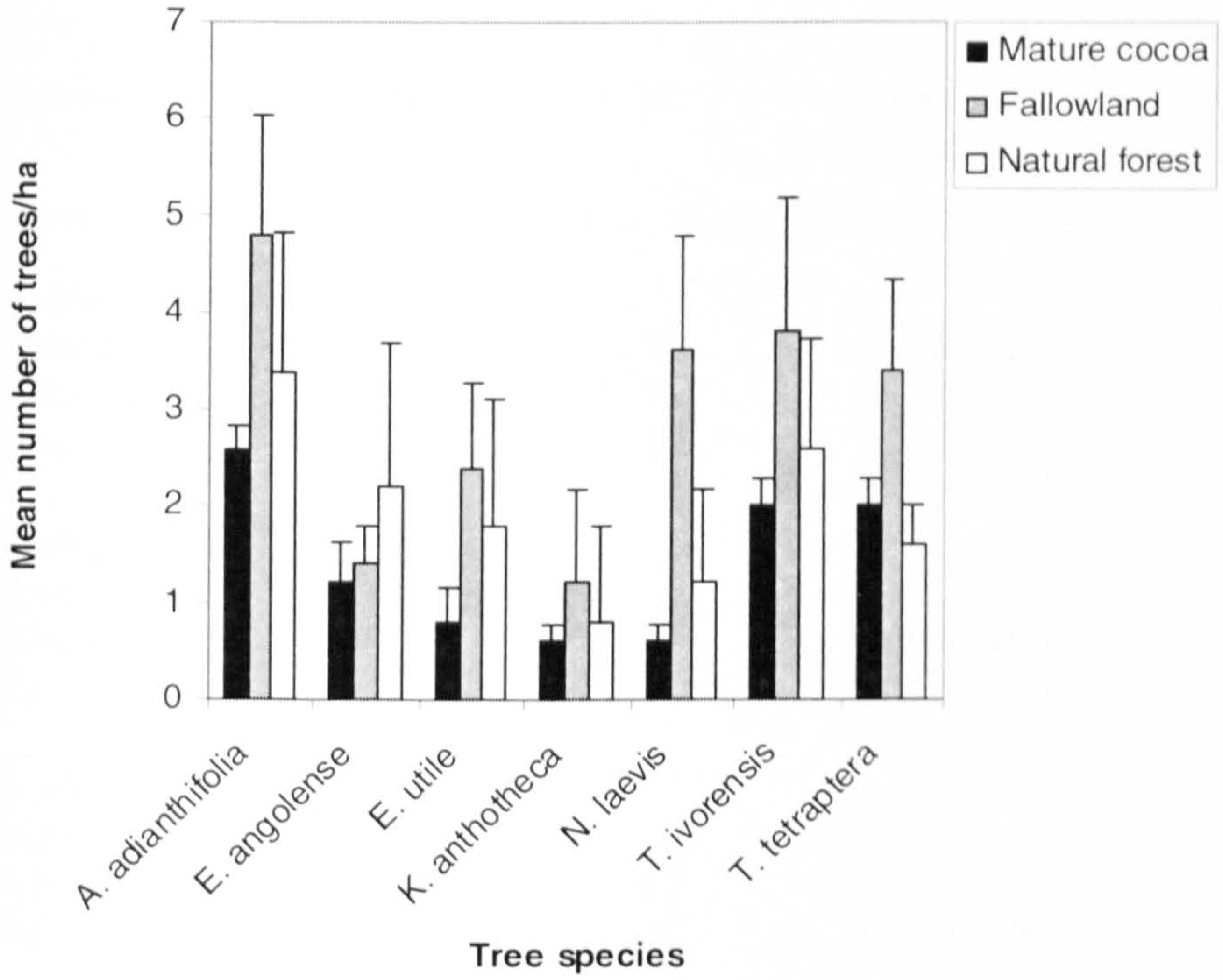


Figure 4.8: Mean population density of the shade tree species in different landuse systems in Atwima.

Table 4.1: Population distribution of the shade tree species with DBH ≥10 cm.

Species/Site	**Area (ha)**	**N**	**Mean DBH (±S.E.)**	**Trees ha^{-1} (Mean±S.E.)**
A. adianthifolia				
Mature cocoa	5	13	45.40(2.82)	2.60±0.23
Fallowland	5	24	26.08(2.98)	4.80±1.24
Natural forest	5	17	25.52(3.09)	3.40±1.44
E. angolense				
Mature cocoa	5	6	49.12(4.35)	1.20±0.43
Fallowland	5	8	25.05(4.08)	1.40±0.40
Natural forest	5	11	27.68(3.75)	2.20±1.50
E. utile				
Mature cocoa	5	4	55.75(3.50)	0.80±0.36
Fallowland	5	12	19.02(2.77)	2.40±0.87
Natural forest	5	9	23.60(3.79)	1.80±1.32
K. anthotheca				
Mature cocoa	5	3	37.00(12.90)	0.60±0.18
Fallowland	5	6	15.18(2.78)	1.20±0.97
Natural forest	5	5	29.32(6.88)	0.80±1.00
N. laevis				
Mature cocoa	5	3	26.63(2.72)	0.60±0.18
Fallowland	5	18	18.78(1.55)	3.60±0.97
Natural forest	5	6	23.58(2.16)	1.20±1.00
T. ivorensis				
Mature cocoa	5	10	57.49(1.98)	2.00±0.28
Fallowland	5	19	21.79(2.15)	3.80±1.39
Natural forest	5	13	28.55(3.90)	2.60±1.12
T. tetraptera				
Mature cocoa	5	10	42.27(1.65)	2.00±0.28
Fallowland	5	17	32.98(4.42)	3.40±0.93
Natural forest	5	8	29.00(5.94)	1.60±0.40

N = cumulative number of trees, with DBH ≥10 cm, observed within the 5 ha area sampled.

Table 4.2: ANOVA of shade tree species distribution in different landuse systems in Atwima, Ghana.

Mature cocoa farm

Source of variation	DF	SS	MS	F	P
Tree species	6	3.021	0.503	2.05	0.092
Error	28	6.866	0.245		
Total	34	9.886			

Fallow land

Source of variation	DF	SS	MS	F	P
Tree species	6	3.1735	0.5289	6.68	0.058
Error	28	2.2165	0.0792		
Total	34	5.3901			

Natural forest

Source of variation	DF	SS	MS	F	P
Tree species	6	2.472	0.412	0.81	0.571
Error	28	14.250	0.509		
Total	34	16.721			

4.3.2. Seedling and sapling population densities

The results in Table 4.3 show the seedling and sapling population of all the tree species in the different landuse systems. There was a relatively high density of seedlings of *A. adianthifolia* and *T. ivorensis* in the mature cocoa farms (102.5 and 60.5 respectively) and in the natural forest (62.50 and 50.00 respectively) compared with the other species, the only exception being seedling population for *N. laevis* in the fallowland (123.5). Sapling populations were generally low for all species, although *N. laevis* had a comparatively higher sapling population (20.0) than the other species. *A. adianthifolia* and *T. ivorensis* appear to have good seedling recruitment in all land types, with *T. Tetrapleura* showing moderate seedling recruitments. The other species, however, showed low mean seedling densities/ha in all landuse systems, and in the case of *N. laevis* no seedlings were encountered in the mature cocoa farms and the natural forest (Table 4.3 and Figure 4.9). The lowest overall seedling recruitment in all landuse systems was recorded for *K. anthotheca*, which posted only one seedling in the mature cocoa farm and only two seedlings each in the fallow land and the natural forest.

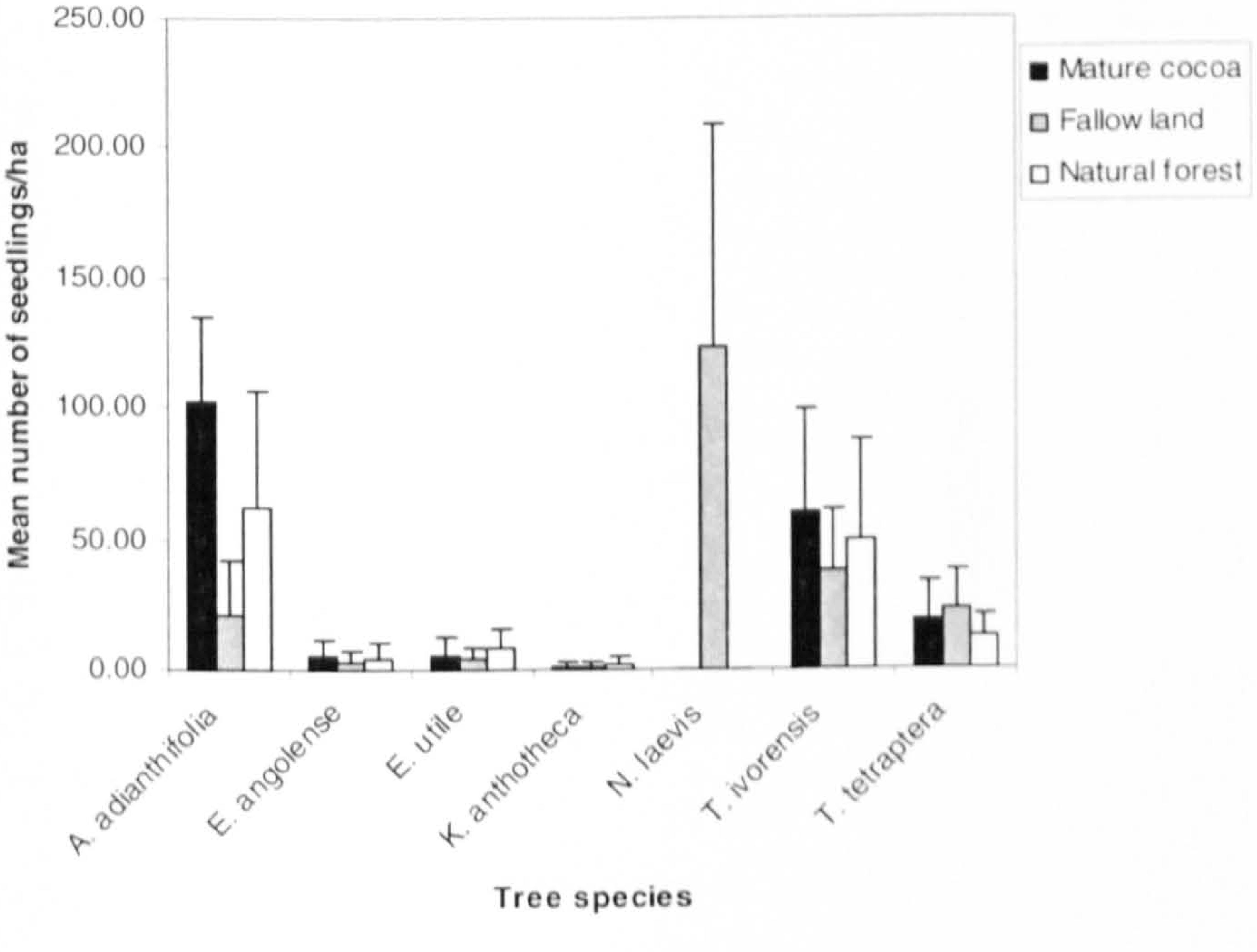


Figure 4.9 Mean number of seedlings/ha of the shade tree species in different landuse system in Atwima.

However, an analysis of variance (Table 4.5) indicated these differences in mean seedling densities/ha in the different landuse systems were not significant.

Sapling population densities/ha were generally low for all species compared to their seedling densities. The highest sapling population density of 20 saplings/ha was recorded for *N. laevis* in the fallow land, with *T. tetraptera* and *A. adianthifolia* recording 14.5 and 9.8 saplings/ha respectively in the fallow land. With the exception of *E. angolense* and *K. anthotheca* all the species recorded their highest sapling densities in the fallow land followed by the natural forest, and the lowest densities in the mature cocoa farms (Table 4.3 and Figure 4.10). In fact, no saplings of *K. anthotheca* were recorded in the mature cocoa farms and the fallow land, while no *N. laevis* seedlings were observed in the mature cocoa farms. In the case of *E. angolense* the highest mean sapling density was recorded in the natural forest while the lowest was recorded in the fallow land. Mean sapling population density/ha did not show any significant difference between the different landuse systems (Table 4.4).

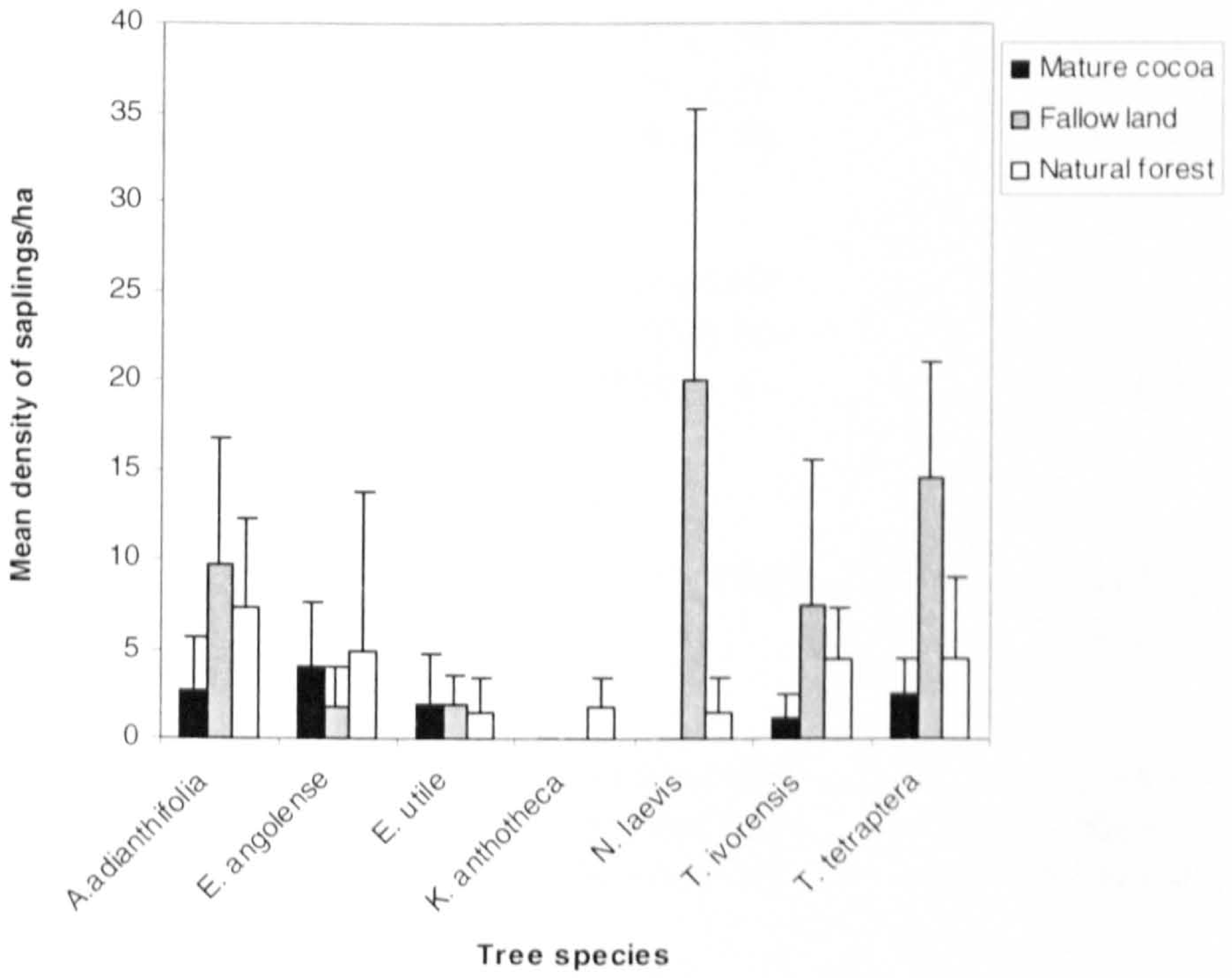


Figure 4.10: Mean density of saplings/ha of the shade tree species in different landuse systems in Atwima.

Table 4.3: Mean (±se) densities of seedlings and saplings of the shade tree species.

Species/Site	N	Seedlings/ha	Saplings/ha
		Mean ± s.e.	Mean ± se
A. adianthifolia			
Mature cocoa	4	102.50±16.17	2.75±1.44
Fallowland	4	21.00±10.79	9.75±3.47
Natural forest	4	62.50±21.76	7.25±2.50
E. angolense			
Mature cocoa	4	5.25±3.20	4.00±1.83
Fallowland	4	3.00±2.38	1.75±1.11
Natural forest	4	4.50±3.20	5.00±4.36
E. utile			
Mature cocoa	4	5.50±3.59	2.00±1.41
Fallowland	4	3.75±2.25	2.00±0.82
Natural forest	4	8.50±3.59	1.50±0.96
K. anthotheca			
Mature cocoa	4	1.00±1.00	0
Fallowland	4	1.50±0.96	0
Natural forest	4	2.00±1.41	1.75±0.85
N. laevis			
Mature cocoa	4	0	0
Fallowland	4	123.50±42.80	20.00±7.62
Natural forest	4	0	1.50±0.96
T. ivorensis			
Mature cocoa	4	60.50±19.40	1.25±0.63
Fallowland	4	38.50±11.30	7.50±4.03
Natural forest	4	50.00±18.60	4.50±1.44
T. tetraptera			
Mature cocoa	4	19.00±7.19	2.50±0.96
Fallowland	4	23.00±7.55	14.50±3.30
Natural forest	4	12.50±4.11	4.50±2.22

N = Number of circular quadrats
Sample plot size = 125.6 m^2

Table 4.4: Analysis of variance for number of seedlings versus Landuse and Trees species.

Source of Variation	DF	SS	MS	F	P
Landuse	2	355	177	0.16	0.858
Tree species	6	10509	1752	1.54	0.247
Error	12	13669	1139		
Total	20	24533			

Table 4.5: Analysis of Variance for number of saplings versus landuse and tree species.

Source	DF	SS	MS	F	P
Landuse	2	4.864	2.432	3.27	0.073
Tree species	6	6.219	1.037	1.39	0.293
Error	12	8.919	0.743		
Total	20	20.003			

4.3.3. Regeneration status of the selected shade tree species

Figures 4.11 and 4.12 shows the general population structure, and hence regeneration status, of the shade tree species in the different landuse systems. *A. adianthifolia*, *T. ivorensis* and *T. tetraptera* generally have good seedling recruitment in the mature cocoa, fallow land and natural forest, while that for the remaining four species appeared to be relatively poor, except for *N. laevis* which displayed very high seedling recruitment in the fallow land. With the exception of the Meliaceaes all the other species showed a common trend in their population structure with reducing numbers from seedling stage to adult trees, in all land types (Figure 4.12).

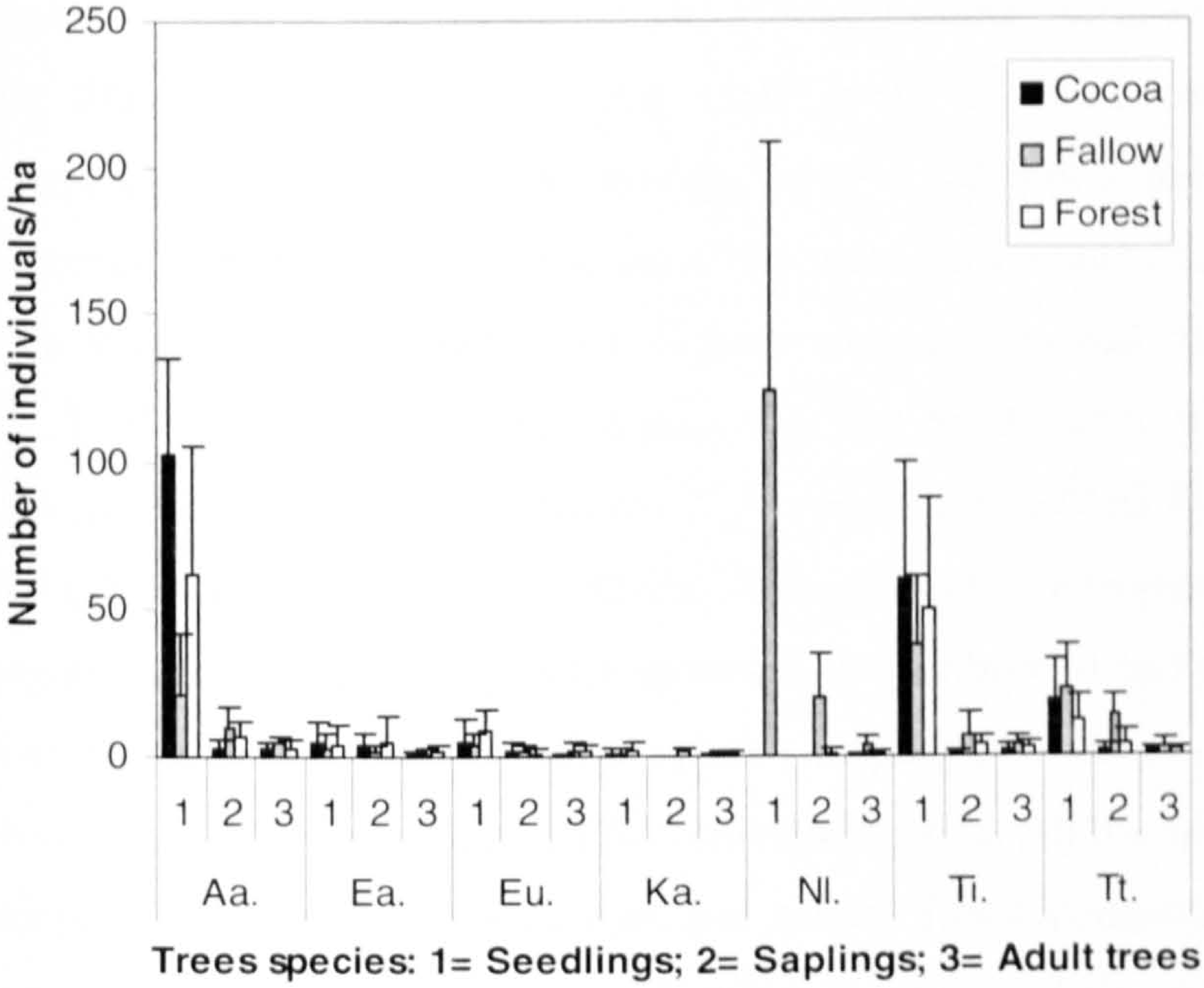


Figure 4.11: Population structure of the shade tree species in the different land types in Atwima (Aa. = *A. adianthifolia*; Ea. = *E. angolense*; Eu. = *E. utile*; Ka. = *K. anthotheca*; Nl. = *N. laevis*; Ti. = *T. ivorensis*; Tt. = *T. tetraptera*).

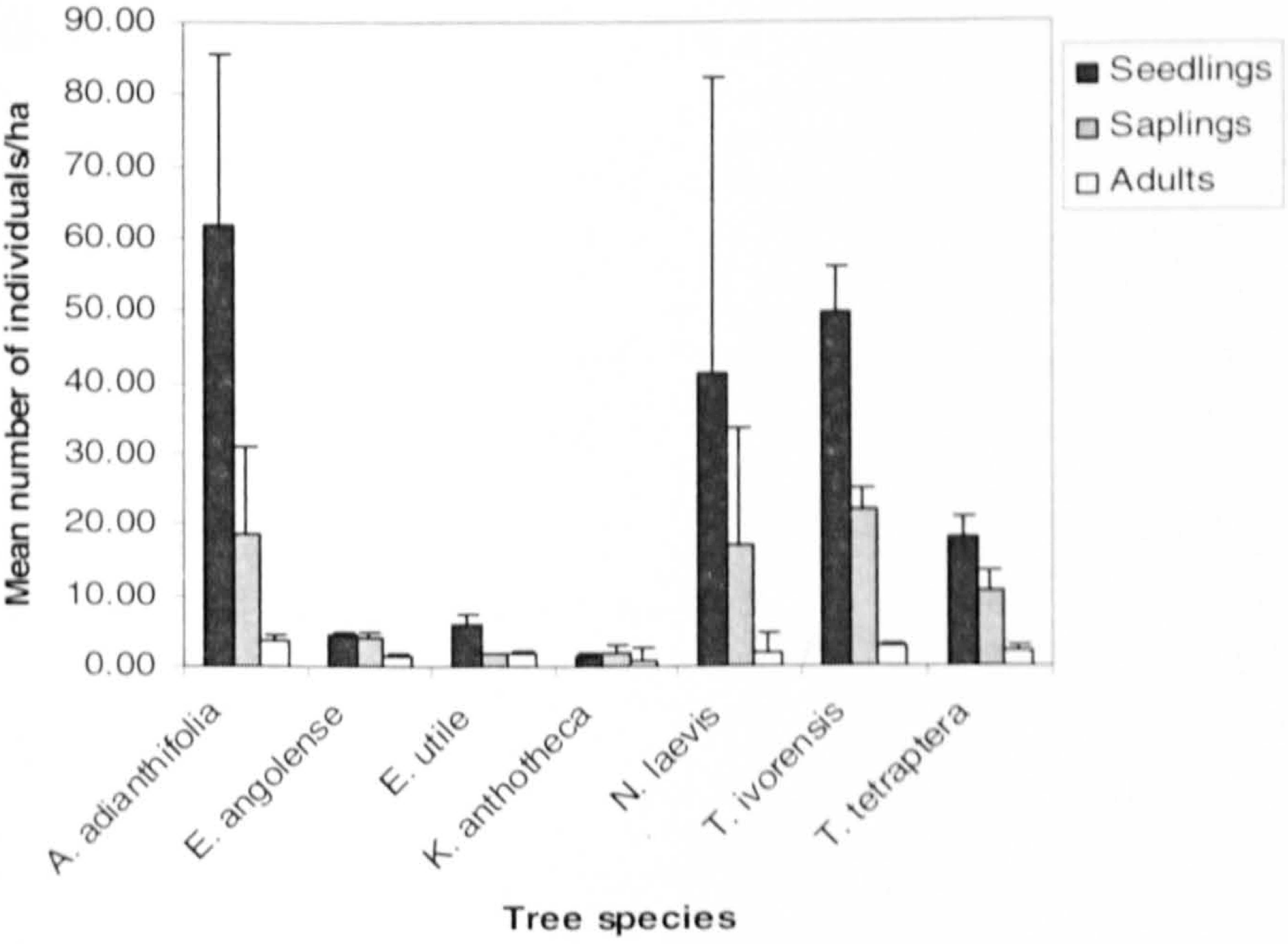


Figure 4.12: Mean population density of seedlings, saplings and adult trees of the different shade tree species in all three landuse systems in Atwima.

Figures 4.12 to 4.18 show the results of least-squares linear regression plots with the size class mid-points of the adult trees in the different land use systems as the independent variable and the average number of individuals in that class as the dependent variable. To obtain straight line plots the average of individuals in each size class was transformed by ln(N*i* + 1) since some classes had zero individuals (Obiri *et al.*, 2002). All the species had a relatively flat SCD slopes within the mature cocoa system, the highest being 0.014 for *T. ivorensis* and -0.0103 for *N. laevis* (Table 4.6). With the exception of *K. anthotheca*, *N. laevis* and *T. tetraptera* which showed weak negative slopes, indicating some decrease in numbers of individuals with increasing size, in this system all the other species displayed weak positive slopes, indicating some slight increase in numbers with increasing size. All the species showed relatively steeper SCD slopes in the fallows and natural forest compared to the mature cocoa system. In the fallows, however, *T. tetraptera* showed the weakest slope of -0.022, while the steepest slope of -0.043 was displayed by *N. laevis* and *T. ivorensis*. The weakest slope in the natural forest was posted by *K. anthotheca* with a SCD slope of -0.017, with *A. adianthifolia* showing the strongest SCD slope of -0.037 in this system. All the species in the fallowland and the mature forest, however, displayed negative adult trees SCD slopes, indicating decreasing numbers of individuals with increasing size classes.

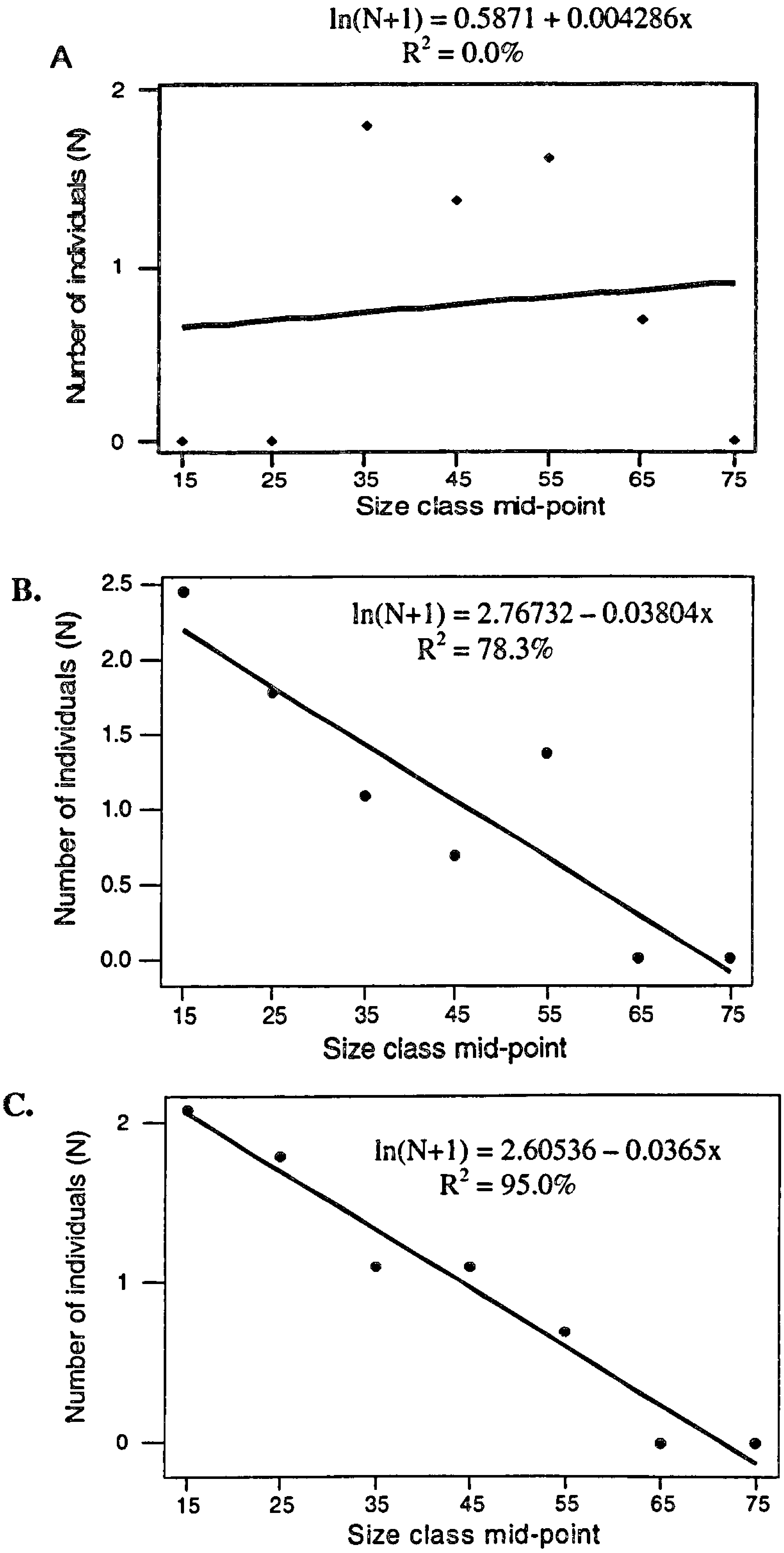


Figure 4.13: Regression plots of size class against mean number of individuals for adult trees of *A. adianthifolia* in: (A) Mature cocoa farms; (B) Fallow land; (C) Natural forest. Mean number of individuals (N) in each size class was transformed by ln (N + 1) since some classes had zero trees.

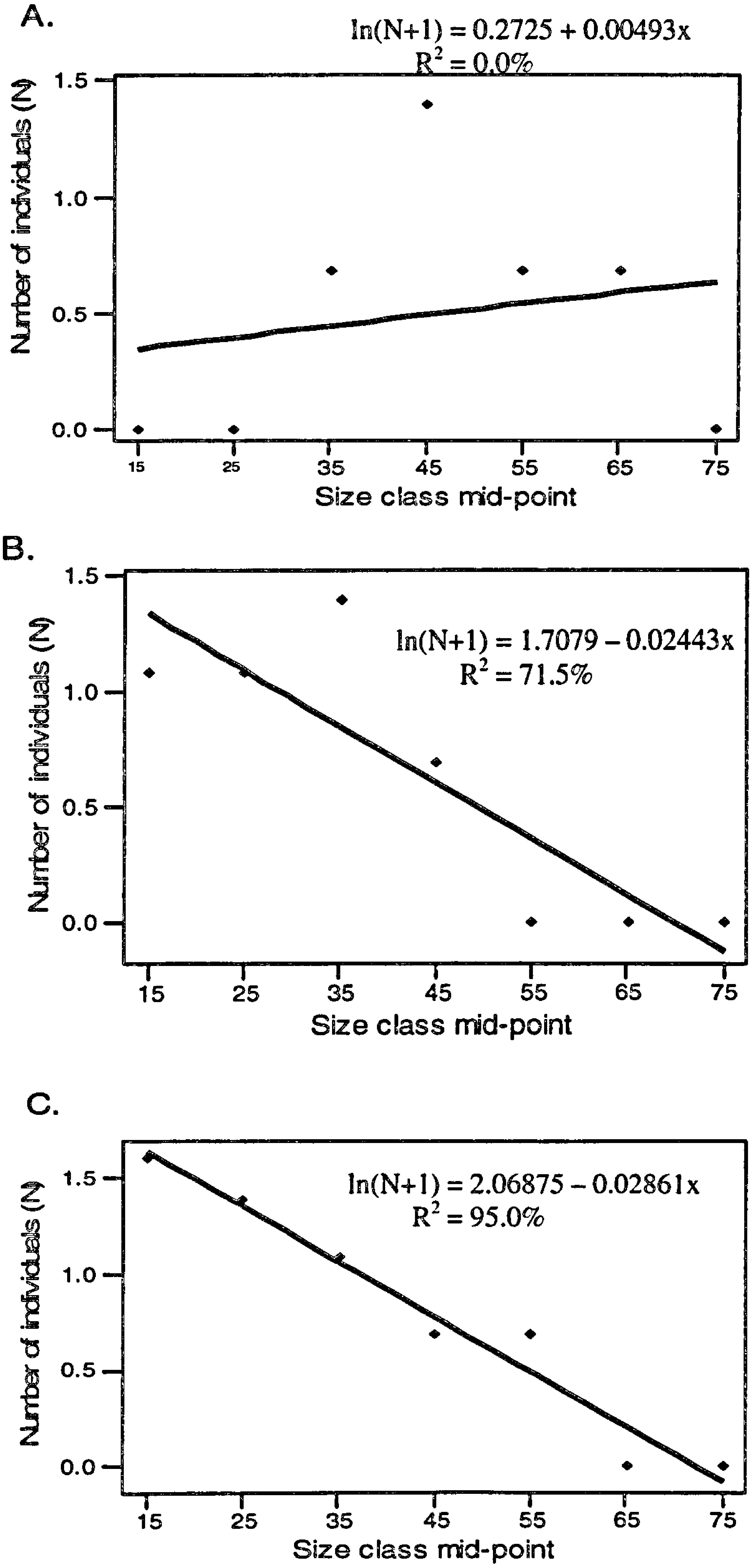


Figure 4.14: Regression plots of size class against mean number of individuals for adult trees of *E. angolense* in: (A) Mature cocoa farms; (B) Fallow land; (C) Natural forest. Mean number of individuals (N) in each size class was transformed by ln(N + 1) since some classes had zero trees.

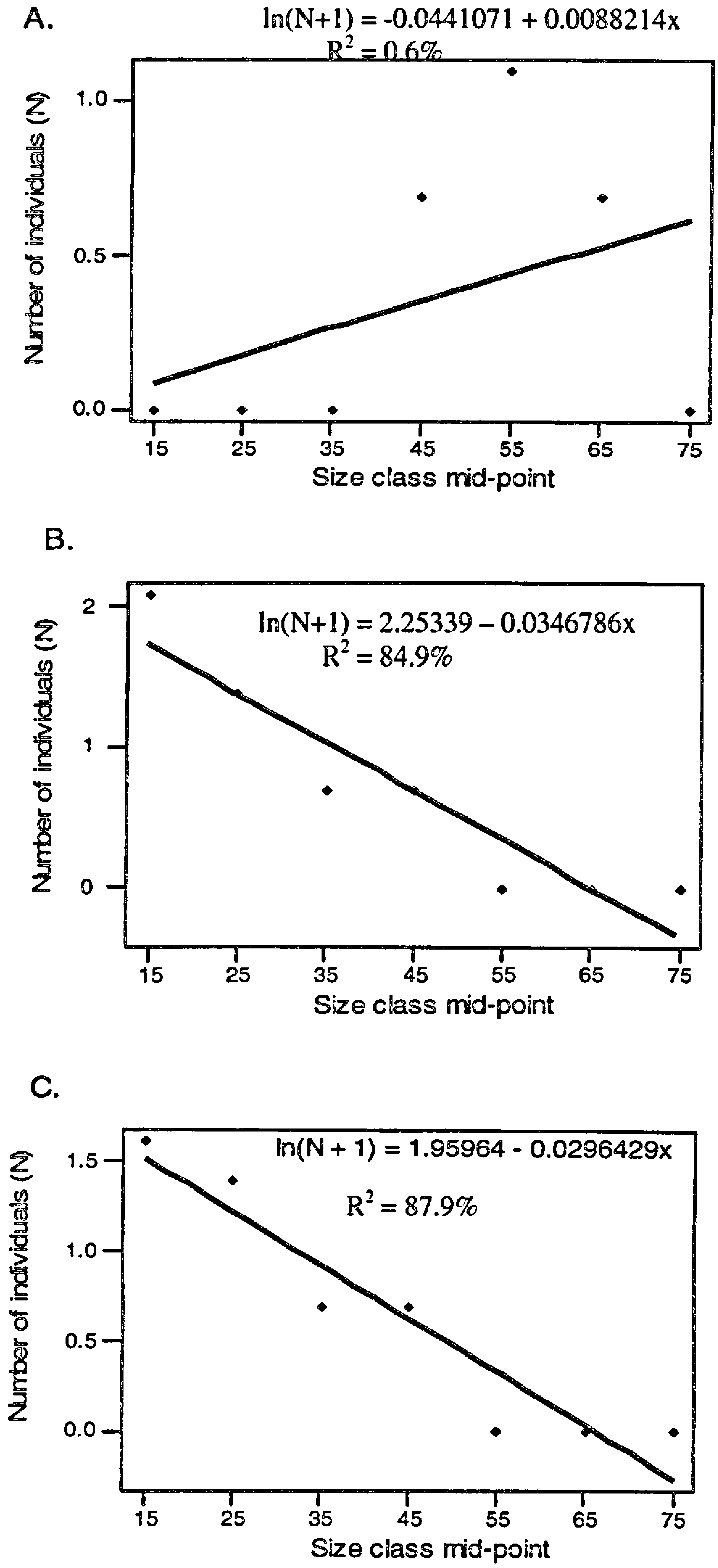


Figure 4.15: Regression plots of size class against mean number of individuals for adult trees of *E. utile* in: (A) Mature cocoa farms; (B) Fallow land; (C) Natural forest. Mean number of individuals (N) in each size class was transformed by ln(N + 1) since some classes had zero trees.

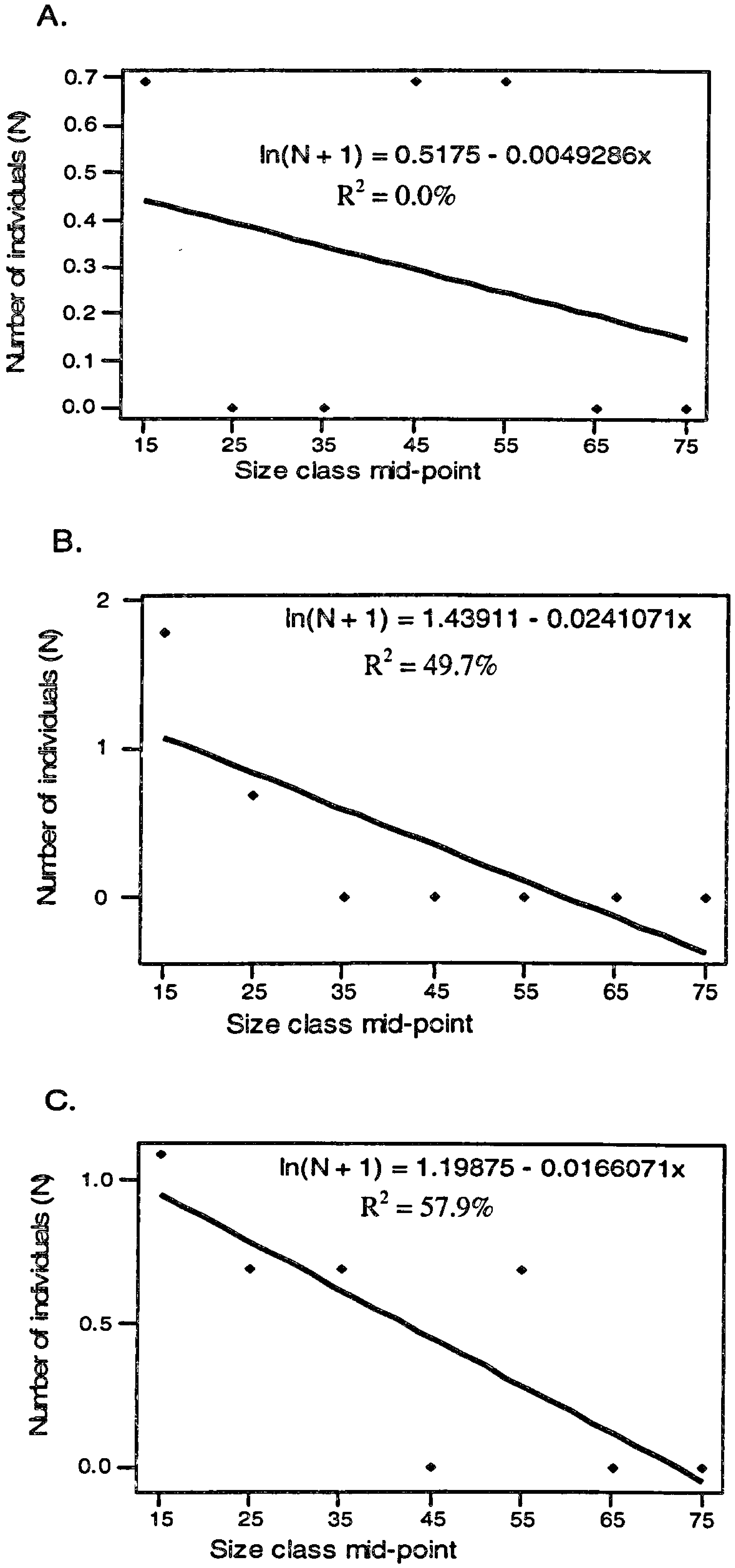


Figure 4.16: Regression plots of size class against mean number of individuals for adult trees of *K. anthotheca* in: (A) Mature cocoa farms; (B) Fallow land; (C) Natural forest. Mean number of individuals (N) in each size class was transformed by $\ln(N + 1)$ since some classes had zero trees.

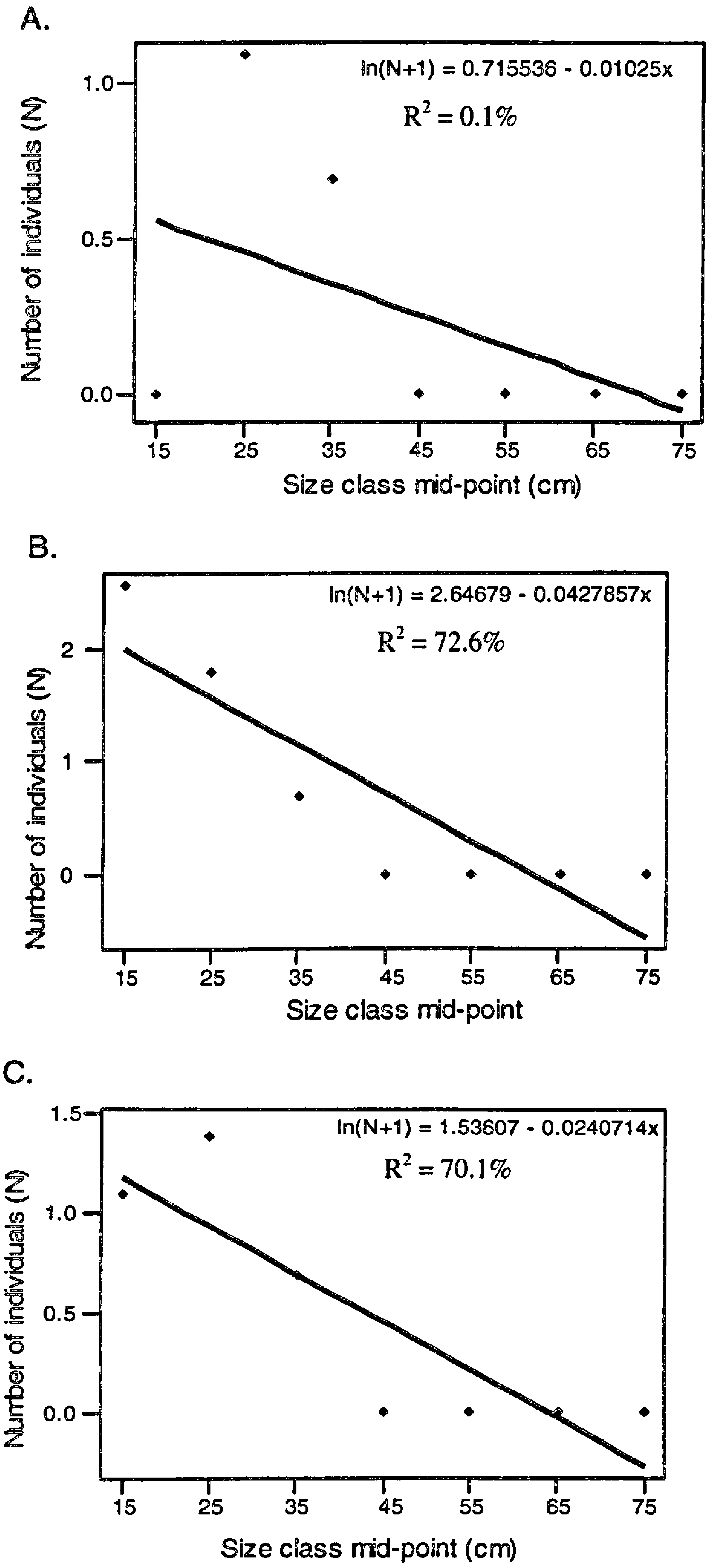


Figure 4.17: Regression plots of size class against mean number of individuals for adult trees of *N. laevis* in: (A) Mature cocoa farms; (B) Fallow land; (C) Natural forest. Mean number of individuals (N) in each size class was transformed by ln(N + 1) since some classes had zero trees.

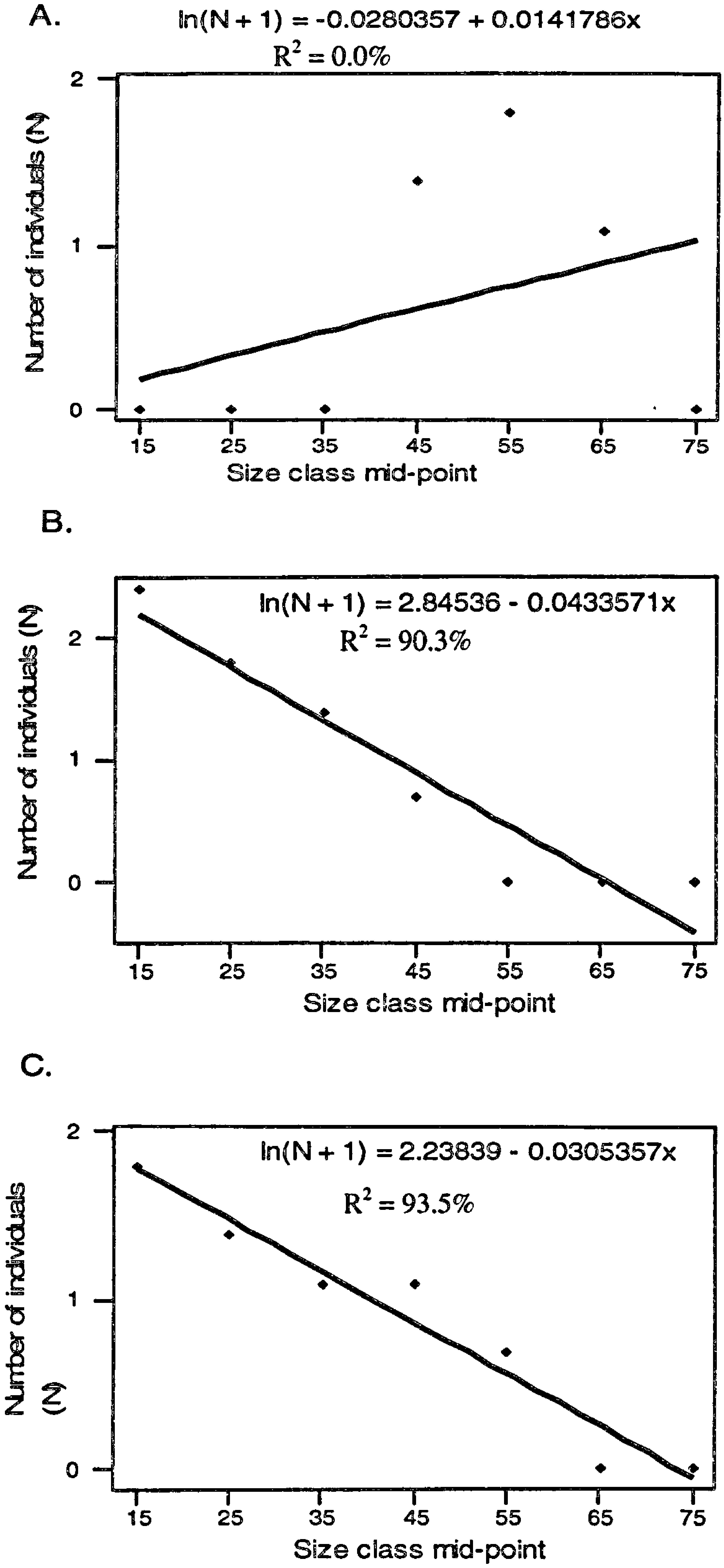


Figure 4.18: Regression plots of size class against mean number of individuals for adult trees of *T. ivorensis* in: (A) Mature cocoa farms; (B) Fallow land; (C) Natural forest. Mean number of individuals (N) in each size class was transformed by ln(N + 1) since some classes had zero trees.

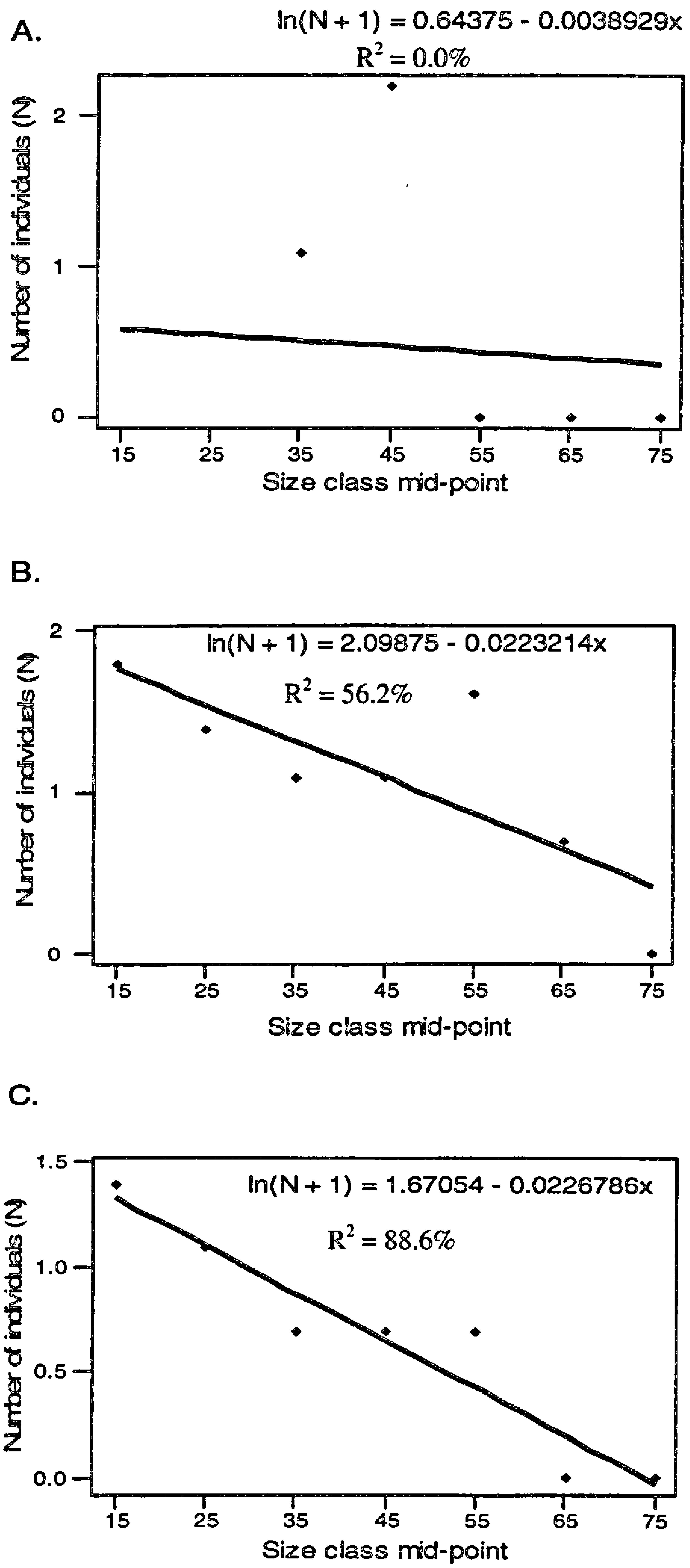


Figure 4.19: Regression plots of size class against mean number of individuals for adult trees of *T. tetrapleura* in: (A) Mature cocoa farms; (B) Fallow land; (C) Natural forest. Mean number of individuals (N) in each size class was transformed by ln(N + 1) since some classes had zero trees.

Table 4.6: Regression slopes of adult tree (DBH ≥ 10cm) size class distributions of the shade tree species in the different land use systems in Atwima.

	Adult Size class distribution slopes		
Species	**Cocoa**	**Fallow**	**Forest**
A. adianthifolia	0.004	-0.038	-0.037
E. angolense	0.005	-0.024	-0.029
E. utile	0.009	-0.035	-0.029
K. anthotheca	-0.005	-0.024	-0.017
N. laevis	-0.0103	-0.043	-0.024
T. ivorensis	0.014	-0.043	-0.031
T. tetraptera	-0.004	-0.022	-0.023

4.4. Discussion

The density of trees, saplings and seedlings, together with the relative distribution of individuals in different size classes, as shown in Figures 4.1 – 4.12 and Tables 4.1 – 4.3, facilitate the assessment of the population structure and regeneration potential of the tree species in any one particular site. From the results obtained, the pattern of the population structure and regeneration status of the different shade tree species in the different landuse systems is summarised and discussed as follows.

4.4.1. Mature cocoa farm

It was observed that the population of all the shade tree species on the mature cocoa farms is made up of individuals in the higher diameter class, and of seedlings. Lower diameter trees were absent while sapling population here was virtually insignificant. The absence of saplings here may be attributed mainly to weed control measures and canopy closure, which inhibited regeneration. For instance, Hawthorne (1995) observed that for *A. adianthifolia* seedlings are quite common in the shade while saplings are almost exclusively found exposed to sun, i.e. in the open.

The larger size class distribution of the species in the mature cocoa farm can also be attributed to the cocoa management system, which begins with the selective thinning of the original forest stand to leave a few large desirable tree species as shade for the developing cocoa. Subsequent regeneration of tree species is considered as weed growth and they are therefore removed during weeding, or under natural circumstances they may not persist due to the heavy shading from the cocoa canopy.

The pattern of regeneration observed here has significant implications for the continuity of the species in the area, and the conclusion that might be drawn would be that of a population in decline (Knight, 1975), judging from the very low or negligible sapling populations and the near flat size class distribution (SCD) slopes of adult trees for all the species in this system. This conclusion is supported by Auclair and Cottam (1971), Horn (1976) and Austin (1977) who have all stressed the importance of the presence of saplings under adult trees for the future composition of a community. Lykke (1998) also indicated that flat SCDs can indicate a lack of rejuvenation and declining populations. Though Condit *et al* (1998) did point out that flat SCDs could be caused by a number of other factors, including; (i) rapid growth in small size classes and (ii) high survival rate overall, non of these factors are applicable in this case as indicated by the near absence of saplings. The positive SCD slopes encountered for most of the species in this system amply indicate the fact that there are fewer individuals in the lower DBH classes than in the higher classes; an indication of lack of natural regeneration of the shade tree species here.

In terms of species composition on cocoa farms *A. adianthifolia*, *T. ivorensis* and *T. tetraptera* appeared to be the most common shade tree species encountered among the seven trial species. *E. utile*, *K. anthotheca* and *N. laevis* were virtually absent here. The preference for *Albizia adianthifolia*, *Terminalia ivorensis* and *Tetrapleura tetraptera* on cocoa farms may be attributed to their growth habits, which conform to the attributes of good shade trees described by farmers in chapter 3, i.e. light crowns (for *Albizia* and *Tetrapleura*) and high crown (for *Terminalia*) both of which attributes ensure good air circulation underneath. This is necessary to prevent humid conditions and lower the risk of pest and diseases within the cocoa crop. *Albizia* and *Tetrapleura* have light, spreading crowns, while *Terminalia* has a high spreading crown.

Tetrapleura tetraptera is further preferred and maintained on cocoa farms for its fruits which are valuable for their food (they serve as very good spice for cooking for the local communities) and medicinal value.

4.4.2. Fallowland

There was a relatively good recruitment of seedlings in the fallows, though sapling populations tended to be much lower than that of the seedlings. With the exception of the *Entandrophragmas* and *Khaya anthotheca*, which all recorded low seedling and sapling densities, all the other species recorded relatively high seedling densities. This would appear to contradict the findings of Hopkins (1983) who pointed out that seed-borne regeneration of woody and herbaceous species is rarely a major mechanism of secondary succession. Swaine (1992) also reported that seed-borne regeneration is often unsuccessful in dry forests in Ghana, and that most species show a strong capacity for regrowth vegetatively. This seeming discrepancy may be explained by the fact that during the assessment of the regeneration status of the tree species a distinction was not made between seedlings/saplings originating from seed and those originating from coppice stools. It is therefore likely that of the populations of seedlings and saplings recorded for the different species a substantial proportion originated through coppicing. However, the fact that the fallows were relatively old (14 – 16 years) means that they have become secondary forests with some appreciable level of canopy development. This could also possibly contribute to enhancing seed-borne regeneration within this system.

Mean size class (DBH) distribution here was the lowest among all three landuse systems, ranging from the low of 14.6 cm for *K. anthotheca* to the high of 33.25 cm for *T. tetraptera* (Table 4.1). The larger mean DBH recorded for *T. tetraptera* can be attributed to the fact that trees of this species, as well as *N. laevis*, are usually left standing during land clearing for cultivation. This is corroborated by Hall and Swaine (1981). Thus the fallows tend to contain bigger diameter trees of these species as remnants of the old farm. The lower mean DBH of the tree species in this system, compared to the mature cocoa and the natural forest, however, may indicate the relative degree of protection or sheltering from disturbance that the species enjoy at the latter sites.

On the regeneration status of the tree species, the Meliaceaes (*Entandrophragmas* and *Khaya*) appear to have very poor rejuvenation and to be under threat of extinction in this area, with very low seedling and sapling recruitments and subsequently very low density of adult trees (Tables 4.1 and 4.2). *K. anthotheca* particularly had no saplings and an average of only 1 adult tree/ha in this landuse system. Even though it was observed that the 3 species have relatively steeper adult tree SCD slopes than *T. tetraptera* in the fallowland (Figures 4.12 to 4.18 and Table 4.7), their seedling, sapling and adult tree populations were found to be generally very low (Figure 4.11), and thus indicate a lack of regeneration and declining populations of these species within this landuse system, as pointed out by Lykke (1998). Condit *et al* (1998) also pointed out that large numbers of juveniles relative to adults is an indication that a population is stable, perhaps growing, while a few juveniles can be seen as a warning that the population is in decline. The reason for this low recruitment rate in the fallows may be due to the very low density of adult (seed bearing) trees of these species in the nearby Jimira Forest reserve. This is quite uncharacteristic of these species in this vegetation zone (Moist Semi-deciduous North West subtype) where Hall and Swaine (1981) found the species to be more abundant than in other vegetation zones. A possible reason for this may be due to the logging activities by local illegal chainsaw operators who operate in this area and who persistently fell mature trees of these species for their valuable timber, thus eroding the area of the requisite seed source for these tree species. This low regeneration potential for the 3 species has serious implications for the provision of shade on cocoa farms as farmers generally rely on naturally occurring trees when clearing old fallows for cocoa establishment. It has implications for forest regeneration, composition and structure.

The remaining 4 species – *A. adianthifolia, N. laevis, T. ivorensis* and *T. Tetrapleura* – appear to be regenerating relatively well on the fallow lands as evidenced by their relatively steep SCDs, with high seedling densities, intermediate sapling and low adult population densities, and further supported by their negative adult tree SCD slopes (Table 4.7). This is because, for a population to maintain a relatively constant population, more individuals are required in the smaller size classes than in the larger ones (Lykke, 1998). Swaine *et al* (1976) also point out that some individuals will inevitably die before maturity, and in fire-dominated environments a particularly large share of the small individuals dies.

4.4.3. Natural forest

Seedlings, saplings and adult trees in all stages were observed in the natural forest. Here again, just as in the fallows, seedlings, saplings and adult tree populations of *E. angolense*, *E. utile* and *K. anthotheca* showed a more or less flat distribution, as encountered in the fallows. This clearly indicates the declining state of these species in this area as it shows a decline in regeneration potential due to poor seedling and sapling recruitment. This is supported by Condit *et al* (1998) who stated that species in the process of being eliminated from the forest – perhaps during succession – fail to reproduce and thus lack sufficient advanced regeneration. *K. anthotheca* was observed to have a particularly low distribution for all three stages. Again this could have been as a result of severe illegal logging of these species by timber firms and local chainsaw operators, resulting in the erosion of the seed bearing adult trees. This is supported by Hawthorne and Abu Juam (1995) who found that the Jimira Forest Reserve has been severely logged and is now mostly degraded.

N. laevis on the other hand was virtually absent in the natural forest, where no seedlings were recorded. This would be mainly due to the fact that the species does not regenerate well under forest canopy, and is more commonly found in fallows and around settlements. Hawthorne (1995) also points out that smaller size of the species do not survive under forest canopy.

A. adianthifolia, *T. ivorensis* and *T. tetraptera* however, showed a negatively sloping distribution pattern, with high seedling, intermediate sapling and low adult tree population densities. *A. adianthifolia* and *T. ivorensis* showed a particularly pronounced size class distribution slope from seedlings to adult trees in the natural forest. And for their adult trees, all three species contained more trees in the smaller and intermediate diameter size classes, as illustrated by the regression plots in Figures 4.11 to 4.17. This structure indicates frequent reproduction, and hence appreciable regeneration potential as indicated by Knight (1975), Swaine *et al* (1976) and Lykke (1998). Condit *et al* (1998) also indicate that, all things being equal, increasing populations should have steeper size class distributions than decreasing populations, and that in general, population health correlates with size distribution. However, seedling populations were far higher than sapling populations, indicating a high level of mortality or failure of seedlings to establish. This is because as pioneer species most of these require sunlight for full establishment and development, thus the seedlings tend to die out due to over-shading under the forest canopy, as pointed out by Hall and Swaine (1981) and Hawthorne (1995) for a number of species.

CHAPTER 5

PHENOLOGY AND CROWN STRUCTURE OF THE SHADE TREE SPECIES

5.1. Introduction

Phenology has been defined as the study of (i) the rhythm of repetitive biological events, (ii) the biotic and abiotic causes of these events, and (iii) the relationship between phenophases (i.e. periods during which specific phenological events occur) for individual or different species (Broadhead et al., 2003b, citing Leith 1974). Okullo *et al* (2004) also define phenology as the study of the growth of buds, leaf flushing, anthesis, fruiting and leaf fall in relation to seasonality. Phenological studies provide information on functional rythms of plants and plant communities, where the timing of various phenological events may reflect biotic and/or abiotic environmental conditions. These studies are also important from the point of view of the conservation of tree genetic resources and forestry management as well as for a better understanding of plant species and community level interactions (Okullo *et al.*, 2004).

An increasing number of tropical species become deciduous as the intensity of the dry season increases, while both evergreen and deciduous species often produce leaves episodically (Reich, 1995). Seasonal variation in rainfall and consequent effect on soil moisture availability are predominant in determining tree water status (Reich and Borchert, 1984), although the structural and functional state of the trees is also important (Reich, 1995) as periods of maximum leaf cover do not always coincide with the rainy seasons (Broadhead et al.,., 2003a). The most obvious way in which phenological events will have an impact is in determining the trees' ability to capture resources successfully.

The time of development and duration of the canopies of taller deciduous trees will clearly affect the environment, and hence the resource capture of lower storey crops in many ways. They can also diminish water loss from the soil surface, which may represent a large fraction of rainfall (Huxley, 1996). Spatial separation of resource use by trees and crops offers the possibility of reducing competition in agroforestry

(Broadhead, 2003a). The importance of temporal separation of resource capture has been demonstrated for pigeonpea/sorghum mixtures, for which seasonal light interception was greater than in equivalent sole crops due to intrinsic differences in the duration and timing of canopy development (Willey *et al.,* 1986 cited by Broadhead, *et al.,* 2003a). Temporal complementarity between trees and crops minimises competition for water and nutrients and increases the utilization of off-season rainfall (Broadhead et al., 2003b).

Despite evidence from intercropping in savannah systems that successful co-existence in mixtures depends on temporal complementarity (Ong and Black, 1994), tree phenology is a neglected aspect of agroforestry research (Broadhead et al., 2003a). The paucity of research concerning the importance of tree phenology in agroforestry systems, despite its potential impact on understorey crops, has also been noted (Huxley, 1996), while Broadhead et al., (2003b) emphasise that elucidation of the leafing patterns of trees relative to the prevailing climatic conditions and growth periods of associated crops is essential for a full understanding of the functional aspects of agroforestry.

On the other hand, it has been noted that canopy light interception is dependent on the incident solar radiation arriving at the top of the canopy, the optical properties of the plant elements, the density of the plant elements and the canopy architecture (Chen *et al.,* 1994). Light is a primary source of energy for plants (Stuefer and Huber, 1998) and its capture by plants depends on two factors: first the fraction of the incident photosynthetically active radiation (PAR) that is intercepted by each species, and second the efficiency of conversion of the intercepted radiation by photosynthesis (Ong *et al.,* 1996). Shading may influence crop growth by reducing the supply of PAR, and hence assimilate production (Lott *et al.,* 2000). The crown shape and the consequential display of leaves directly affect light capture, water transport and the competitive advantage of trees (Givnish, 1986; King, 1986; Küppers, 1989; Kuuluvainen, 1992).

As pointed out by Dickmann (1985) and Wang and Jarvis (1990) factors such as inclination and orientation of leaves and the geometric properties of twigs and branches, can contribute to variation in crown characteristics. Crown characteristics, which are affected by many factors such as inclination and orientation of leaves and the geometric properties of twigs and branches, influence the interception of photosynthetically active radiation (Stenberg *et al.*, 1994; McCrady and Jokela, 1998).

Dry matter production of the components of agroforestry systems is often linearly related to the quantity of radiation absorbed by their canopies, in the absence of other limiting factors. The amount of light intercepted by the tree canopy and the amount of light that is transmitted to the understorey crop determines the productivity of both the tree and the associated crop, and is in turn determined by the crown architecture and leaf cover density of the shading tree.

5.1.2. Hypothesis and study objectives

The hypothesis for this study is that there is temporal separation between the leafing phenologies of natives trees used as shade for cocoa and the cocoa crop itself. It is futher hypothesised that this temporal separation in phenological patterns enhances temporal separation of resource use between the shade trees and cocoa and thereby minimises competition for light.

The specific objectives of the phenological study were to:

i. determine seasonal patterns of leaf cover, flowering and fruiting in the selected shade tree species;
ii. determine the crown architectural characteristics of the selected shade trees;
iii. determine the relationship between leaf cover, crown architecture and PAR interception by the trees.

5.2. Data collection

5.2.1. Phenology

Observations of phenological changes were carried out on at least 10 trees of each shade tree species growing on 12 to 16 year old fallows in Bontomuruso in the Atwima district of Ghana. New cocoa farms are usually established on old or 'mature' fallows, mostly within this age bracket, where soils are considered fertile and there are enough trees for the provision of shade for the newly planted cocoa. The vegetation here is dominated by scattered forest trees of various species, and thick swards of *Chromolaena odorata* and *Panicum maximum*; and it is these scattered trees which are selectively managed to provide shade for young cocoa during establishment.

The phenological observations were recorded at fortnightly intervals from August 2001 to July 2002 and again from October 2002 to September 2003, and involved the monitoring of leafing, flowering and fruiting events. The method described by Bonaparte and Danquah (1985), Aronson *et al* (1994) and Akpo (1997) was used in studying the phenological events. Leafing in each tree was scored visually, according to the extent of leaves on the canopy at each observation occasion, on a scale of 0 – 10, where 0 signifies complete leaf fall (leafless tree, bearing no buds) while 10 represented full (maximum) leaf cover. The scale was graded in four categories: 0 = complete leaflessness; 1 – 3 = low leaf cover; 4 – 6 = medium leaf cover; and 7 - 10 indicates high to full canopy (leaf) cover; with each class further broken down into finer categories as much as possible. For instance within the low leaf cover category (1 – 3), 1 = first appearance of new leaf buds on few branches, 2 = leaf buds on more than half of the branches, with a few open buds, 3 = buds on almost all branches, with most open into small fresh new leaves.

Flowering and fruiting were scored on a scale of 0 – 5, where 0 indicates the absence of any reproductive structures (flower or fruit) on the tree, 1 = first appearance of flower buds on a few branches; 2 = appearance of flower buds on half the tree branches with a few open into flowers; 3 = flower buds on more than half the tree crown with many open; 4 = all branches bearing flowers but with few unopen flower buds stillon some branches; 5 = all branches bearing fully open flowers. For fruiting, 1 = first appearance of few newly formed fruits on a few branches; 2 = appearance of new fruits on half the tree branches with a few of them increased in size; 3 = fruits on more than half the tree crown with many of them increasing in size; 4 = all branches bearing fruits but with few small immature fruits on some branches; 5 = all branches bearing fully mature fruits.

5.2.2. Crown architecture

A minimum of ten trees of each tree species, growing on fallow land, were assessed for their crown characteristics, with the exception of *K. anthotheca* for which five trees were assessed due to its low density in the study area (Chapter 4). Assessment involved a measurement of tree DBH, total height, crown length or depth (C_l), and crown diameter (C_d). Crown ratio (C_r) and crown shape ratio (C_{sr}) were then derived from these measurements for each species. Crown length (C_l) was derived as C_l = total tree height – height to lowest live branch; C_r = total tree height – lowest live branch height divided by total tree height (i.e. $C_r = C_l$/total height), and $C_{sr} = C_l/C_d$ (McCrady and Jokela, 1996; Foli *et al.*, 1999). Tree DBH was measured using a diameter tape, while height was assessed with the aid of a Suunto clinometer. The diameter (maximum extension) of the crown in two directions was measured with a metric tape, projecting the crown on to the ground, and the average of the two measurements calculated for each tree.

5.2.3. PAR and light quality

The amount of photosynthetically active radiation (PAR), as well as the quality of the PAR (i.e. the proportion Red/Far Red radiation) passing through the canopy of each species to reach the understorey crops was measured fortnightly alongside the tree phenology. PAR was measured using a hand held ceptometer, the AccuPAR PAR-80 ceptometer (Decagon devices, Inc., Pullman, Washington USA), while the Red/Far Red (R/FR) radiation was measured with a hand held SKR 110/100 660/730 (Red/Far Red) measuring system (Skye Instruments Ltd., 21, Ddole Enterprise Park, Llandrindod Wells, Powys, LD1 6DF, UK). On each occasion PAR and R/FR readings were taken in the open and recorded as above-canopy PAR and R/FR respectively. Readings beneath the canopy of each species were then taken and recorded as below-canopy light. On each recording occasion for each species, five above-canopy and five below-canopy readings were taken at different locations outside and beneath the canopy of each tree species and the average computed. PAR and R/FR light transmission through the canopy of each tree species each month of the year was then calculated as a percentage of the total incident (above-canopy) light that is received beneath the canopy of each species in each month.

5.2.4. Data analysis

Leaf cover data was computed as percentage leaf cover, with 100% representing full canopy leaf cover and zero percent representing leaflessness. The two years data for leaf cover, flowering and fruiting were converted into mean monthly recordings for the 12 months of the year, and phenograms constructed to illustrate the patterns of annual leaf cover, flowering and fruiting for all the shade tree species. All data sets were first tested for normality using the Kolmogorov-Smirnov test in Minitab (Appendix 5). To determine similarities and differences in the leafing phenologies, a cluster analysis was performed on the data for the mean monthly percentage leaf cover of the shade tree species. Following the test for normality, Pearson correlation tests was ran to determine the correlation between rainfall and leafing phenology, while a Spearman rank correlation test was performed on the flowering and fruiting data, as these were not normally distributed. Correlation between leafing phenology and light transmission was also analysed using the Pearson correlation test. Data on the crown characteristics of the different shade tree species was also subjected to analysis of variance to determine differences in the mean crown characteristics. Statistical analyses were performed using Minitab 13 statistical package for windows.

5.3. Results

5.3.1. Phenology

5.3.1.1. Leaf cover

The seasonal patterns of leaf cover for all the seven shade tree species are shown in Figure 5.1, with the standard error bars of the treatment means revealing the degree of asynchrony between the replicates.

In *A. adianthifolia* (Albizia), major reductions in leaf cover occurred during the dry season preceding the major rains. Individual trees started shedding their leaves from the middle of October, and by January most trees of the species were virtually leafless. It was, however, observed that leaf cover increased appreciably by the middle of March when the first substantial average monthly rainfall of 70.7 mm, covering a total of seven rainy days, was recorded. For most trees, maximum leaf cover was reached by May (though mean percentage leave cover was about 80%), and this was maintained through the rainy season up to the middle part of November, when substantial reduction in leaf cover was observed.

In *E. angolense* (Edinam) major reduction in leaf cover started towards the second half of November, with the onset of the major dry season, average leaf cover dropped from about 65% to some 40%; and by January – February most trees had just 30% leaf cover remaining. However, most trees had recovered substantial leaf cover by the second week of March and by May maximum leaf cover had been achieved by most of the trees (Figure 5.1). Unlike in *Albizia* where most trees were leafless at the peak of the dry season (January – February), there was no complete leaf shedding in any of the trees monitored, and even at the peak of their deciduousness, which occurred in the dry season, most trees still retained at least 25 – 30% leaf cover.

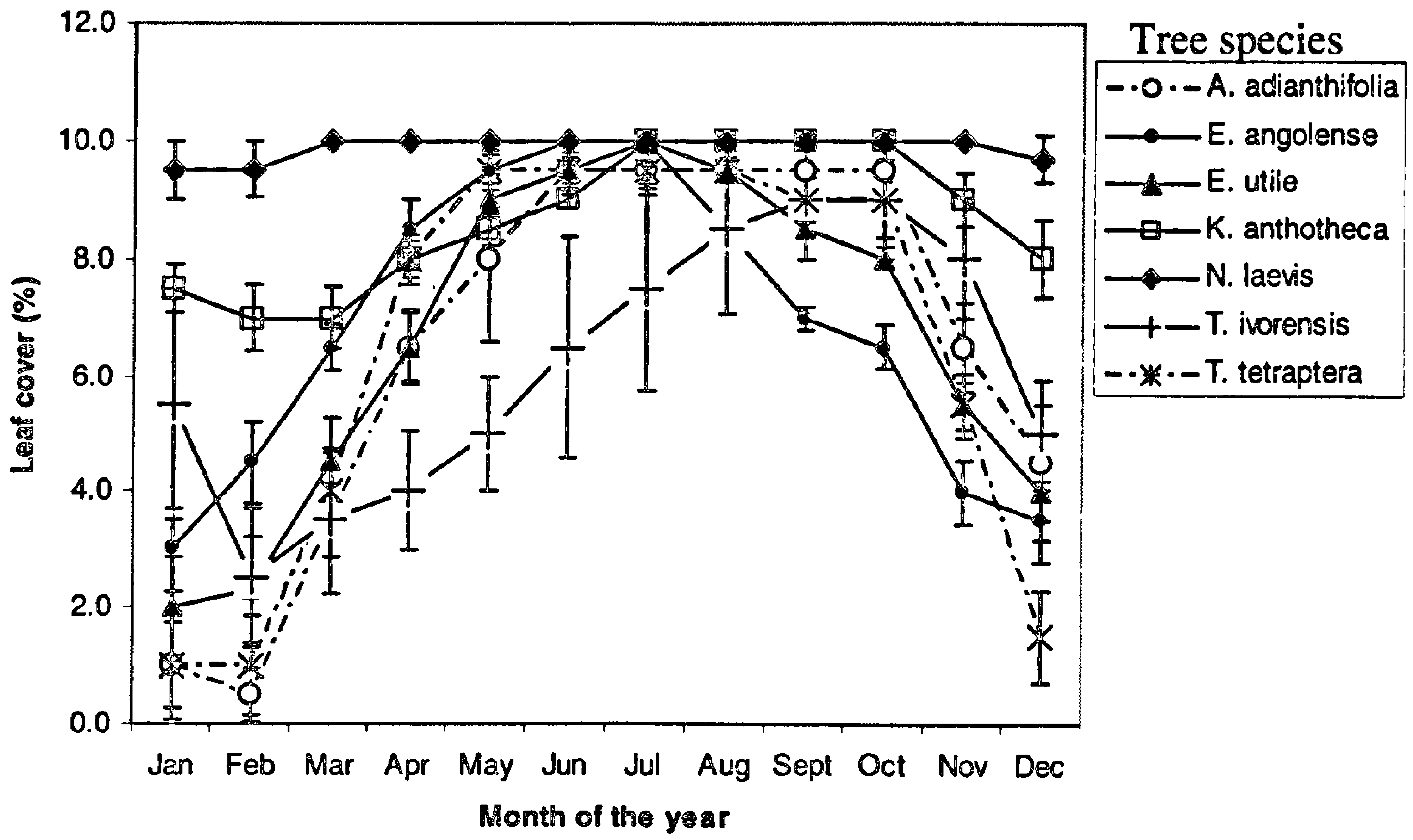


Figure 5.1: Leafing phenology of different cocoa shade tree species in Atwima district, Ghana.

The pattern of leaf fall and leaf cover in *E. utile* (Utile) was generally similar to that of Edinam with minimum average leaf cover of 20% recorded in January – February and maximum leaf cover attained from about May through August. Major reduction in leaf cover occurred in November, though some deciduousness was observed in September (Figure 5.1).

K. anthotheca (Khaya) exhibited much less episodic phenophases than all the other species, with the exception of *N. laevis*. It retained substantial leaf cover throughout the observation period, although leaf cover generally declined during the major dry season – i.e mid-November to March. Minimum leaf cover of about 70% for this species was recorded in February – March. However, leaf cover increased after the first substantial seasonal rains in March, and by June most tress had attained full leaf cover.

Of all the species examined, *N. laevis* (Sesemasa) exhibited the least episodic phenophases. Almost all trees retained 100% leaf cover throughout the year, with the exception of the three driest months – December to February – when slight yellowing and dropping of a few leaves was observed. The species generally appeared to be evergreen all year round, unlike all the other shade tree species studied in this area.
The most varied episodic phenophases was observed in *T. ivorensis* (Emire). Individuals of this species were most asynchronous in their leafing phenology, and although average minimum leaf fall was recorded in the driest months of December through February, individual trees were found to be in widely varying degrees of leaf cover throughout the course of the year (Plate 1). Even at the peak of the rainy season some trees still had less than 50% leaf cover (Figure 5.1). Thus for this species, rainfall did not appear to be the driving factor for leafing phenology.

Plate 1: Pictures of *T. ivorensis* showing the differential leafing patterns exhibited by individual trees of the species during the dry season.

The pattern of leafing phenology in *T. tetraptera* (Prekese) was found to be very similar to that of *Albizia* throughout the period of observations. Major reductions in leaf cover for individual trees started in about the middle of November, at the beginning of the main dry season. By January and February most trees of this species had recorded the minimum leaf cover of about 10%, with a number of individuals loosing their leaves completely. The short minor dry season in late July – mid-September (Table 5.2) appeared to have slight impact on leaf cover as a slight drop in percentage cover was observed in September, prior to the major leaf shedding from November to February (Figure 5.1).

In spite of the similarities and differences observed in the leafing phonologies of the seven shade tree species in the Atwima district, a cluster analysis of the average percentage leaf cover for the species throughout the twelve months of the year revealed three main clusters. Figure 5.2 shows a dendrogram of leafing phenology clustering for the shade tree species studied. Cluster 1 was made up of *Albizia adianthifolia*, *Tetrapleura tetraptera*, *E. utile* and *E. angolense*. The analysis showed that these 4 species were similar in their pattern of leafing phenology, with closest being *Albizia* and *Tetrapleura* which exhibited about 73% similarity in leaf cover pattern. *E. utile* and *Albizia* were 70% similar, while *E. angolense* and *Albizia* showed 50% similarity (Table 5.1).

The second cluster was *Khaya anthotheca* and *N. laevis*. These species were shown to be 69% similar in their pattern of leafing phenology (Figure 5.2 and Table 5.1).

The analysis, however, showed that *T. ivorensis*, which formed the third cluster, was isolated and showed the least similarity to any of the other six species in its leafing phenology (Figure 5.2 and Table 5.1).

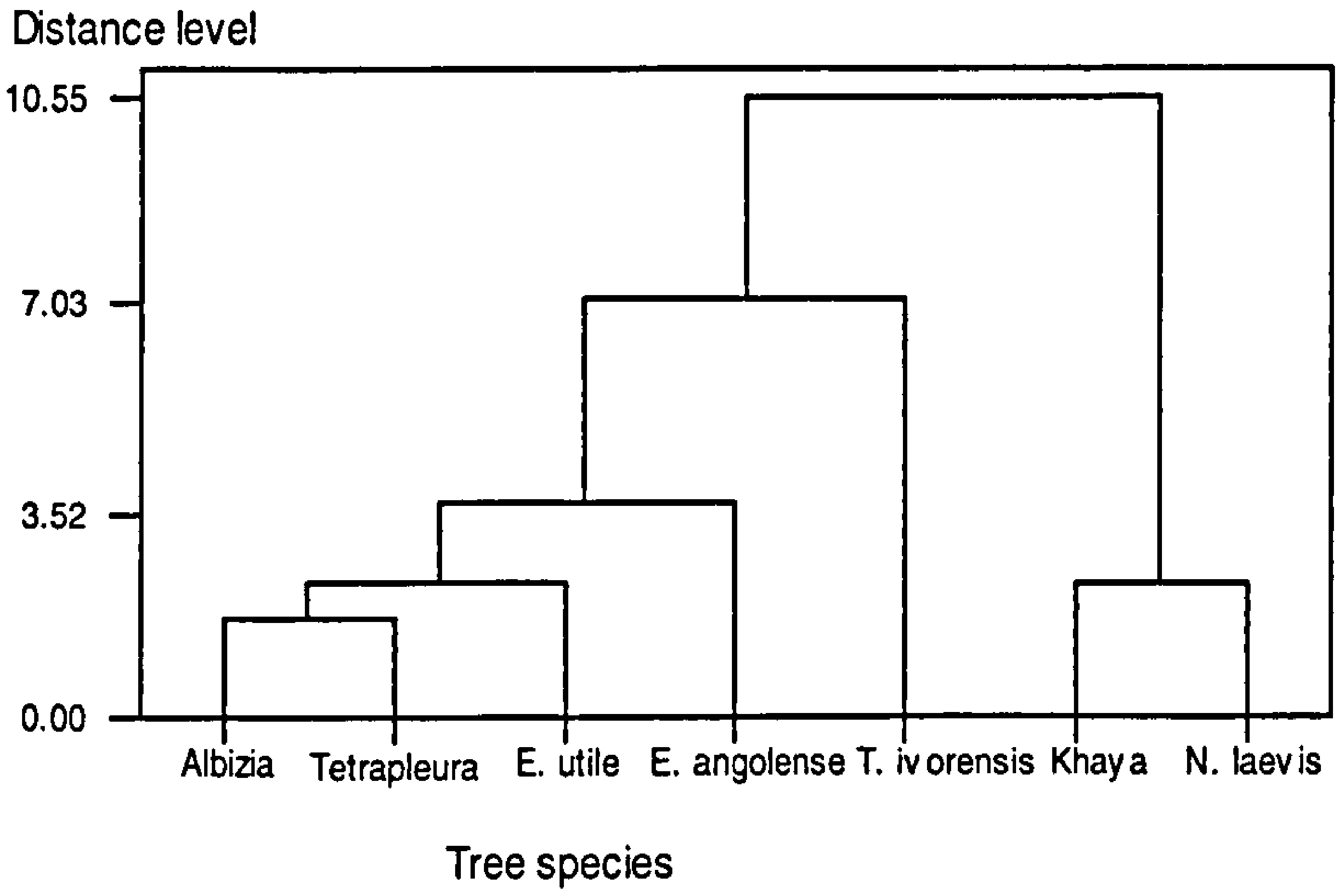


Figure 5.2: Dendrogram of leaf phenology clustering using Ward linkage.

Table 5.1: Cluster Analysis of leaf cover observations

Similarity level	Distance level	Clusters (Species) joined	
72.24	1.708	*A. adinthifolia*	*T. tetraptera*
69.57	2.305	*A. adianthifolia*	*E. utile*
50.25	3.702	*A. adianthifolia*	*E. angolense*
69.10	2.279	*K. anthotheca*	*N. laevis*
4.41	7.113	*A. adianthifolia*	*T. ivorensis*

Table 5.2 shows the Pearson correlation coefficients for correlation between monthly rainfall amounts and average percentage leaf cover for the seven shade tree species monitored. Cluster 1 species, *Albizia, E. angolense* (Edinam), *E. utile* and *T. tetraptera*, showed high correlations of 0.719, 0.655, 0.789 and 0.772 respectively, between rainfall and average leaf cover per month. Cluster 2 species, *Khaya anthotheca* and *N. laevis*, on the other hand showed moderate correlations of 0.589 and 0.469 respectively. However, there was a weak correlation between leafing phenology and rainfall for *T. ivorensis*, with a correlation coefficient of 0.333. There was a significantly positive correlation between rainfall and leafing phenology for *Albizia* (P = 0.008), *E. angolense* (P = 0.021), *E. utile* (P = 0.003), *K. anthotheca* (P = 0.044) and *T. tetraptera* (P = 0.002). However, no significant correlation was found for *N. laevis* (P = 0.124) and *T. ivorensis* (P = 0.29) (Table 5.2).

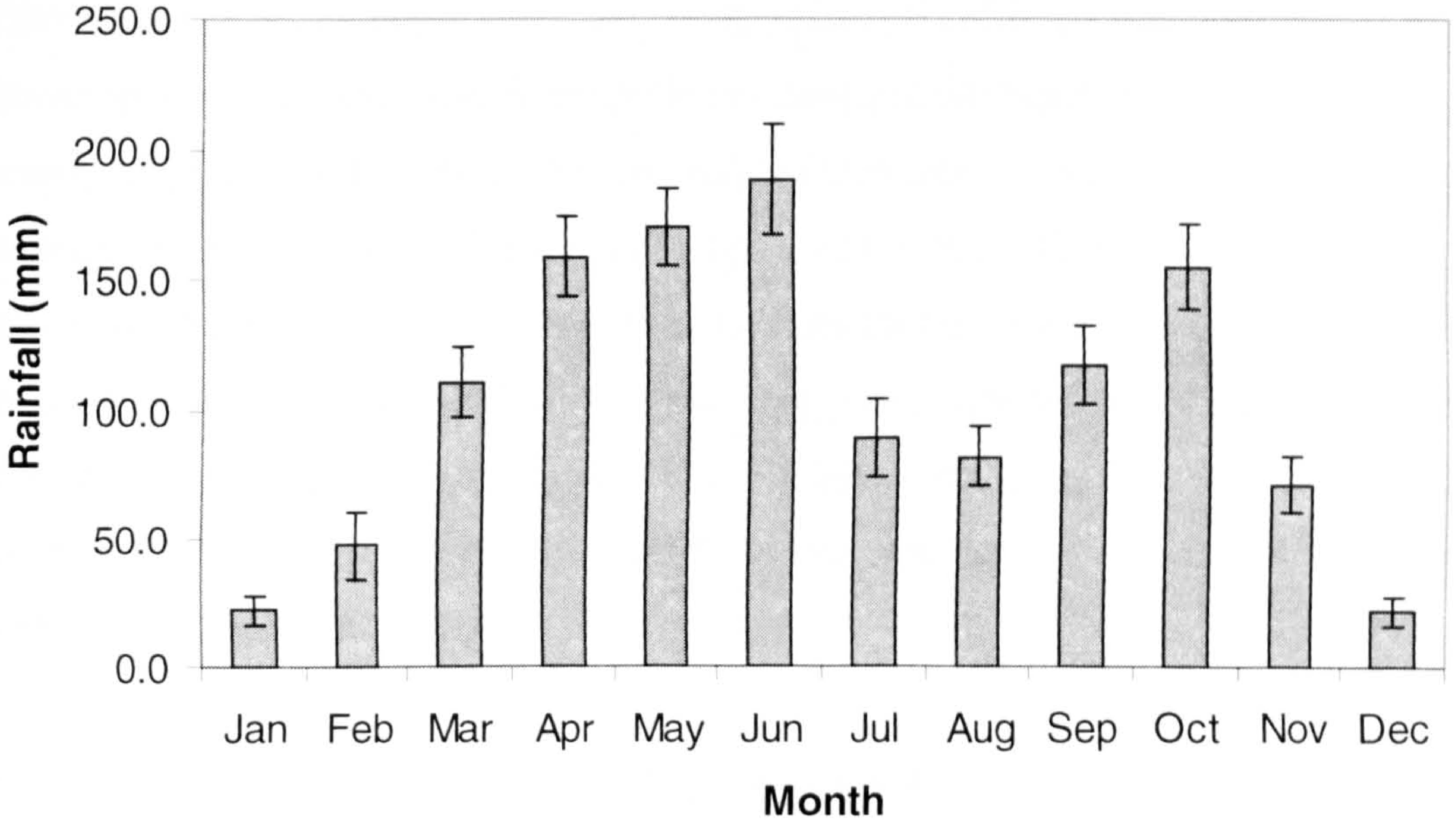


Figure 5.3: Average monthly rainfall data for the Atwima district for the years 1991 to 2002 (Source: Cocoa Services Division, Ministry of Food and Agriculture, Atwima District).

Table 5.2: Correlation coefficients between monthly rainfall and percentage leaf cover for the selected cocoa shade tree species in the Atwima district.

		%Leaf cover					
	Aa.	Ea.	Eu.	Ka.	Nl.	Ti	Tt.
Rainfall	**r** = 0.719**	0.655*	0.784**	0.589*	0.469	0.333	0.772**
	P = 0.008	0.021	0.003	0.044	0.124	0.290	0.002

(* P<0.05; ** P<0.01); **r** = Pearson correlation coefficient

Aa. = *A. adianthifolia*; Ea. = *E. angolense*; Eu. = *E. utile*; Ka. = *K. anthotheca*; Nl. = *N. laevis*; Ti. = *T. ivorensis*; Tt. = *T. tetraptera.*

5.3.1.2. Flowering

With the exception of *Khaya*, *T. ivorensis* and *T. tetraptera*, in which flowering was initiated at the beginning of the major rainy season (i.e. March and April respectively), flower initiation for the other four species occurred at the beginning and peak of the dry season (Figure 5.4). In *Albizia* the first sign of flowering was noticed by the middle of January, with a few flower buds appearing on a few trees. This increased quite rapidly and by the beginning of April almost all the trees under observation were fully covered in bright coloured flowers. Though flowering was generally being replaced by fruits after this period flowering persisted for a few individual trees into May. However, by the peak of the rainy season in June all flowering activity had stopped for this species, with fruits taking over.

Flowering in *E. angolense* and *E. utile* generally started at the same time, at the onset of the main dry season in December. However, it started earlier in *E. angolense* at the beginning of December, than in *E. utile* where the first flowers were noticed towards the middle of the month. Peak flowering was also achieved earlier, by February, in *E. angolense* than in *E. utile* when it occurred in March, but by the time rains were peaking, in May, flowering in both species had fully ceased.

In *Khaya* flowering generally began in mid-March and continued into late August, although in a few individuals it extended into late November. This species displayed the most varied pattern of flowering for individual trees, with trees flowering at different times of the year over a wide period of time, unlike in the rest of the monitored species where flowering peaked and was generally over within three months (Figure 5.4).

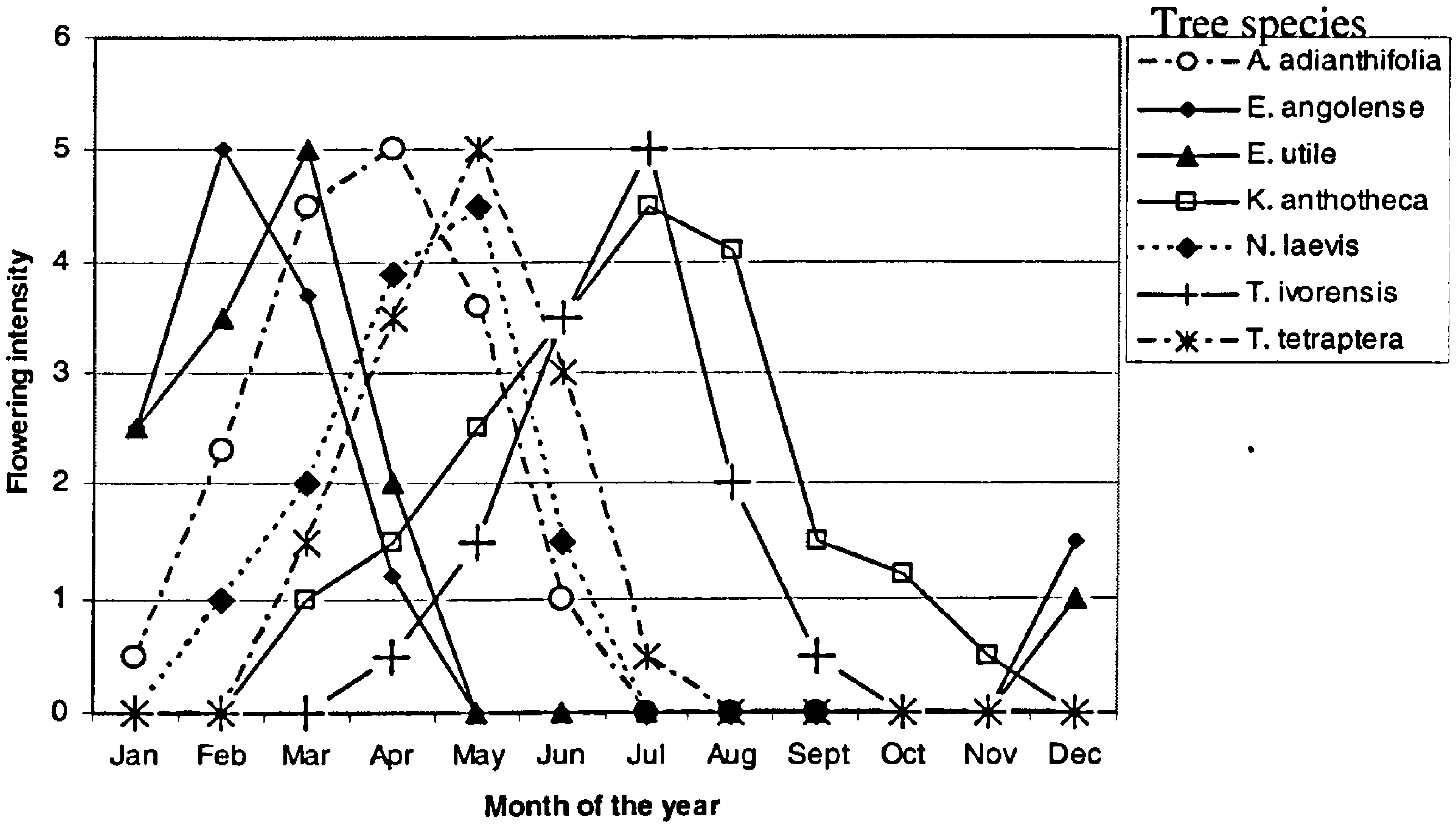


Figure 5.4: Flowering phenology of some cocoa shade tree species in Atwima district.

N. laevis and *T. tetraptera* displayed a generally similar flowering pattern, with the difference being in the time of initiation of flowering. Whereas flowering was observed to start in mid-February for *N. laevis*, it started in early March for *T. tetraptera*. However, peak flowering was noticed for both species in May. And by July and August flowering had ceased in both species.

T. ivorensis was the only species in which flowering was observed to start later than all the other species. Flower initiation was noticed in a few individuals in the first half of April. The number of individuals flowering and the flowering intensity per tree increased steadily and by July had peaked in most trees monitored. However, by September there were virtually no flowers observed on the trees and they were almost all covered in newly formed fruits.

Table 5.3: Correlation between rainfall and flowering in selected cocoa shade tree species in the Atwima district.

	Flowering						
	Aa.	Ea.	Eu.	Ka.	Nl.	Ti.	Tt.
Rainfall	r = -0.263	-0.611*	-0.562	0.774**	-0.061	0.821**	0.570*
	P = 0.408	0.035	0.057	0.003	0.851	0.001	0.046

(*P<0.05; **P<0.01); r = Spearman rank correlation coefficient

Aa. = *A. adianthifolia*; Ea. = *E. angolense*; Eu. = *E. utile*; Ka. = *K. anthotheca*; Nl. = *N. laevis*; Ti. = *T. ivorensis*; Tt. = *T. tetraptera.*

The Spearman rank correlation test showed that flowering was negatively correlated with monthly rainfall amounts, for *Albizia, E. angolense, E. utile* and *N. laevis*, with flowering of these species occurring mainly in the drier months (Table 5.3). Flowering in *K. anthotheca, T. ivorensis* and *T. tetraptera* was however positively correlated to amount of rainfall per month, with their flowering occurring mainly in the rainy season. However, only *E. angolense, K. anthotheca, T. ivorensis* and *T. tetraptera* showed a significant correlation (P<0.05 and P<0.01), while there was no significant correlation in the other species (Table 5.3).

5.3.1.3. Fruiting

Fruit initiation occurred mainly at the beginning of the major rainy season (March – April) for most of the shade tree species; the major exception being *K. anthotheca* in which fruit initiation was observed to commence at the onset of the minor dry season (September) and peak at the end of the minor rains (mid-November). Whereas most of the species reached peak fruit production at the peak of the rains, *T. ivorensis* and *T. tetraptera* were observed to attained maximum fruiting in the minor rainy season, in the months of September – October (Figure 5.5).

A Spearman rank correlation analyses showed that the correlation between rainfall and fruit production in *K. anthotheca, T. ivorensis* and *T. tetraptera* was not significant

(P<0.05). However, it was observed that a significant positive correlation exists between monthly rainfall and fruit production in *Albizia, E. angolense, E. utile* and *N. laevis* (P<0.05; P<0.01) (Table 5.4).

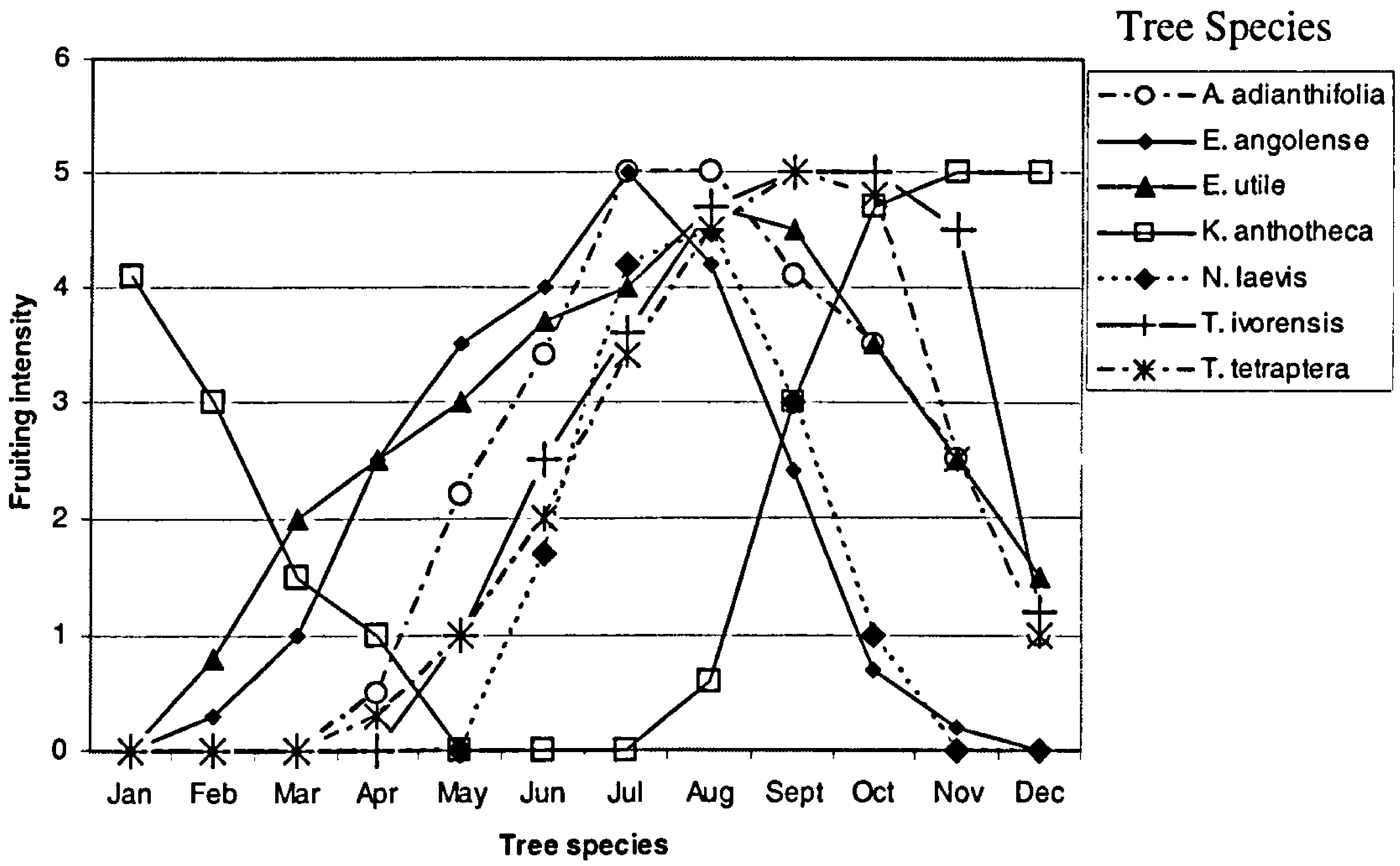


Figure 5.5: Fruiting phenology of some cocoa shade tree species in the Atwima district.

Table 5.4: Correlations between rainfall and fruiting in some cocoa shade Tree species in the Atwima district.

	Fruiting						
	Aa.	Ea.	Eu.	Ka.	Nl.	Ti.	Tt.
Rainfall	r = 0.721**	0.807**	0.621*	-0.577	0.608*	0.513	0.467
	P = 0.009	0.004	0.034	0.096	0.036	0.088	0.126

(* P<0.05; ** P<0.01); r = Spearman rank correlation coefficient.

Aa. = *A. adianthifolia*; Ea. = *E. angolense*; Eu. = *E. utile*; Ka. = *K. anthotheca*; Nl. = *N. laevis*; Ti. = *T. ivorensis*; Tt. = *T. tetraptera.*

5.3.2. Crown Characteristics of the shade tree species.

Table 5.5 shows the mean tree heights, clear bole lengths and DBH, mean crown length, crown diameter, crown ratio, crown shape ratio and projected crown areas of the shade tree species in Atwima. Total tree height varied significantly (P = 0.000) among the species monitored (Table 5.6). *E. utile* and *N. laevis* trees were significantly shorter than the rest of the species, with mean heights of 9.5 m and 8.7 m respectively, while the tallest mean height recorded was for *E. angolense* (19.7 m), followed by *A. adianthifolia, T. ivorensis, T. tetraptera,* and *K. anthotheca* in that order, with mean total heights of 17.9, 16.5, 14.9 and 12.7 m respectively.

Analysis of variance showed highly significant differences (P = 0.000) in the mean clear bole lengths of the shade tree species (Table 5.7). Mean clear bole length was greatest in *E. angolense*, with a mean value of 14.3m. However, unlike mean total height, mean bole length for *T. ivorensis* (10.5 m), *T. tetraptera* (10.2 m) and *A. adianthifolia* (8.3) were statistically similar, while that of *K. anthotheca* (8.1) and *E. utile* (6.9) did not also differ significantly. *N. laevis* again posted the shortest clear bole length of 2.1 m which was significantly lower than for the rest of the species (Table 5.5).

With regards to mean tree crown length (C_l), the results show that *A. adianthifolia* has the longest crown while *E. utile* had the shortest. Mean tree crown length values were generally in the order 9.7 m, 6.5 m, 5.4 m, 5.2 m, 4.8 m, 3.5 m and 2.4 m for *A. adianthifolia, N. laevis, E. angolense, T. ivorensis, K. anthotheca, T. tetraptera* and *E. utile* respectively (Table 5.5). An analysis of variance showed that these differences between mean tree crown lengths were significant (P = 0.000; Table 5.9), with *A. adianthifolia* having a significantly longer crown and *E. utile* having a significantly shorter crown than the other species.

Mean tree crown diameter (C_d) was also expectedly varied among the species; and these variation were significant (Table 5.10). The largest crowns, in terms of width were found in *A. adianthifolia, T. ivorensis* and *T. tetraptera*, with diameters of 10.7, 10.1 and 9.3 m respectively, which were significantly larger than the other species. A mean tree crown diameter of 7.5 m was recorded for *K. anthotheca*, while the other two

Meliaceae species, *E. angolense* and *E. utile*, had crown diameters of 5.8 and 6.3 m respectively; with *N. laevis* possessing a significantly narrower crown (2.2 m) than all the study species (Table 5.5).

Crown area (C_a), which is an indication of the extent of shade provided by individual trees of each species, followed the same trend as mean crown diameter. *A. adianthifolia* tree crowns appeared to spread and cover larger areas than all the other species while *N. laevis* trees, with their narrow crowns, covered the least area. Mean tree crown size, in terms of area of coverage by individual trees of each species, was found to be in the order of 90.6, 80.6 67.7, 43.7, 33.9, 26.6 and 3.8 m^2 for *A. adianthifolia, T. ivorensis, T. tetraptera, K. anthotheca, E. utile, E. angolense* and *N. laevis* respectively (Table 5.5). All the species differed significantly (P = 0.000) from each other in their crowm diameters. (Table 5.11).

In terms of mean tree crown ratio (C_r) – which is a measure of the proportion of the crown length relative to total tree height – and mean tree crown shape ratio (C_{sr}) – which is a measure of the ratio of crown length to crown width – the results show that *N. laevis*, has the highest crown ratio and crown shape ratio of 0.75 and 3.13 respectively (Table 5.5). The smallest crown ratio and crown shape ratio of 0.18 and 0.30 respectively were found in *E. utile* as trees of this species tended to display relatively shallower crowns than the other species studied. Generally, mean crown ratio was found to be in the order *N. laevis* > *A. adianthifolia* > *K. anthotheca* > *T. ivorensis* > *T. tetraptera* > *E. angolense* > *E. utile*, with values of 0.75, 0.54, 0.38, 0.31, 0.28, 0.27 and 0.18 repectively (Table 5.5). With regards to mean crown shape ratio, the trend was found to be slightly different from that of the crown ratio, and was in the order *N. laevis* > *A. adianthifolia* > *E. angolense* > *K. anthotheca* > *T. ivorensis* > *T. tetraptera* > *E. utile*, with magnitudes of 3.13, 0.93, 0.91, 0.67, 0.54, 0.45 and 0.30 respectively (Table 5.5). Like crown ratio which, showed significant difference between species (Table 5.12), significant difference was found in crown shape ratio (Table 5.13), with *N. laevis* having a significantly higher crown ratio (P = 0.000) than all the other species. *A. adianthifolia* differed significantly from the other species with the exception of *E. angolense*, while *E. utile* differed from the others except *T. tetraptera*. *K. anthotheca* on the other hand had a similar crown shape ratio as *T.*

ivorensis but was significantly different form the other five species, while *T. ivorensis* and *T. tetraptera* were also similar in their crown shape ratios (Table 5.5).

Table 5.5: Mean (±se) tree height, bole length, DBH and crown characteristics of selected cocoa shade tree species growing in fallows in Bontomuruso, Atwima district.

Species/ Parameter	*A. adianthifolia*	*E. angolense*	*E. utile*	*K. anthotheca*	*N. laevis*	*T. ivorensis*	*T. tetraptera*
Tot. Ht. (m)	17.9^{ad} (3.1)	19.7^{a} (3.3)	9.5^{b} (1.7)	12.7^{c} (1.9)	8.7^{b} (0.8)	16.5^{de} (3.5)	14.9^{ce} (3.7)
Bole Ht. (m)	8.3^{acef} (1.9)	14.3^{b} (1.2)	6.9^{c} (1.6)	8.1^{cf} (2.1)	2.1^{d} (0.3)	10.5^{e} (3.3)	10.2^{ef} (3.7)
DBH (cm)	52.9^{a} (7.4)	44.3^{b} (3.7)	27.9^{c} (9.9)	28.7^{c} (2.9)	19.3^{d} (1.6)	43.4^{b} (10.8)	60.0^{e} (18.4)
C_l (m)	9.7^{a} (2.2)	5.4^{b} (2.2)	2.4^{c} (0.4)	4.8^{db} (1.4)	6.5^{ebd} (0.8)	5.2^{fbde} (0.8)	3.5^{gbcdf} (1.4)
C_d (m)	10.7^{a} (2.5)	5.8^{b} (1.4)	6.3^{bc} (0.5)	7.5^{cf} (1.9)	2.2^{d} (0.5)	10.1^{ea} (1.8)	9.3^{fae} (3.3)
C_a (m^2)	90.6^{a} (37.9)	26.6^{b} (12.1)	33.9^{c} (4.9)	43.7^{d} (19.8)	3.8^{e} (1.7)	80.6^{f} (28.6)	67.7^{g} (47.6
C_r	0.54^{a} (0.08)	0.27^{bc} (0.07)	0.18^{b} (0.02)	0.38^{c} (0.21)	0.75^{d} (0.04)	0.33^{c} (0.09)	0.25^{b} (0.08)
C_{sr}	0.93^{a} (0.23)	0.91^{a} (0.17)	0.30^{b} (0.04)	0.67^{c} (0.21)	3.13^{d} (0.96)	0.53^{ec} (0.09)	0.44^{fbe} (0.14)

Note: Tot. Ht. = Total height of tree; Bole Ht. = Clear bole length; C_l = Crown length; C_d = Projected crown width or diameter; C_r = Crown ratio; C_{sr} = Crown shape ratio; C_a = Crown area. Means, within the same row, followed by a common letter as superscript are not significantly different at P≤0.05 according to the Tukey's multiple comparison test.

Table 5.6: Analysis of Variance for total height of cocoa shade tree species growing in fallows in Bontomuruso, Atwima district.

Source	DF	SS	MS	F	P
Tree species	6	522.10	87.02	10.78	0.000
Error	28	225.99	8.07		
Total	34	748.09			

Table 5.7: Analysis of Variance for mean clear bole height of cocoa shade tree species growing in fallows in Bontomuruso, Atwima district.

Source	DF	SS	MS	F	P
Tree species	6	414.50	69.08	12.53	0.000
Error	28	154.33	5.51		
Total	34	568.83			

Table 5.8: Analysis of Variance for mean DBH of cocoa shade tree species growing in fallows in Bontomuruso, Atwima district.

Source	DF	SS	MS	F	P
Tree species	6	6686.1	1114.3	14.80	0.000
Error	28	2108.1	75.3		
Total	34	8794.1			

Table 5.9: Analysis of Variance for mean crown length (C_l) of cocoa shade tree species growing in fallows in Bontomuruso, Atwima district.

Source	DF	SS	MS	F	P
Tree species	6	162.74	27.12	12.94	0.000
Error	28	58.67	2.10		
Total	34	221.40			

Table 5.10: Analysis of Variance for mean crown diameter (C_d) of cocoa shade tree species growing in fallows in Bontomuruso, Atwima district.

Source	DF	SS	MS	F	P
Tree species	6	264.96	44.16	11.77	0.000
Error	28	105.02	3.75		
Total	34	369.98			

Table 5.11: Analysis of Variance for mean crown area (C_a) of cocoa shade tree species growing in fallows in Bontomuruso, Atwima district.

Source	DF	SS	MS	F	P
Tree species	6	29382	4897	8.62	0.000
Error	28	15912	568		
Total	34	45294			

Table 5.12: Analysis of Variance for mean crown ratio (C_r) of cocoa shade tree species growing in fallows in Bontomuruso, Atwima district.

Source	DF	SS	MS	F	P
Tree species	6	1.07562	0.17927	22.85	0.000
Error	28	0.21965	0.00784		
Total	34	1.29527			

Table 5.13: Analysis of Variance for mean crown shape ratio (C_{sr}) of cocoa shade tree species growing in fallows in Bontomuruso, Atwima district.

Source	DF	SS	MS	F	P
Tree species	6	27.537	4.590	29.83	0.000
Error	28	4.309	0.154		
Total	34	31.846			

5.3.3. Light modification by the cocoa shade tree species

5.3.3.1. Light transmission through the shade tree canopies

The midday (between 10.00am and 2.00pm) PAR reaching the soil surface in the open (control) on the measurement days in each month varied, and ranged between 1077.3 – 2456.7μmol m^{-2} s^{-1} throughout the year. In the dry season – i.e. November to March – “above-canopy” PAR averaged 1932.3±524.4 μmol m^{-2} s^{-1}, while an average above-canopy PAR value of 1513.8±436.5 μmol m^{-2} s^{-1} was recorded for the rainy seasons (major and minor season – April to October). It was observed that light penetration through the canopies of the shade tree species also varied seasonally and with tree species. In general, there was a higher relative PAR transmission to below-canopy environments, for all the species, in the dry season than in the rainy season (Figure 5.6). The highest relative light transmission was recorded in January when relative PAR received under the canopies of *A. adianthifolia* and *T. tetraptera* were 70.5% and 72.1% respectively of the total PAR received on the soil surface, while PAR beneath the canopies of the *E. angolense, E. utile* and *N. laevis* was reduced to 58.6%, 64.8% and 37.1% respectively. Unlike the above five species, however, maximum light transmission under the canopies of *K. anthotheca* and *T. ivorensis* was recorded in March when relative PAR was reduced to 51.1% and 63.7% respectively for the two species. By the peak of the rainy season, in June – July, below-canopy light transmission had reached its lowest for most of the species, with values of 39.5, 23.3, 32.1, 22.8 and 41.4% respectively for *A. adianthifolia, E. angolense, E. utile, N. laevis* and *T. tetraptera*; the exception being *K. anthotheca* and *T. ivorensis*, where lowest relative light transmission was recorded in October (34.1%) and September (28.7%) respectively (Figure 5.6).

In the dry season, mean relative PAR was reduced to 66.7±5.0% of the total incident light under the canopy of *T. tetraptera* (and this was the highest among all the species), while the highest reduction in total incident PAR occurred under the canopy of *N. laevis*, where mean relative PAR was reduced to 32.9±5.6%. Mean relative PAR reductions under the canopies of the other species were intermediate between these two values and ranged from 61.6±7.7, 42.8±13.8, 56.4±5.3, 46.9±7.3 and 46.7±13.3% for *A. adianthifolia, E. angolense, E. utile, K. anthotheca* and *T. ivorensis* respectively.

In the rainy season – i.e. April to November – PAR reductions under the canopies of the shade tree species were generally greater than in the dry season. Mean relative PAR was reduced to 45.5±11.7% under the canopies of *T. tetraptera*, while under the canopies of *N. laevis* it was reduced to only 27.0±5.4% of the above-canopy PAR.

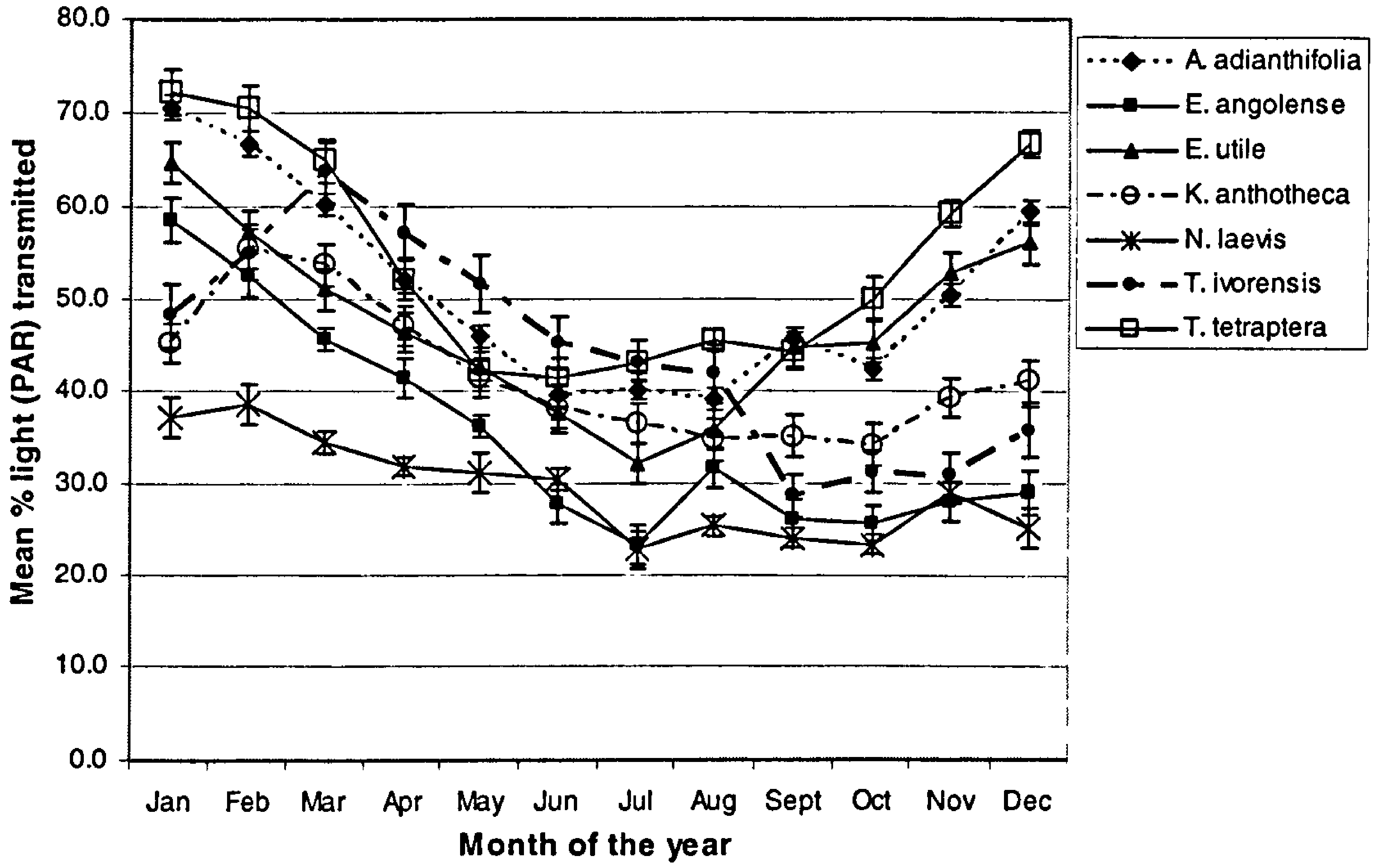


Figure 5.6: Relative light transmission (PAR) through the canopies of some cocoa shade tree species in the Atwima district, Ghana (Mean±se).

5.3.3.2. Relation between transmitted PAR and Tree crown characteristics

A Pearson correlation analysis for correlation between below-canopy light transmission and tree crown characteristics – leafing phenology, crown length and crown diameter – showed that light penetration through the canopies of the shade tree species is influenced to varying degrees by these characteristics. In general, below-canopy light transmission was negatively correlated with the leafing phenologies of all the shade tree species. *A. adianthifolia* (Aa), *E. utile* (Eu), *T. ivorensis* (Ti) and *T. tetraptera* (Tt) had significantly strong negative correlations with PAR ($P<0.05$), with correlation coefficients (r) of -0.988, -0.956, -0.837 and -0.977 respectively (Table 5.14. The analysis, however, revealed poor negative correlations between leafing phenology and light transmission for *E. angolense* (Ea), *K. anthotheca* (Ka) and *N. laevis* (Nl), with coefficients of -0.547, -0. 439 and -0.392, respectively (Table 5.14).

No significant correlation was found between below-canopy light transmission and crown length and crown diameter respectively. Crown length generally had a weak negative correlation with below-canopy light transmission, with coefficients of -0.282 (P = 0.375), -0.369 (P = 0.238), -0.202 (P = 0.340), -0.308 (P = 0.179), -0.381 (P = 0.291), -0.309 (P = 0.329) and -0.176 (P = 0.318) for *A. adianthifolia, E. angolense, E. utile, K. anthotheca, N. laevis, T. ivorensis* and *T. tetraptera* respectively. Crown diameters also showed weak negative correlations with light transmission for all the species. Correlation coefficients ranged from -0.211 (P = 0.150), -0.254 (P = 0.168), -0.179 (P = 0.278), -0.224 (P = 0.149), -0.164 (P = 0.244), -0.184 (P = 0.167) and -0.285 (P = 0.373) respectively for the above species.

Table 5.14: Pearson correlation coefficients for leafing phenology (Leaf) and below-canopy light transmission (PAR) for the different shade tree species.

	Aa. leaf	Ea. Leaf	Eu. Leaf	Ka. Leaf	Nl. Leaf	Ti. Leaf	Tt. Leaf
Aa. PAR	**-0.988*** **0.000**						
Ea. PAR	-0.870 0.000	**-0.547** **0.146**					
Eu. PAR	-0.878 0.000	0.918 0.000	**-0.956*** **0.000**				
Ka. PAR	-0.843 0.001	0.799 0.002	-0.343 0.274	**-0.439** **0.079**			
Nl. PAR	-0.817 0.001	0.768 0.004	-0.344 0.273	0.916 0.000	**-0.392** **0.042**		
Ti. PAR	-0.499 0.099	0.451 0.141	0.183 0.570	0.696 0.012	-0.301 0.342	**-0.837*** **0.001**	
Tt. PAR	-0.941 0.000	0.953 0.000	-0.885 0.000	0.713 0.009	-0.985 0.000	0.918 0.000	**-0.977*** **0.000**

* = Significant at P<0.05.

Note: Aa. = *A. adianthifolia*, Ea. = *E. angolense*, Eu. = *E. utile*; Ka. = *K. anthotheca*; Nl. = *N. laevis*; Ti. = *T. ivorensis;* Tt. = *T. tetraptera.*

5.3.3.3. Light quality

The mean red/far red light ratios recorded under the canopies of the shade tree species are presented in Figure 5.7. There was a wide variation in mean R/FR ratio transmitted to below-canopy arrays throughout the year for all the species. Mean values ranged from 0.3±0.05 for *N. laevis*, in August, to 1.16±0.09 for *T. tetraptera* in January.

As with PAR transmission, a strong seasonal variation in the mean R/FR ratio of light transmitted through the canopies of the shade tree species was observed, with higher ratios generally recorded in the dry season – November to March – than in the rainy season – April to October. The highest ratios, for most of the species, were recorded in January when mean R/FR was about 1.16, 0.90, 0.67, 0.66, 0.55 and 0.46, respectively for *T. tetraptera, A. adianthifolia, K. anthotheca, E. utile, E. angolense* and *N. laevis.* The highest value for *T. ivorensis* (1.03) was, however, recorded in February (Figure 5.7). By the beginning of the rainy season – in April, below-canopy mean R/FR ratios were in the order *T. tetraptera>T. ivorensis>A. adianthifolia>E. angolense>E. utile>K. anthotheca>N laevis,* with values of 0.79, 0.73, 0.60, 0.55, 0.53, 0.48 and 0.34 respectively, and by the peak of the rainy (growing) season, mean R/FR received below-canopy had further reduced to 0.49 and 0.46 for *T. tetraptera* and *T. t. ivorensis,* respectively in July, and 0.0.46, 0.37, 0.37, 0.35 and 0.30 for *A. adianthifolia, E. angolense, E. utile, K. anthotheca* and *N. laevis,* respectively, in August (Figure 5.7). Overall, *N. laevis* canopies transmitted the lowest levels of R/FR ratio while *T. tetraptera* transmitted the highest, in all the months throughout the monitoring period (Figure 5.7).

There was a strong negative correlation between R/FR ratio and leafing phenology, and the correlations were quite significant ($P<0.05$) for all the species, except for *N. laevis* which was not correlated (Table 5.15). Correlation coefficients ranged from -0.933, -0.687, -0.736, -0.822, -0.351, -0.587 to -0.893 for *A. adianthifolia, E. angolense, E. utile, K. anthotheca, N. laevis, T. ivorensis* and *T. tetraptera* respectively, and showed that for all species there is an increase in R/FR ratio of transmitted light with decreasing leaf cover.

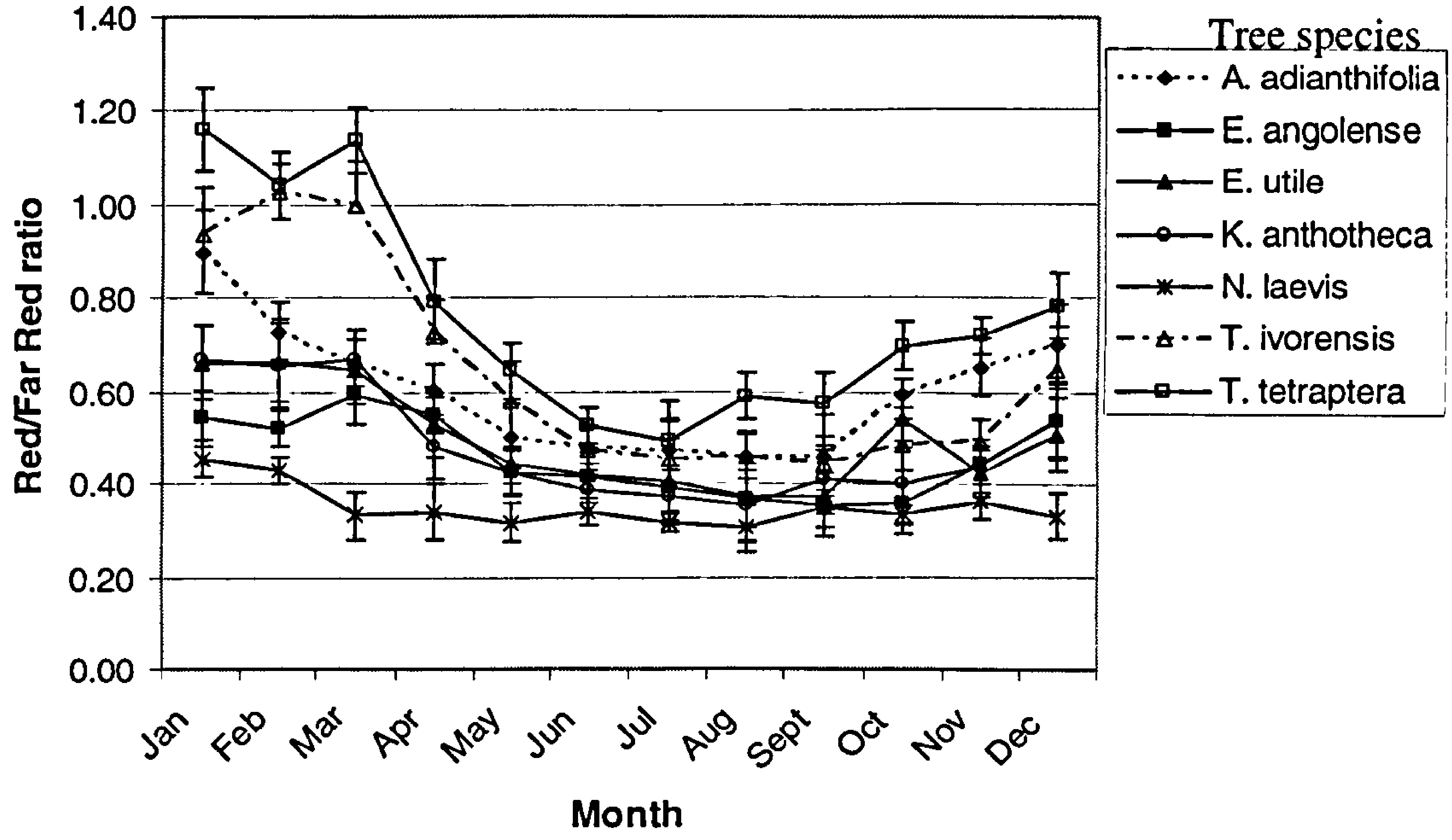


Figure 5.7: Red/far red ratio of light (mean±se) transmitted through the canopies of some cocoa shade tree species in the Atwima district, Ghana.

Table 5.15: Pearson correlation coefficients for the relationship between monthly leaf cover and Red/Far Red Light transmission through the canopies of the shade tree species.

	Aa.leaf	Ea.Leaf	Eu.Leaf	Ka.Leaf	Nl.leaf	Ti.leaf	Tt.leaf
A. R/FR	**-0.933**						
	0.000						
Ea. R/FR	-0.808	**-0.687**					
	0.001	**0.014**					
Eu. R/FR	- 0.822	- 0.758	**-0.736**				
	0.001	0.004	**0.006**				
Ka. R/FR	-0.940	- 0.728	-0.898	**- 0.822**			
	0.000	0.007	0.000	**0.001**			
Nl. R/FR	-0.590	- 0.426	- 0.716	-0.398	-0.351		
	0.043	0.167	0.009	0.200	0.263		
Ti. R/FR	0.893	0.793	0.756	0.915	0.737	**- 0.587**	
	0.000	0.002	0.004	0.000	0.006	**0.045**	
Tt. R/FR	0.918	0.771	0.878	0.777	0.921	0.562	**-0.893**
	0.000	0.003	0.000	0.003	0.000	0.057	**0.000**

Note: Aa. = *A. adianthifolia*; Ea. = *E. angolense;* Eu. = *E. utile*; Ka. = *K. anthotheca*; Nl. = *N. laevis*; Ti. = *T. ivorensis;* Tt. = *T. tetraptera.*

5.4. Discussion

5.4.1. Crown characteristics in relation to light transmission

5.4.1.1. Phenology

Phenological studies are essential to increase knowledge of specific functions of trees in any ecosystem, and they must be taken into account in conservation and rational management schemes (Aronson, *et al* 1994). Tree periodicity patterns provide an insight into seasonal organisation of floral, fruit and seed resources, and into the spatial organization of multistrata agroforestry systems. The phenology of tropical woody plants has been shaped by both biotic and abiotic factors (Okullo *et al* 2004). Richards (1952) pointed out that almost all tropical environments vary seasonally in temperature, humidity, rainfall, wind speed and daylength, although the amplitude of the variation may be small, and Longman and Jenkins (1974) suggested that all these factors are known to play a role, either alone or in combination, in triggering phenological changes in tropical plants. It has also been suggested that plants may stagger their phenological activities to avoid competition for pollinators and dispersal agents or they may opt for clumping of phenological activity to attract the pollinators and dispersers or swarm predators by producing the vulnerable organs in concentrated bursts (van Schaik *et al* 1993). Khan (1999) also suggested that plants may time their phenological activity to coincide with favourable weather conditions for optimum performance.

In all the species studied, reductions in the degree of leaf cover was observed only during the dry season. It was observed that all the species, with the exception of *K. anthotheca* and *N. laevis*, shed most of their leaves in the major dry season, from mid-November to mid-March, while recovery of leaf cover started with onset of the rains, thus giving the indication that the leafing phenophase of these species is influenced, to some extent, by soil moisture content. This conclusion is enhanced by the relatively strong and significant inverse correlation between rainfall and mean monthly leaf cover for these species (Table 5.2), and supported by the findings of Frankie *et al.*, (1974) who observed that the period of greatest leaf fall in tropical wet and dry forests in Costa Rica coincided with the relatively xeric conditions of the first long dry season. Investigating seasonality and phenology in a dry tropical forest in Ghana, Lieberman

(1982) observed that moisture appears to be a major determinant of the timing of leaf flushing. Okullo *et al* (2004) also reported maximum reductions in leaf cover for *Vitellaria paradoxa* in the dry season, in Uganda. This phenomenon of leave shedding at low soil moisture levels may be explained by Reich and Borchert's (1984) assertion that during the early dry season, the increasing evaporative demand, and the declining soil moisture, impose increasing water stress on the trees and accelerate senescence and the shedding of leaves. They point out that leaf fall reduces water loss dramatically, and the subsequent water uptake is sufficient to rehydrate the bare trees and cause shoot emergence during continued drought. Reich (1995) also points out that the timing of leaf fall and bud break is generally determined by the tree water status, which in turn is a function of the interaction between the water status of the environment and the structural and functional state of the tree.

In contrast to the five species – *A. adianthifolia, E. angolense, E. utile, K. anthotheca* and *T. tetraptera*, there were no significant reductions in leaf cover for *N. laevis* and *T. ivorensis*. Rainfall, and hence soil moisture did not appear to have any significant effect (P = 0.124 and P = 0.29, respectively) on leaf cover for these two species (Table 5.2). However, unlike *N. laevis* in which individual trees were virtually evergreen throughout the year, *T. ivorensis* exhibited the most asynchronous leafing phenology of all the species, with individual trees shedding their leaves and becoming leafless at different times of the year.

Evergreeness in *N. laevis*, as in other evergreen species, is due to a constant leaf exchanging phenomenon within a tree's canopy in which new leafs continuously replace old senescent leaves without a clear distinction between the two phases. It is suggested that this phenomenon occurs mostly in trees that experience minimal water deficit, apparently because of a combination of deep rooting and (or) low whole canopy transpiration. Such trees would flush in the dry and (or) wet season and display asynchronous leaf senescence and production often among branches within an individual (Reich, 1995). The evergreen nature of *N. laevis* may thus be due to low whole canopy transpiration, due to the tree's relatively narrow compact and generally small crown, and possibly deep rooting habit. This, however, will require further investigation.

In the case of *T. ivorensis*, the asynchronous nature of leaf shedding among individual trees within the same area, coupled with the weak correlation with rainfall, suggests that other factors other than rainfall influence leaf phenology in this species. It is possible that leafing phenology in this species is facultative, and may be controlled more by a combination of endogenous factors than by environmental factors such as rainfall, as suggested by Borchert (1980) Reich and Borchert (1984) and Broadhead et al., (2003b). Borchert (1980) further pointed out that this asynchrony of seasonal development within a population subject to the same climatic conditions suggests that the developmental sequence in such trees is not under direct climatic control, and goes on to suggest that this might therefore constitute a suitable model system for the study of the interaction between environmental and correlational controls determining seasonal tree development. Reich (1995) suggests that the mechanisms responsible for inducing leaf loss in such species may be moderated by environmental factors even when the primary cues are endogenous. Under such circumstances, water stored in the soil or in the trees themselves may act as a buffer against current environmental conditions by allowing leaf cover to be maintained at times when there is little or no input of water to the system (Broadhead et al., 2003b). Nevertheless, the observation of an increase in leaf shedding within and among individual trees in the dry season, and the increase in leaf cover with increasing rains is an indication that rainfall or soil moisture content does play a role.

These patterns of leafing phenology present some implications for temporal complementarity of resource use in multi-strata cocoa agroforestry systems. Reductions in leaf cover in the dry season, when soil moisture is low, will limit extraction of soil water by the shade trees, thereby decreasing competition with the cocoa crop during the dry season, as concluded by Broadhead et al., (2003b). On the other hand, maintenance of full or high leaf cover throughout the year, and especially in the dry season, as exhibited by *N. laevis* and, to a large extent, *K. anthotheca*, will result in result in high competition between these species and the cocoa crop for the limited dry season water supply. Thus, based on this factor, all the other species, except *N. laevis* and *K. anthotheca* give indications of good temporal complementarity with cocoa, based on their leafing phenologies alone. However, with regards to shade provision, the reverse is the case. Maintenance of good dry season leaf cover is desirable as this is the period when the intensity of the sun is highest. A balance therefore needs to be struck between competition for below-ground resources and provision of shade. On the face of the above factors, *T. ivorensis*, with its highly asynchronous leafing pattern, appears to offer such a balance better than the other species, though actual assessment of seasonal water uptake and canopy light transmission need to be carried out for all the species before definite conclusions can be drawn.

Flowering in all the species, except *T. ivorensis*, generally commenced in the dry season (Figure 5.4), when leaf cover was generally minimal and one would expect a low soil moisture content. And this was usually followed almost immediately by the onset of leaf flushing. This observation of flower initiation in the dry season corresponds with reported observation of flowering activity of trees in tropical forests by several investigators (e.g. Njoku, 1958 and 1963; Hopkins, 1970; Frankie *et al.*, 1974; Borchert, 1980). Working on herbs and shrubs, in Ibadan (Nigeria), Njoku (1958) found that a difference of 15 minutes in photoperiod was sufficient to initiate the flowering process, and suggested that these small changes in photoperiod may also trigger flowering in trees. Thus, although moisture-related factors may play a role in triggering flowering in these trees species, a change in photoperiod at this time of the year may also be an important stimulus in flower initiation.

Apart from the *Entandrophragmas*, in which flowering was more or less restricted to the dry season, the other species, including *T. ivorensis*, had extended flowering periods lasting well into the rainy season; with *K. anthotheca* having a particularly extended flowering regime. Frankie *et al* (1974), investigating tree phenology in wet and dry tropical forests in Costa Rica, noted similar extended flowering in many wet and some dry forest species and ascribed it to an adaptation by such species to enhance pollination by insects, especially by the large tropical bees. This kind of floral pattern is referred to as "trap-lining", in which the foraging activity of the bee is such that it visits on a regular basis a widely spread series of plants to obtain a sufficient quantity of floral nectar. And since many of the plants are of the same species, this movement allows for effective out-crossing of these species (Frankie *et al.*, 1974). They point out that the plants appear to be adapted to this foraging pattern since they accommodate the pollinators by producing a few flowers daily for extended time periods. Citing other literature, Frankie *et al* (1974) pointed out that the importance of pollen vectors in the reproduction of tropical trees is emphasized by the fact that a high proportion of tree species are self-incompatible or dioecious. Consequently, since most of these trees are obligated to out-cross, and since wind pollination in the tropics is rare, they are depended upon animals for effective pollen transfer.

Fruit formation in all the species generally coincided with the rainy seasons, when soil moisture content is high, while fruit maturation coincided with the major dry season. This wet season fruiting pattern is generally comparable with the fruiting patterns reported for trees in some tropical forests in the Amazonia (Peres, 1994) and in Uganda (Muhanguzi *et al.,* 2003). As the fruits/seeds of these species are mainly wind-dispersed, this timing of fruit maturation ensured that fruits/seeds were matured at the time when the winds – mainly the North-easterly winds – blew with the strongest intensity and frequency, thereby ensuring wider dispersal of seeds. This is further enhanced by the fact that leaf cover for most of these species is minimal during this period, thus exposing the mature fruits/seeds to the forces of the wind.

5.4.2. Crown characteristics and shade provision

Tree characteristics – i.e. total height, bole height, Dbh, crown length and crown diameter – were varied within and between species in this study. Rao *et al* (1998) have pointed out that understorey microclimatic conditions in a multi-strata agroforestry system are influenced by the shade tree species canopy characteristics and size and density of the trees in the system. During indigenous knowledge elicitation (Chapter 3) farmers in the study area also pointed out that good cocoa shade trees should be tall, with light crowns well above the cocoa canopy, to ensure good air circulation within the cocoa crop, as this will minimise the incidence of diseases, especially the black pod disease. Height of the shade tree was also considered very important and was linked to below canopy micro-climatic factors such as air circulation and humidity. They were clear in their understanding that short, heavy-crowned trees tend to prevent proper ventilation beneath them. Based on this premise, and from the results of this study, *A. adianthifolia, E. angolense, K. anthotheca, T. ivorensis* and *T. tetraptera* displayed heights that are well above the cocoa canopy, and would thus allow good air circulation, as opposed to *E. utile* and *N. laevis* with their relatively short clear bole heights (and low crowns) of 6.9 and 2.1m respectively. However, whereas *N. laevis* generally has a short clear bole height, with a rather long crown, – indicated by the small standard error (0.3) in this study – the relatively short boles encountered in *E. utile* was rather unusual and does not give a fair representation of the species' bole length at maturity. As pointed out by Taylor (1960), this species is a large tree with a light crown, and the smaller trees recorded here is clearly due to the fact that they are juvenile trees regenerating on the fallows on which the assessment was carried out. It is also possibly due to the activities of illegal chainsaw operators, who cut and saw bigger trees for lumber. Thus, in terms of height, all the species have a good potential for cocoa shade provision, with exception of *N. laevis*.

However, for shade provision, tree height and bole length needs to be considered alongside crown parameters, like crown length (depth), crown diameter and crown area. In terms of crown length, the study revealed that *A. adianthifolia* had the longest crown, in absolute terms, while *E. utile* had the shortest crown (Table 5.5). Considering relative crown length – which gives a clearer picture of crown proportion, and which is represented by the crown ratio – *N. laevis*, with a crown ratio of 0.75, had the longest mean relative crown length among all the species with *E. utile* having the shallowest crown. *N. laevis* also had the smallest crown diameter (2.2 m) and crown area (3.8 m^2) among all the species, implying that effective shade provision per tree is low and will therefore require more trees per farm to provide effective shading. This will however mean increased competition for below-ground resources, and coupled with its short bole, it could also result in adverse microclimatic conditions that could favour an increased incidence of pest and diseases. Apart from *N. laevis*, the relatively large mean crown diameters and crown areas of the other species, especially *A. adianthifolia, K. anthotheca, T. ivorensis* and *T. tetraptera* (Table 5.5), means they can cover larger areas per tree.

With regards to light transmission to below-ground arrays, the higher PAR and R/FR values recorded in the dry season for all the species could be due to a higher irradiance usually received by the canopy during the dry season, as a result of reduced cloud cover as pointed out by Chazdon & Fletcher (1984) and Rich *et al* (1993), and the reduced leaf cover. The R/FR ratios found beneath the canopies of the shade tree species (0.3 – 1.16) are comparable to figures reported by Varlet-Grancher *et al* (1993). Both crown length and crown diameter, in general, had poor, negative correlations with both PAR and R/FR transmission; and these were insignificant. Bellow and Nair (2003) also found weak negative correlation between crown diameter and PAR transmission in a shaded perennial agroforestry system in Costa Rica. In their study, crown length also showed a weak correlation with PAR transmission. Thus both crown depth and crown diameter did not significantly affect PAR and R/FR transmission through the crowns of the seven shade tree species studied. This conclusion is also supported by Wang and Jarvis (1990) who stated that the influence of crown shape (which is a ratio of crown length to crown diameter) on the daily amounts of PAR absorbed by the tree crown in a stand is very small. However, investigating light transmission and radiation use efficiency by loblolly pines, McGrady and Jokela (1998) found significant correlation between total tree height and live crown length on one hand, and PAR transmission, and, citing Tadaki (1977), concluded that both variables favour more efficient light interception by distributing foliage throughout the crown (large vertical distances), and by placing the crown above competing vegetation.

The only assessed parameter which had a strong correlation with PAR and R/FR transmission was leaf cover. The negative correlations mean that more light is transmitted through the crowns of the shade tree species as leaf cover reduces. Wang and Jarvis (1990) found a significant influence of total area of leaves on PAR transmission in Sitka spruce and concluded that the total area of leaves and their spatial distribution within a tree crown are far more important than either crown shape or leaf inclination angle distribution of the crown in their influence on PAR transmission. They pointed out that the total area of leaves within the tree crown plays a predominant role in determining the physical and physiological processes of the canopy. The amount of leaves on the crown of a tree (leaf cover) at any given time will directly determine both total area of leaves and their spatial distribution on the crown, hence Wang and Jarvis' (1990) findings can be applied to these species. The increased PAR and R/FR transmission with decreasing leaf cover, which generally coincides with the dry season, have implications for shade tree-cocoa complementarity. As pointed out by Broadhead et al., (2003a & b), the dry season patterns of lower leaf cover and higher PAR and R/FR transmission will imply reduced below-ground and above-ground competition between the shade trees and the cocoa crop for water and nutrients and for light. Thus *A. adianthifolia*, *T. ivorensis* and *T. tetraptera*, with their lower leaf cover and higher PAR and R/FR transmittance in the dry season, compared to the other species, coupled with their larger crown areas appear to present better temporal complementarity with the below-canopy crop, at least in the dry season. However, the higher PAR transmission during this period, when the intensity of the sun is higher, will also mean big reductions in shade levels for the cocoa; therefore a combination of these with the other species, especially the *Entandrophrama spp.* and *K. anthotheca* will seem more appropriate.

CHAPTER 6

SEED PRETREATMENT, GERMINATION AND VEGETATIVE PROPAGATION OF SELECTED SHADE TREE SPECIES – *T. tetraptera*

6.1. Introduction

Soil acidity and drought associated with degraded cocoa soils are major constraints to plant growth and development. Hence if a species has the ability to initiate and complete the germination process and further seedling development under these sub-optimal edaphic conditions, it is an early indication of the species' potential for acid tolerance. Although a species may be drought resistant and acid tolerant and thus be able to germinate and grow under the sub-optimal soil conditions found on degraded cocoa lands, the germination of the seeds may be delayed because of seed dormancy, due to the hard impervious seed coat, such as encountered with seeds of *Tetrapleura tetraptera.*

Dormancy itself is presented as a physiological state in which germination is blocked by a seed-related mechanism, as opposed to lack of germination due to inadequate environmental conditions. This state can be induced by environmental and/or material effects during seed development or after dispersal, and can consist of many different mechanisms, which arrest continued development at any one of the steps necessary for seed germination (imbibition, activation of metabolism, visible growth). Thus dormancy and germination are concurrent processes, since the dormant seed can progress to different stages in the germination sequence depending on the point(s) at which development is blocked. Breaking dormancy, or successful completion of the germination process, requires that all the necessary elements for germination be in place and functioning (Eira, 1983). Citing Barton (1965), Phartyal *et al.,* (2002) also pointed out that dormancy in many seeds is caused by the inhibitory influence of structures covering the embryo, like testa and endocarp. Species of the tropical highland zones possess varying degrees of dormancy requiring specific moist stratification treatments to overcome the condition; and depending on the type of dormancy, the pre-treatment requirement differs. The most common pre-treatments, according to Phartyal *et al.,* (2002), are warm or cold moist stratification, chemical or mechanical scarification, soaking of seeds in hot and cold water, etc. If a seed is not exposed to sufficient moisture, proper temperature, oxygen, and for some species light, the seed will not germinate. In this case, the seed's dormancy is due to unfavourable environmental conditions. On the other hand, some seeds may not germinate because of some inhibitory factor of the seed itself. This particular kind of dormancy consists of two general types (Evans and Blazich, 2004):

- Seed coat or external dormancy
- Internal (endogenous) dormancy

The seeds of *Tetrapleura tetraptera* belong to the first group, and are difficult to germinate normally due to their hard seed coat. Seed coat dormancy results from a seed's hard seed coat that is impervious to water and gases. The seed will not germinate until the seed coat is altered physically. Any process of breaking, scratching, or mechanically altering the seed coat to make it permeable to water and gases, known as scarification, will greatly enhance germination of such seeds. Scarification can be done by soaking seeds in acid, usually sulphuric acid, (acid scarification), or by physically abrading the seed coat (mechanical scarification), or by soaking seeds in hot water (hot water scarification). All these methods have their varying degrees of success depending on the thickness of the seed coat.

Reports in the literature have indicated the effectiveness of concentrated sulphuric acid scarification pre-treatment in breaking seed dormancy and enhancing germination of legume seeds (e.g. Doran *et al.,* 1983; FAO, 1985; Vora, 1989; Hashim, 1990). However, differences in optimum scarification time (period of exposure to acid) for maximum germination response occur in different species (Bebawi and Mohamed, 1985; Kariuki and Powell, 1988). Hence for an efficient use of the sulphuric acid pre-treatment method, knowledge of the optimum time length of seed exposure to the acid to achieve maximum germination response for a species is essential.

There is ample literature on the ecology, regeneration, seed phenology and germination of seeds of some Ghanaian forest tree species (e.g. Kyere, 1994; Hawthorne, 1995; Swaine *et al.,* 1997). Vegetative propagation techniques, however, offer an opportunity to produce a reliable and adequate supply of planting stock (Tchigio and Duguma, 1998). The development of a fast and economic means of raising superior planting stock through vegetative propagation also offers a means to greatly enhance the management of the species for cocoa rehabilitation.

6.1.2. Hypothesis and study objectives

The hypothesis for this study is that germination of *T. tetraptera* seeds can be significantly enhanced by pretreating seeds before sowing. It is further hypothesised that planting stock of this species can also be raised from juvenile stem cuttings and that the rootability of such cuttings will be improved by the use of rooting hormnes.

The specific objectives for this study were to:

1. determine the effect of different seed pre-treatment techniques on the germination of *T. tetraptera* seeds;
2. determine the effect rooting hormone (IBA) treatments on the rooting of leafy stem cuttings of *T. tetraptera*;
3. determine the effect leaf area on the rooting of leafy stem cuttings of *T. tetraptera.*

Studies were, therefore, carried out to ascertain the optimum time length for effective scarification of *Tetrapleura tetraptera* seeds in concentrated sulphuric acid. Due to the limitations of the use of sulphuric acid by the farmers because of the dangers involved, it was also necessary to explore the use of other acid media that will be readily available to the local farmers. Hence the use of the acidic juice from the locally grown and readily available *Citrus jambhiri* Lush. was also investigated. In addition, the effects of mechanical scarification and hot water scarification, as well as cold water treatment, on germination of the seeds were also investigated.

Since no report is available in the literature on the vegetative propagation of *Tetrapleura tetraptera*, a study was also undertaken in Ghana to assess the rooting capability of juvenile stem cuttings of the species in a non-mist propagator.

6.2. Materials and methods

6.2.1. Seed pre-treatment and germination trials

Seeds of *Tetrapleura tetraptera* collected from trees growing in the wild were used for this experiment which was carried out in the laboratory of the Forestry Research Institute of Ghana (FORIG).

Seeds were first placed in large quantities of water to facilitate the removal of seeds which were floating (as these represented non viable seeds).

Treatments tested were:

1. Acid scarification – using concentrated H_2SO_4, and citric acid from lemon fruits
2. Hot water scarification
3. Mechanical scarification – by rubbing seeds between two sheets of sand paper, and by light pounding in a mortar, in 50:50 mixture with sand
4. Cold water treatment
5. Control – no special treatment

The experiment was divided into two (2) parts for ease of implementation.

6.2.1.1. Part 1: Acid Scarification

Two types of acids were tested to determine their efficacy in overcoming seed dormancy in *T.* tetraptera. These were sulphuric acid and citric acid. The citric acid was obtained from locally grown lemon (*Citrus jambhiri* Lush.) trees, by cutting ripened fruits in two and sqeezing the juice from them.

Four (4) time-length treatments (5, 10, 15 and 20 minutes), and a control (C), were applied to test the effect of 98% concentrated H_2SO_4 scarification on seed germination. The citric acid treatment involved soaking of the seeds in the undiluted lemon juice, obtained as above, for 12 hours. A control treatment, where seeds were not give any pre-treatment was also tested.

For each treatment 100 seeds were taken and their mean mass ±se recorded. Each batch of 100 seeds was placed in a large dry glass beaker and 30ml of 98% concentrated H_2SO_4 and the lemon juice (citric acid) decanted over them. The seeds were stirred occasionally with a glass rod for the specified length of time for each treatment. Immediately the time was reached for each treatment, seeds were washed thoroughly in free running tap water for about 5 – 10 minutes to remove all the acid.

For each treatment the scarified, washed seeds were placed between sheets of moistened paper towels in covered germination trays (20 seeds per germination tray for each of the 5 acid treatments and the control). The control treatment was set up with unscarified seeds. The germination trays were then kept in the greenhouse at a temperature of 27/20±2°C day/night.

Each treatment was replicated 4 times in a randomised complete block design consisting of four (4) blocks each containing six (6) Petri dishes containing the 5 acid and 1 control treatments.

6.2.1.2. Part 2: Other pre-treatment methods

i. Hot water treatment
ii. Cold water treatment
iii. Mechanical scarification

The Cold water treatment consisted of three (3) sub-treatments:

a. soaking in cold water for 6 hours
b. soaking seeds in cold water for 12 hours
c. soaking for 24 hours

Mechanical scarification involved rubbing the seeds between two sheets of sand paper, and pounding a 50:50 mixture of seed:sand in a mortar, to wear off part of the seed coats.

For the Hot water treatment, seeds were poured into boiling water and the water left to cool to room temperature. The boiling water was obtainedby heating water in an electric kettle to boiling point and then pouring this over the seeds in a glass beaker.

In effect there were six (6) treatments for this second experiment, and these were:

a. Hot water Scarification
b. Mechanical Scarification:
    i. Sand paper abrasion
    ii. Pounding a 50:50 seed:sand mixture in a mortar
c. Cold water treatment:
    i. C6
    ii. C12
    iii. C24

Set up was in a randomised complete block design with 4 replicates, as for Part 1.

6.2.2. Vegetative propagation of *Tetrapleura tetraptera*

There are numerous propagation systems used in commercial horticulture. These are usually based either on spraying mist, fogging or enclosing the cuttings in polythene. Leakey *et al* (1990) reported on some low cost techniques for the vegetative propagation of tropical trees. The basic features of all propagators are aimed at improving the rooting environment of cuttings. Non-mist propagators (Longman, 1993) were used in this experiment, to investigate the effect of the presence of leaves and the application of growth regulator on rooting of juvenile stem cuttings of *Tetrapleura tetraptera*.

Since indole-3-butyric acid (IBA) has been proven as a hormone of choice for tropical tree species (Longman, 1993; Hartmann and Kester, 1997), it was used in this experiment.

Cuttings were prepared from leader shoots and branches of vigorously growing coppice shoots. Length of cuttings was dependent on internode length, but was cut to contain two internodes. Terminal buds were clipped off from all cuttings but lateral buds, active or dormant, were retained along the entire length of the cuttings. Cuttings were prepared with or without leaves, and there were 4 leaf area treatments, viz:

(i) cuttings retaining a pair of untrimmed leaves;
(ii) cuttings retaining a pair of leaves trimmed to half of their original area;
(iii) cuttings with a pair of leaves trimmed to one third their original area;
(iv) leafless cuttings.

The cuttings were treated with IBA rooting hormones in four (4) concentrations: 0.2%, 0.4%, 0.8% and 1.6%, in addition to a control (0% – no auxin treatment). The rooting medium consisted mainly of washed, sterilised medium textured river sand, sieved through a 2 mm mesh. The cuttings were watered twice daily (mornings and late afternoons), using a knapsack sprayer, to main a high humidity in the propagator. Temperature in the propagators was measured at 29/20 ± 2°C day/night over the rooting period.

The experiment was divided into two parts. Part one investigated the effect of auxin concentration on rooting of leafy stem cuttings, with the leaves trimmed to half their size. It consisted of five (5) treatments containing ten (10) cuttings each and replicated 3 times in a randomized complete block design; giving rise to 150 cuttings altogether for this experiment. Part two investigated the effect of leaf area on rooting of stem cuttings, using one auxin concentration (0.4% IBA), and was made up of four (4) leaf area treatments with 10 cuttings per treatment, and replicated 3 times in a randomized complete block design. Thus 120 cuttings were used for this experiment.

6.3. Data collection and analysis

6.3.1. Seed pre-treatment and germination

6.3.1.1. Percent germination

Germination was monitored daily for one week. The primary data on number of seeds germinating over the specified time periods were recorded and used to calculate percent germination. Details of the analytical method for percent germination have been reviewed by Scott *et al* (1984).

Data was tested for normality using the Kolmogorov-Smirnov test, before further statistical analysis was performed (Appendix 6.1). Arcsin transformations were performed on percent germination data before significant levels of treatment effects were determined by analysis of variance. Significant differences in treatment means were separated by Tukey's multiple range test at $P<0.05$. All statistical analyses were performed using the Minitab 13 statistical package.

6.3.1.2. Germination index

Germination index (GI), which is an index of the resistance of the seeds to germination, was calculated from the formula:

$$GI = \Sigma T_i N_i / S$$

where T_i is the number of days after sowing, N_i is the number seeds germinated on day i, and S is the total number of seeds sown (Scott *et al.,* 1984).

Analysis of variance for the values for GI was performed and the Tukey's multiple comparison test used to separate treatment means.

6.3.1.3. Coefficient of velocity

The coefficient of velocity (CV), which is a measure of the distribution of germination over time, for each treatment was calculated as:

$$CV = 100[\Sigma N_i/\Sigma N_i T_i]$$

Where N is the number of seeds germinated on day i and T is the number of days from sowing (Scott *et al.,* 1984).

Values of CV for the different treatments were subjected to an analysis of variance and the Tukey's test for differences in treatment means, using the Minitab 13 statistical package.

6.3.2. Vegetative propagation

It has been pointed out that the capacity for stem cuttings to form roots can be assessed by: (a) the percentage of cuttings rooted; (b) the number of roots per rooted cutting; and (c) the speed with which roots emerge after setting. These three criteria are not necessarily related, although the longer a cutting takes to root the fewer roots develop (Leakey, 1985).

In this study, therefore, the proportion of cuttings rooted and unrooted was counted and recorded weekly for five weeks. The number of roots formed per cutting was also recorded for each treatment.

All recorded data were tested for normality using the Kolmogorov-Smirnov test (Appendix 6.2), before further statistical analysis was performed. The data for percentage rooting was transformed using the arcsin transformation while root numbers were transformed using square root transformation, before analysis of variance was performed. Where the test for normality revealed non normal distribution in a particular data set, the Kruskal-Wallis test was used to confirm the results of the ANOVA. Since all the leafless cuttings failed to root within the trial period, statistical analysis for comparison and separation of means was performed on the remaining three leaf area treatments. Treatment means were separated using Tukey's multiple comparisons in the Minitab 13 statistical package.

6.4. Results

6.4.1. Seed pre-treatment

The effects of the different seed pre-treatment methods on the germination of *T. tetraptera* seeds are shown in Table 6.1 and Figure 6.1. Highly significant differences ($P<0.01$) were observed between the treatment means (Table 6.2). The highest germination percentage of 74.3% was obtained after seeds were scarified for 20 minutes with concentrated H_2SO_4, and this was 71.8% higher than the control. There was no germination recorded with the 24 hours cold water soaking during the one week that the experiment lasted. In general the H_2SO_4 scarification treatments gave the best results, overall, of over 60% germination within one week, while moderate germination (43.9%) was obtained with the citric acid obtained by squeezing the juice from lemon. Mechanical scarification by lightly pounding a 1:1 mixture of seeds and sand in a mortal also produced moderate germination of 29.4% within the one week trial period, while the germination obtained after rubbing the seeds between sheets of rough sand paper (sand papering) to wear off the seed coat was 5.4%. On the other hand, the germination rates obtained with both cold and hot water treatments during the same time period (1.1%, 3.3%, 0.0% and 1.2%) were very low.

With regards to the acid scarification treatments, the concentrated H_2SO_4 scarification for twenty minutes produced a significantly higher germination response (74.3%) than the other scarification time lengths which n turn did not differ significantly from each other. However, all the concentrated H_2SO_4 treatments produced significantly higher germination responses than the citric acid scarification.

Table 6.1: Germination response of *T. tetraptera* seeds to different pretreatment measures.

Treatments	Mean % germination (arcsin)	SD
H_2SO_4 (5 minutes)	66.4^a	4.0
(10 minutes)	62.8^a	5.2
(15 minutes)	66.5^a	9.5
(20 minutes)	74.3^b	4.0
Citric acid	43.9^c	8.2
Sand papering	5.4^d	6.0
Light pounding	25.8^e	11.9
Cold water soak – 6hrs	1.1^{fg}	2.0
- 12hrs	3.3^f	2.0
- 24hrs	0.0^g	0.0
Hot water soaking	1.2^{fg}	2.1
Control	2.5^f	4.2

Means carrying different letters as superscripts are significantly different at $P<0.01$ according to the Tukey's multiple comparison test.

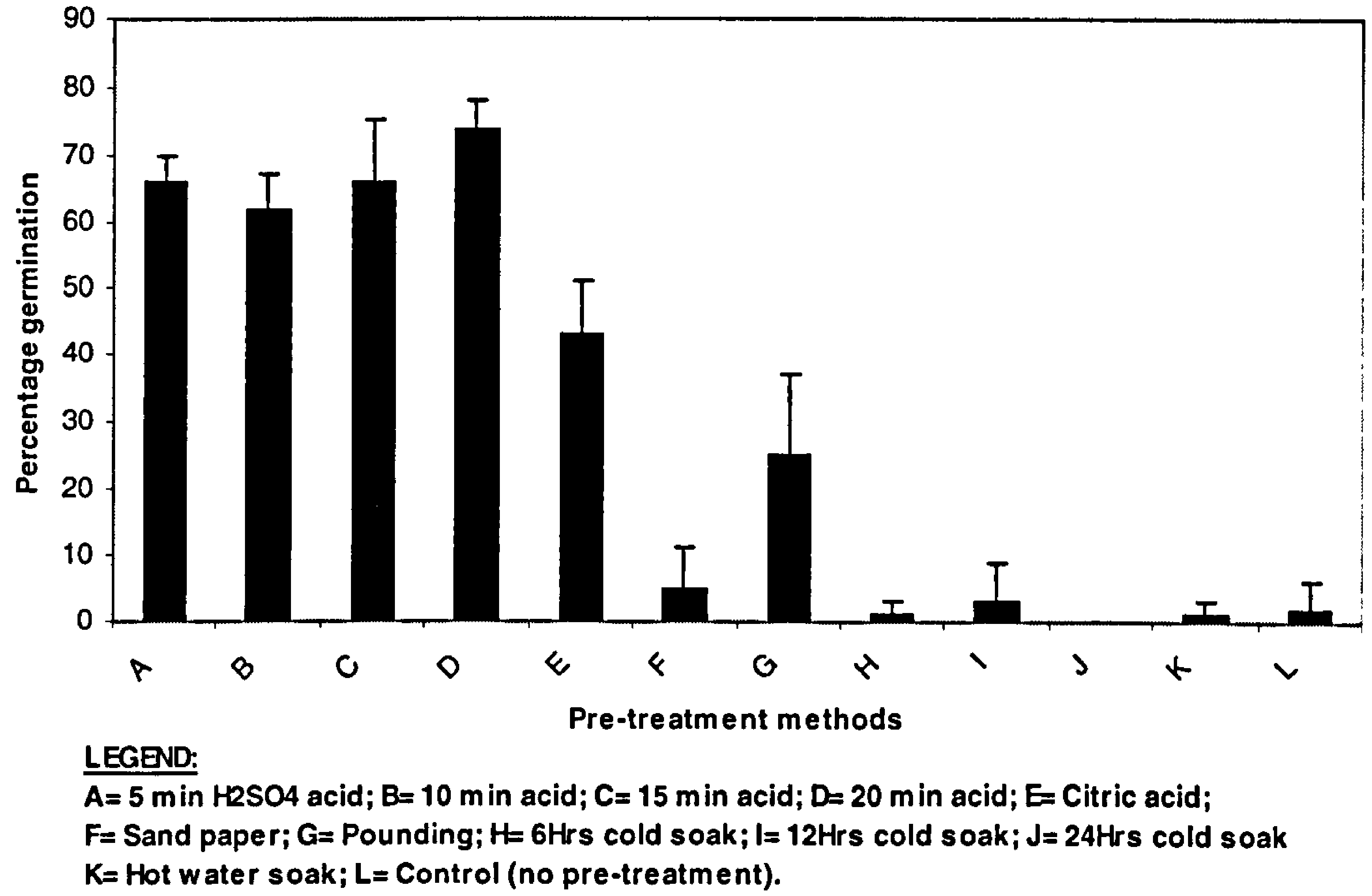


Figure 6.1: Germination response of *T. tetraptera* seeds to different pre-treatment methods (values presented are mean±se).

Table 6.2: Analysis of variance for effect of different pre-treatment methods on mean germination percentage of *T. tetraptera* sseds.

Source	DF	SS	MS	F	P
Treatment	11	26100.4	2372.8	59.09	0.000
Error	36	1445.6	40.2		
Total	47	27546.0			

Since the cold and hot water treatments and the control did not produce any good response they were left out of any further analysis. Thus germination index and coefficient of velocity computations were done for the acid and mechanical scarification treatments only. Tables 6.3 and 6.5 and Figures 6.2 and 6.3 show the values for germination index and coefficient of velocity, respectively, and indicate the effects of the different acid and mechanical scarification on germination time in *T. tetraptera*. There were significant differences ($P<0.01$) in the effects of the different scarification methods on the rate at which germination occurred (Tables 6.4 and 6.6). All the H_2SO_4 treatments and the light pounding resulted in significantly higher germination indices and stimulated coefficient of velocity, although the fastest germination resulted from the H_2SO_4 scarifications.

Table 6.3: Effect of different seed scarification methods on Germination Index of *T. tetraptera* seeds.

Treatment	Mean Germination Index	SD
H_2SO_4 – 5 minutes	6.10^{a}	3.39
- 10 minutes	5.53^{ab}	4.99
- 15 minutes	4.82^{ab}	2.90
- 20 minutes	6.06^{a}	2.65
Citric acid	4.44^{b}	3.10
Sand papering	0.24^{c}	0.40
Light pounding	4.46^{a}	3.34

Means carrying different letters as superscripts are significantly different at $P<0.01$ according to the Tukey's multiple comparison test.

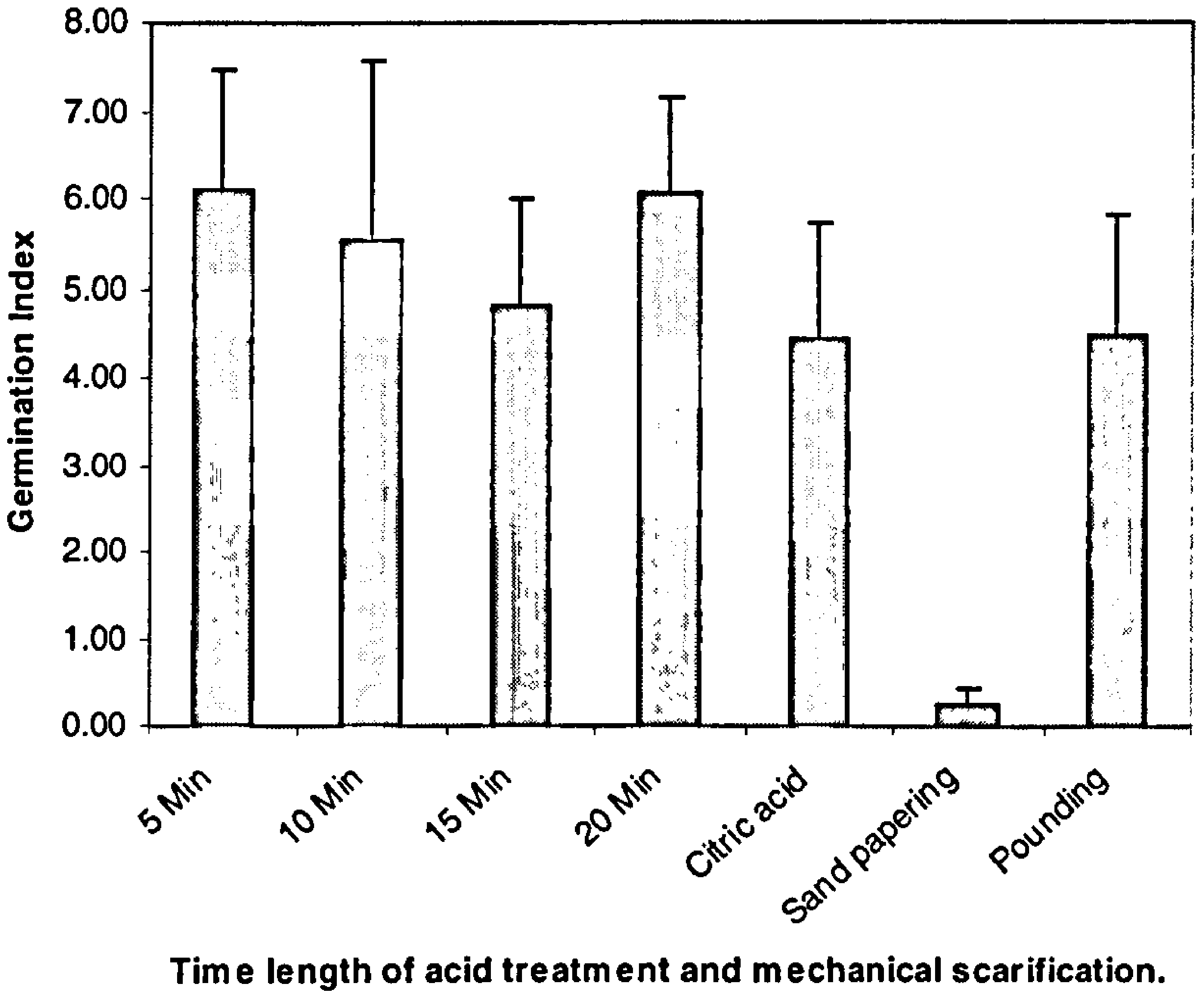


Figure 6.2: Effect of different scarification methods on the germination index of *T. tertraptera* seeds (values are means±se).

Table 6.4: Analysis of Variance for Germination Index of *T. tetraptera* seeds.

Source	DF	SS	MS	F	P
Treatment	6	149.25	24.87	2.72	0.028
Error	35	319.56	9.13		
Total	41	468.81			

There was no significant difference between the effects of the different sulphuric acid scarification times and the light pounding treatments and between the ten and fifteen minutes sulphuric acid and the citric acid scarification treatments. However, all the treatments resulted in significantly faster germination than the sand paper scarification Table 6.3).

Table 6.5: Effect of different pre-treatment methods on Coefficient of Velocity of *T. tetraptera* seeds.

Treatment	Mean Coefficient of Velocity (CV)	SD
H_2SO_4 – 5 minutes	24.88^{ac}	0.48
- 10 minutes	26.29^{a}	0.67
- 15 minutes	25.81^{a}	0.98
- 20 minutes	26.12^{a}	2.64
Citric acid	23.64^{ac}	0.99
Sand papering	6.71^{b}	13.41
Light pounding	22.45^{c}	0.76

Means carrying different letters as superscripts are significantly different at $P<0.01$ according to the Tukey's multiple comparison test.

Table 6.6: Analysis of Variance for Coefficient of Velocity (CV) for *T. tetraptera* seeds.

Source	DF	SS	MS	F	P
Treatment	6	1177.6	196.3	7.23	0.000
Error	21	570.3	27.2		
Total	27	1747.9			

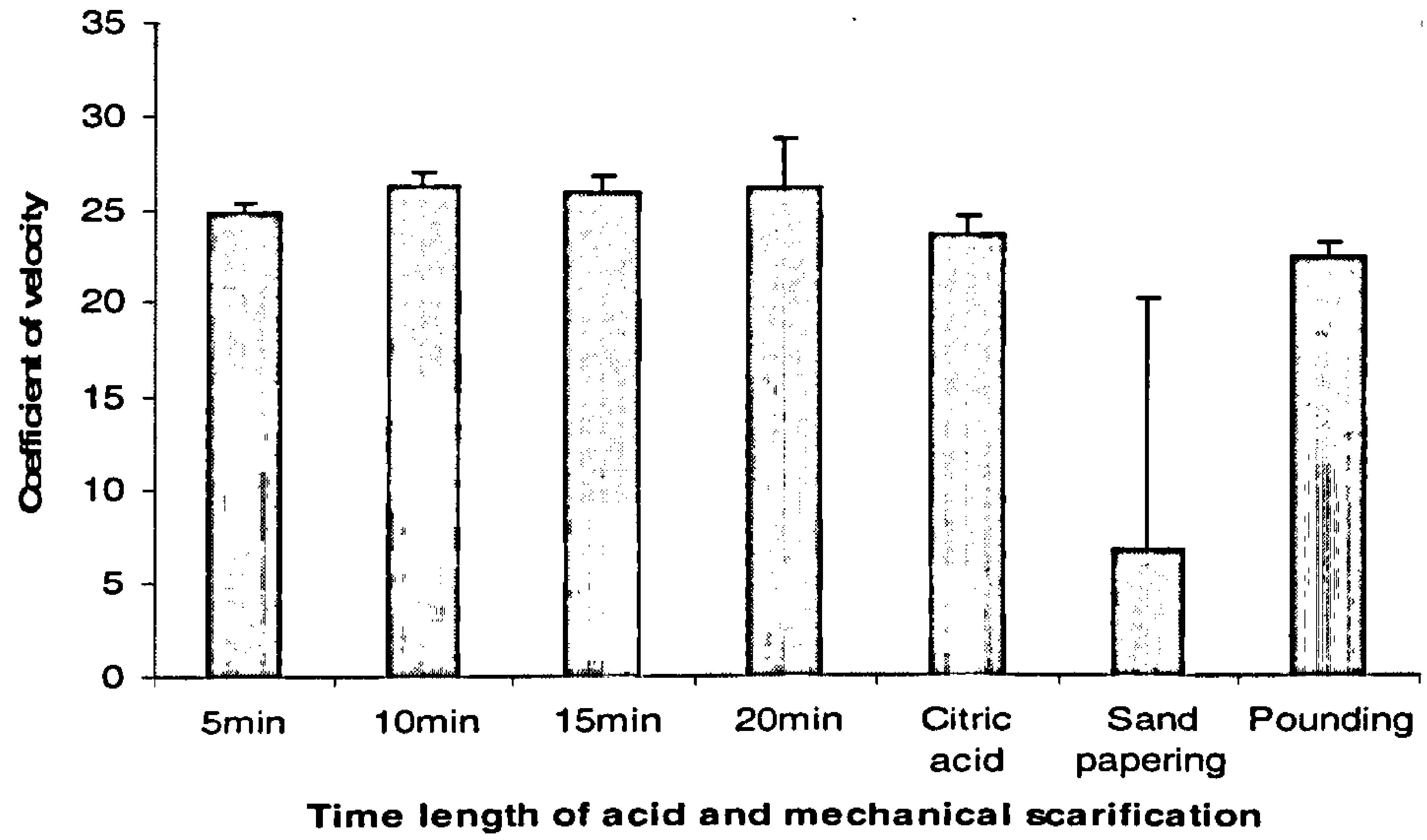


Figure 6.3: Effect of different scarification methods on coefficient of velocity of *T. tetraptera* seeds (values are means±se).

6.4.2. Vegetative propagation

Results of the effect of different hormone (IBA) treatment on the rooting of juvenile leafy stem cuttings of *T. tetraptera* and the number of roots produced per rooted cutting are presented in Table 6.7 and Figures 6.4 and 6.5. At the end of the five weeks experimental period, significant differences (P = 0.009) in rooting percentage were found between the control and all the IBA concentrations (Table 6.8). All the hormone treated cuttings resulted in significantly higher percentage rooting than the control (0% IBA). Among the hormone treated cuttings, the highest rooting percentage of 52.1% was observed in the cuttings treated with 0.4% IBA concentration, while rooting percentages of 50.2%, 48.3% and 41.0% were recorded for the 0.2, 0.8 and 1.6% IBA concentrations respectively. Increasing IBA concentration from 0.2 – 0.8% did not significantly influence rooting percentage of cuttings until the higher percentage of 1.6% when a significantly lower rooting percentage was observed.

The effect of IBA concentration on number of roots per rooted cutting was also significant (P = 0.000) (Table 6.9). The highest mean number of roots per rooted cutting (13.6) was obtained in the 0.8% IBA concentration while the lowest mean number of roots of 4.2 was recorded in the control. The concentrations of 0.2 – 0.8% IBA all produced significantly higher number of roots per rooted cutting than the control and the 1.6% IBA treatment, but did not differ significantly from each other (Table 6.7 and Figure 6.5).

Table 6.7: Effect of rooting hormone on rooting of juvenile leafy stem cuttings of *T. tetraptera* five weeks after insertion.

Treatment	Mean percentage rooting (±se)	Mean number of roots per rooted cutting (±se)
Control (0%)	$8.2(0.54)^a$	$4.2(0.39)^a$
0.2% IBA	$50.2(1.20)^b$	$10.6(0.31)^b$
0.4% IBA	$52.1(1.01)^b$	$12.5(0.45)^b$
0.8% IBA	$48.3(0.63)^b$	$13.6(0.34)^b$
1.6% IBA	$41.0(1.45)^c$	$8.4(0.40)^a$

Means carrying the same superscript are not significantly different at P<0.01 (Tukey's multiple comparison test).

Table 6.8: Analysis of Variance for effect rooting hormone treatment on rooting percentage of leafy stem cuttings of *Tetrapleura tetraptera*.

Source	DF	SS	MS	F	P
IBA conc	4	628.2	157.05	3.85	0.009
Error	45	1837.1	40.82		
Total	49	2465.3			

Table 6.9: ANOVA for effect of IBA concentration on number of roots per rooted cutting of leafy stem cuttings of *T. tetraptera*

Source	DF	SS	MS	F	P
IBA conc	4	556.72	139.18	95.91	0.000
Error	45	65.30	1.45		
Total	49	622.02			

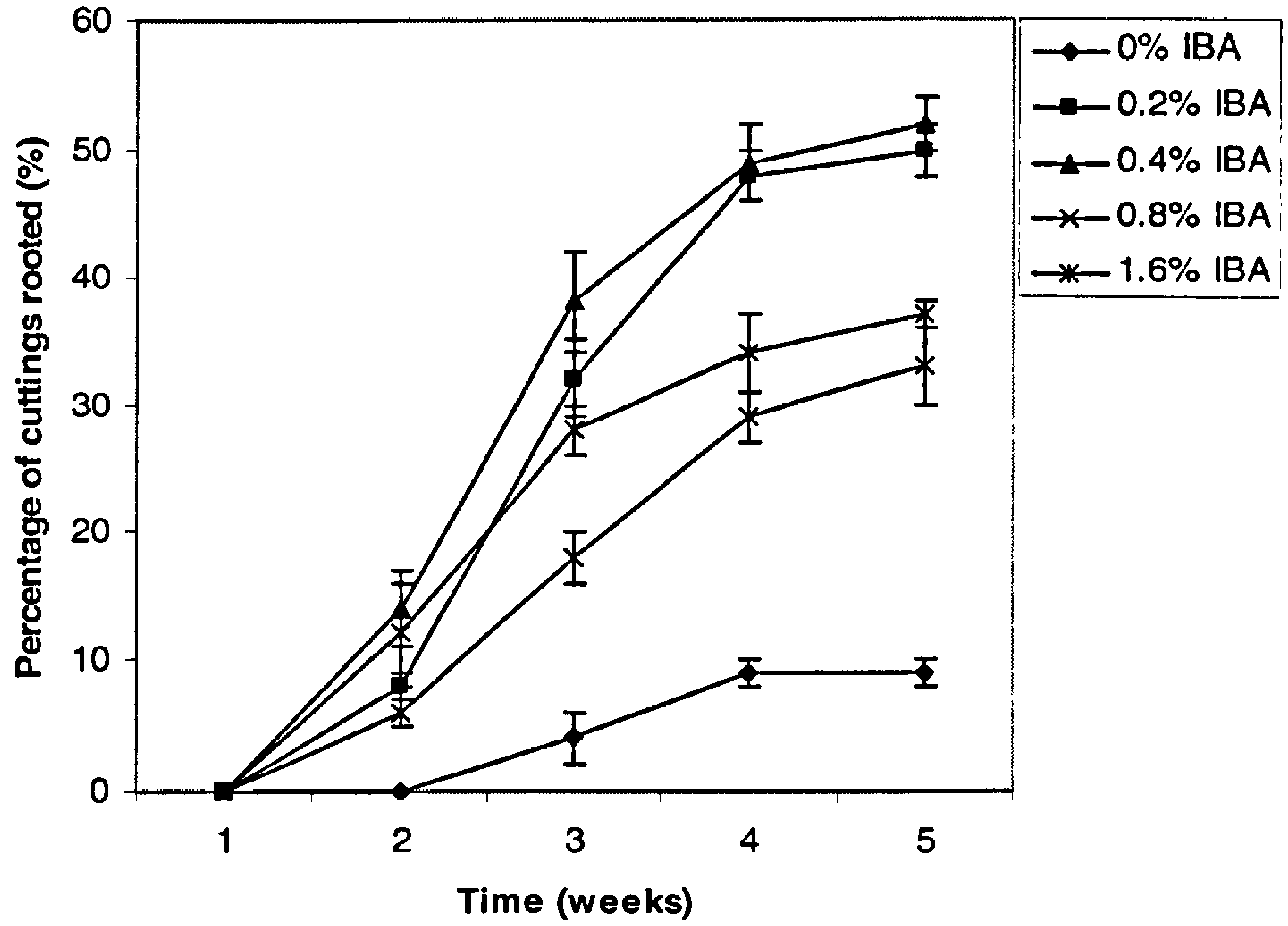


Figure 6.4: Effect of IBA concentration on rooting percentage of leafy stem cuttings of *Tetrapleura tetraptera* (values are means±se).

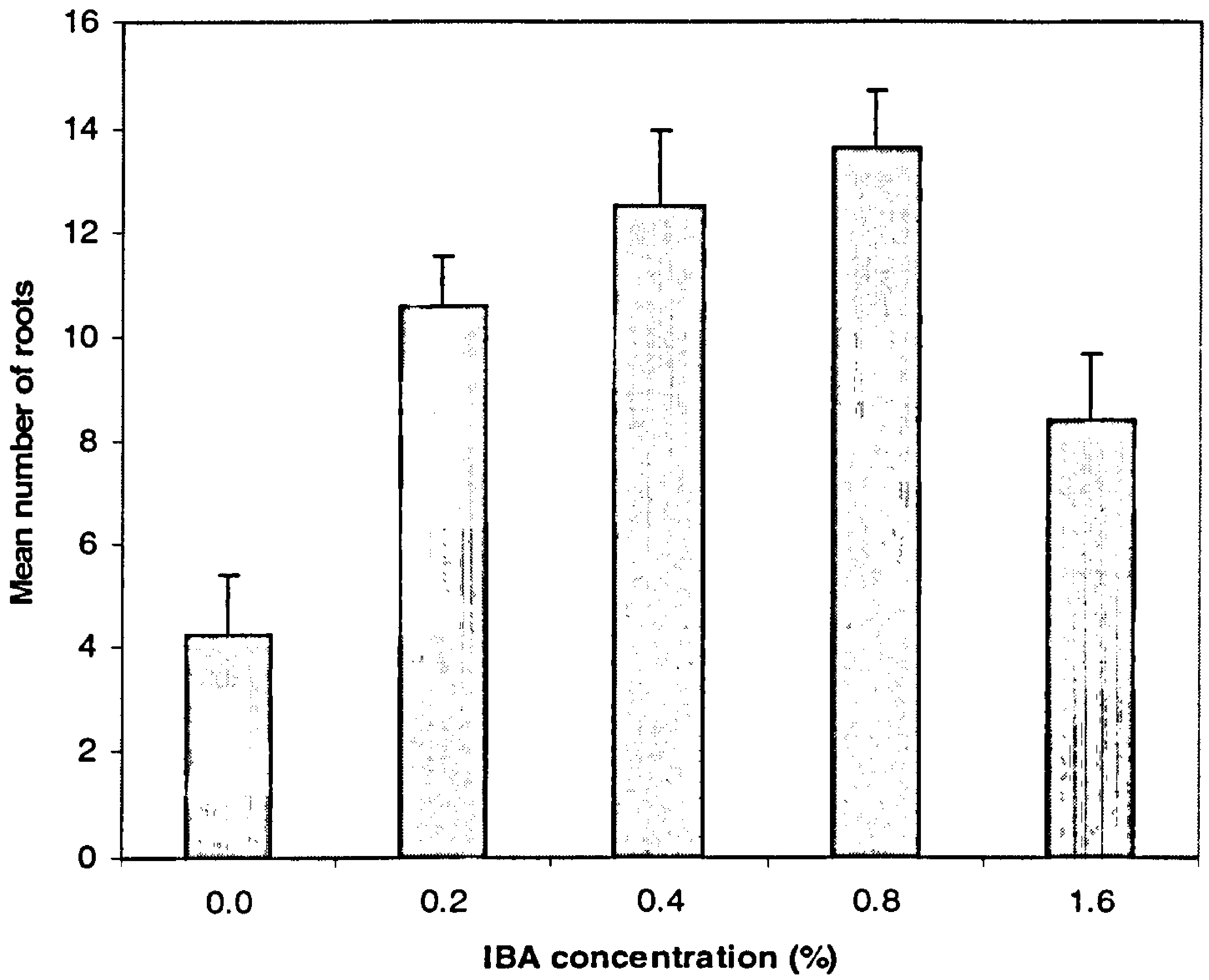


Figure 6.5: Effect of IBA concentration on number of roots per rooted cutting of leafy stem cuttings of *T. tetraptera* (values are means±se).

Table 6.10 and Figures 6.6 and 6.7 present the results of the effect of different leaf sizes on the rooting percentage and number of roots produced per rooted cutting. At the end of the five week period, none of the leafless cuttings produced roots. Rooting percentage increased from one-third leaf size (51.6%) to half leaf size (54.3%), but tended to decrease in the cuttings with untrimmed leaves to a mean of 42.1% (Table 6.10 and Figure 6.6). The analysis of variance showed that leaf size had a significant effect on rooting percentage (Table 6.11), with the one-third and half leaf sizes producing significantly higher rooting percentages (P = 0.001; Table 6.11) than the cuttings with untrimmed leaves. No significant difference was however found between the proportion of one-third leaf and half-leaf cuttings rooted at the end of five weeks (Table 6.10).

With respect to the number roots produced per rooted cutting the results show that, although the half trimmed cuttings produced the highest mean number of roots (5.3) per rooted cutting, the different leaf size treatments had no significant effect (P = 0.640; Table 6. 12); leafless cuttings produced no roots (Table 6.10 and Figure 6.7).

Table 6.10: Effect of leaf trimming on the rooting of leafy stem cuttings of *T. tetraptera.*

Treatment	Mean percentage rooting (±se)	Mean number of roots per rooted cutting (±se)
Leafless	$0(0)^a$	$0(0)^a$
Full leaf	$42.1(0.73)^b$	$3.9(0..38)^b$
Half trimmed	$54.3(0.66)^c$	$5.3(0.30)^b$
Trimmed to 1/3 size	$51.6(1.01)^c$	$3.1(0.43)^b$

Means carrying the same superscript are not significantly different at P<0.01 (Tukey's multiple comparison test).

Table 6.11: ANOVA for effect of leaf trimming on rooting percentage of leafy stem cuttings of *T. tetraptera.*

Source	DF	SS	MS	F	P
Leaf area	2	1.4717	0.7358	8.40	0.001
Error	27	2.3638	0.0875		
Total	29	3.8355			

Table 6.12: ANOVA for effect of leaf trimming on number of roots per rooted cutting of leafy stem cutting of *T. tetraptera.*

Source	DF	SS	MS	F	P
Leaf area	2	276	138	0.45	0.640
Error	27	8201	304		
Total	29	8477			

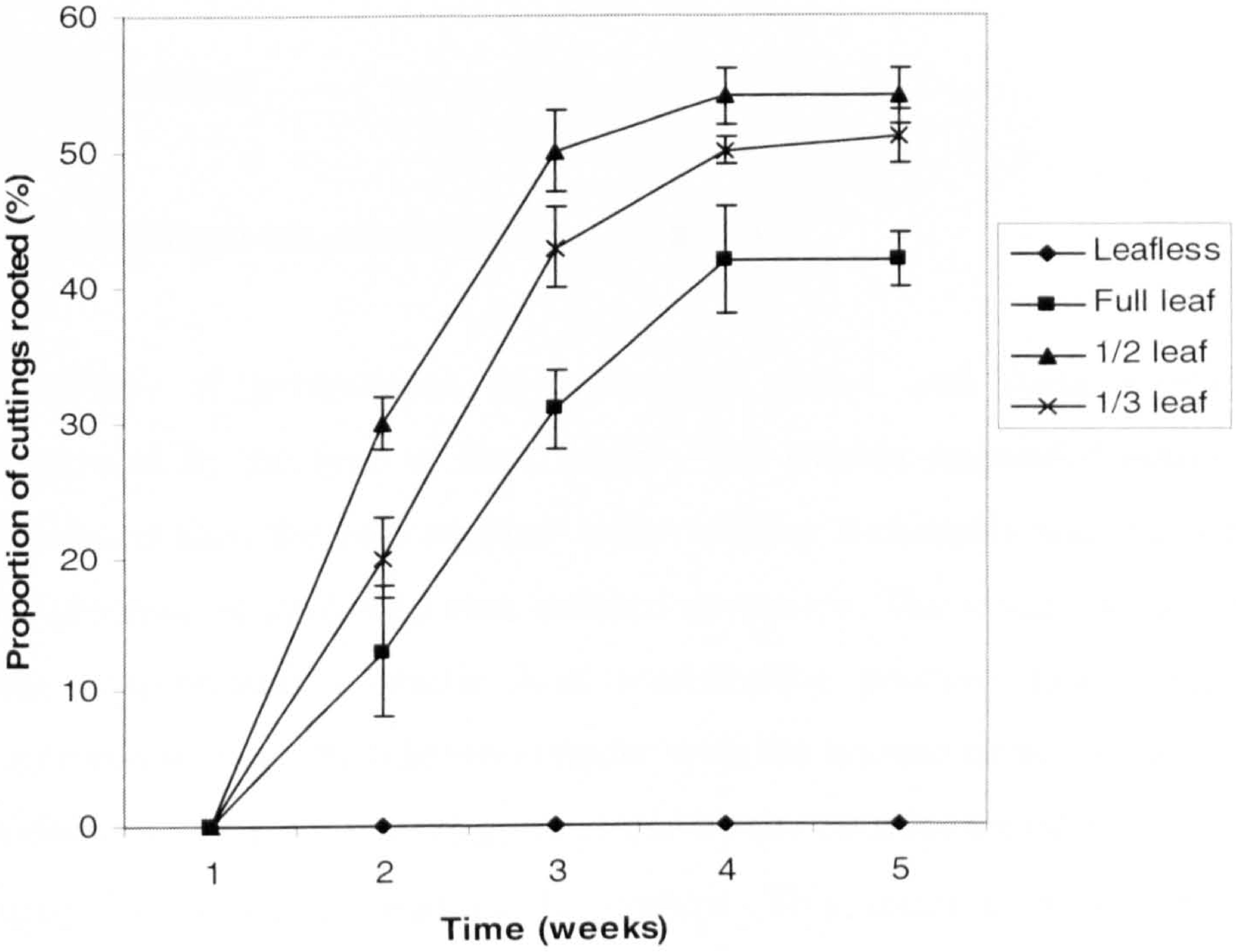


Figure 6.6: Effect of leaf trimming on rooting percentage of leafy stem cuttings of *T. tetraptera* (values are means±se).

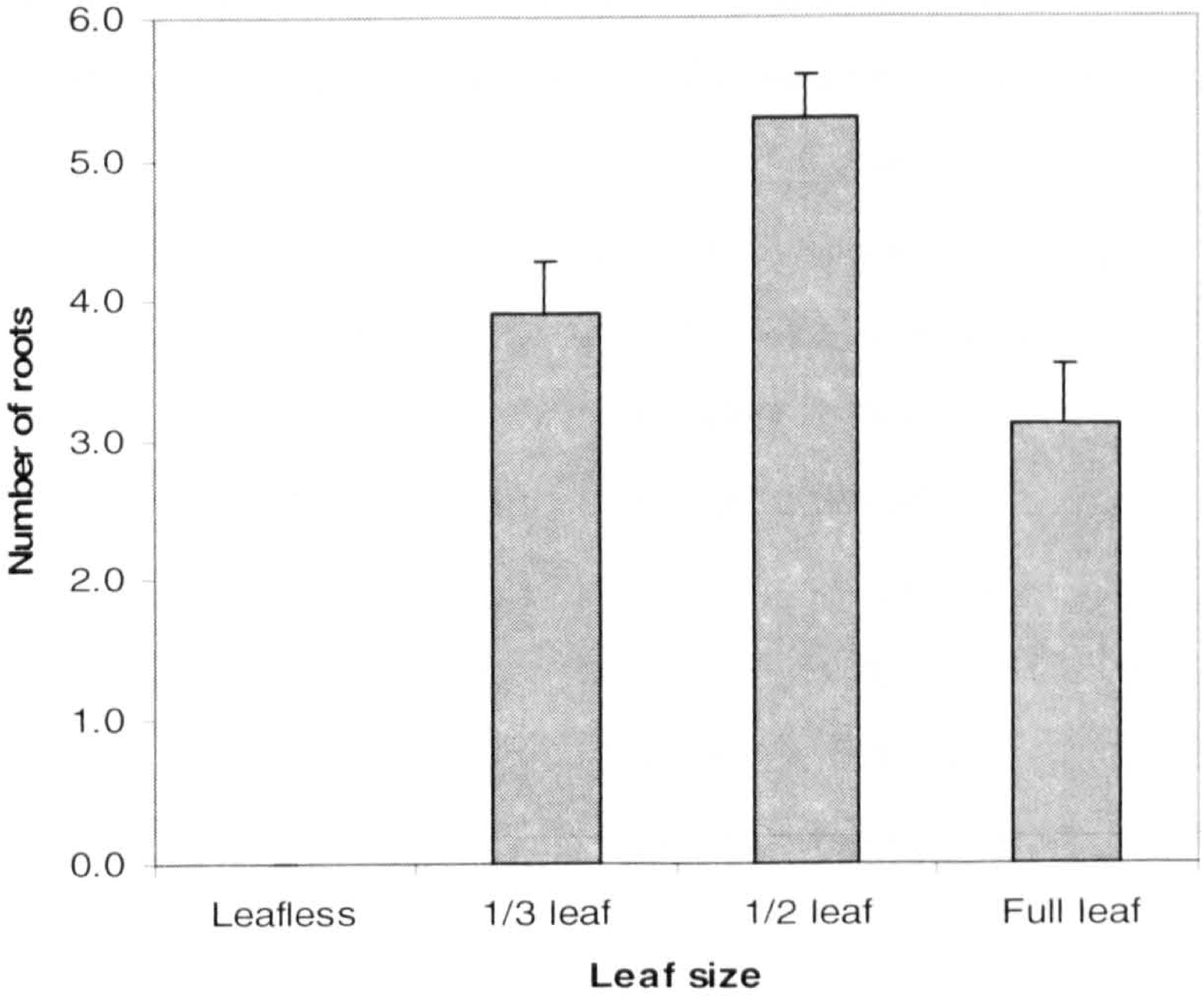


Figure 6.7: Effect of leaf trimming on number of roots per rooted cutting of leafy stem cutting of *T. tetraptera* (values are means±se).

6.5. Discussion

6.5.1. Seed pre-treatment and germination.

A variety of germination responses was found, and these appear to be clearly influenced by the type of scarification. The species responded better to scarification treatments than the cold and hot water soaking treatments and the control, indicating the presence of hard seed coat induced dormancy. The results of the experiment show that concentrated sulphuric acid scarification produce much higher germination responses than all the other treatments; with the highest germination response of 74.3% within one week after sowing, produced by the 20 minutes sulphuric acid scarification, being 71.8% higher than in the control. This result corroborates the findings of Odoemena (1988) who found a 90% germination response in the same species, after ten days. In a study in Niger, on four African *Acacia* species, Masamba (1994) also found that pre-treatment of seeds with sulphuric acid was most effective and produced 97% germination response.

The significantly higher germination response after the longest acid exposure time of 20 minutes is a further indication of a hard seed coat, requiring a longer time to soften in order to enhance inbibition of oxygen and water. The effectiveness of the longer acid scarification time for this species is comparable to findings by Bhagat *et al* (1992), who reported high percentage germination (70%) with *Indigofera gerardiana*, a common shrub of the northwest Himalayas, after soaking seeds in concentrated sulphuric acid for 90 minutes, and support the assertion that sulphuric acid scarification enhances germination, especially when an appropriate period of exposure of seeds to the acid is adhered to (Kariuki and Powell, 1988; Hashim, 1990). The concentrated sulphuric acid appears to have had a corrosive physical action on the hard seed coat of the *T. tetraptera* seeds thereby enhancing inbibition of water and oxygen, resulting in a higher germination capacity.

Although the citric acid scarification produced significantly lower germination responses than the concentrated sulphuric acid, the 43.9±8.2% germination percentage obtained was significantly higher than the germination obtained with other pre-treatment methods and can be viewed as quite comparable to the results with the sulphuric acid treatment. The citric acid appears to have a similar corrosive action on the seed coat as the sulphuric acid and the comparatively lower response achieved will be due to the fact that it is a milder acid. It is therefore possible that higher germination responses can be achieved with longer scarification times than the six hours applied in this experiment.

With mechanical scarification, pounding seeds in 1:1 seed:sand mixture produced moderate germination responses of 25.8±11.9% compared to the 5.4±6.0% obtained with the sand paper and the less than 4% germination obtained with the other pre-treatment methods and the control. The low result obtained with the sand paper treatment is possibly because the sanding was not done sufficiently to wear off the hard seed coat to an appreciable level. Nevertheless, the significantly higher germination percentage compared with the soaking and control treatments indicate an improvement water and oxygen inbibition. The high standard deviation (11.9%) of germination percentage observed in the pounding treatment will be due to the non-uniformity in the abrasion of the seed coat of the seeds, associated with this kind of technique. However, the moderate result obtained makes it a potentially viable pre-treatment procedure for local farmers.

The poor responses produced by the hot and cold water treatments and in the control are further indicative of a hard seed coat dormancy, which need to be broken before germination can occur within a short time after sowing; and the water treatments do not appear to be strong enough to render the seed coat permeable within the six to twenty four hours treatment times employed in this experiment.

The values of the Germination Index and Coefficient of Velocity give an indication of the speed with which germination occurs and the quantity of seeds germinating over time. Scott *et al* (1984) have pointed out that the magnitude of the Coefficient of velocity generally increases as more seeds germinate with shorter germination time. In this experiment, it was observed that apart from the sand paper scarification, which resulted in significantly lower Germination Index and Coefficient of Velocity (0.24 and 6.71 respectively), the acid and mechanical (pounding) scarifications resulted in similar Germination Indices and Coefficients of Velocity (Tables 6.3 and 6.5), though the sulphuric acid scarification generally produced higher values than the citric acid and pounding treatments.

In general, sulphuric acid scarifications and mechanical scarifications are known to result in rapid, uniform and high germination for many species (e.g., Cavanagh, 1987). Though the concentrated sulphuric acid scarification of the seeds was most effective in achieving high germination over the short time period, purchasing and handling such chemicals may not be realistic for the rural population. The moderate responses obtained with the citric acid (locally obtainable from citrus) and pounding treatments – 43.9% and 25.8% respectively – indicate that these techniques hold a good potential for a locally applicable and safe pre-treatment method that can be used by the local farmers for this species. The fact that these two scarification methods have germination indices and coefficients of velocities comparable to some of the sulphuric acid scarification treatments further indicate their comparable strengths as good alternative farmer friendly pre-treatment methods for *T. tetraptera.*

6.5.2. Vegetative propagation.

The role of auxins in promoting adventitious root formation in stem cuttings is widely documented, and has been attributed to their ability to promote the initiation of lateral root primordia and to enhance the transport of carbohydrates to the base of the cuttings (Leakey *et al.,* 1982; Hartmann *et al.,* 1997). Many authors have reported differences in rooting responses, depending on the exogenous auxin or combination of auxins used (Felker and Clarke, 1981; Klass *et al.,* 1987), and with the best results often obtained from IBA (Teklehaimanot *et al.,* 1996; Tchoundjeu *et al.,* 2004). However, highly contrasting responses to the addition of IBA have been reported for different tree species. In Ghana, for instance, Ofori *et al* (1996) reported an optimum IBA concentration for the rooting of *Milicia excelsa* (Welw.) C.C. Berg, a commercial timber tree species, to be 0.2%, which was substantially lower than the 1.6% optimum IBA concentration reported for the rooting of *Cordia alliodora,* another tropical timber species, in Costa Rica by Mesén *et al* (1997). On the other hand, a number of species, such as *Irvingia gabonensis* (Shiembo *et al.,* 1996), *Nauclea diderrichii* (Leakey *et al.,* 1990) and *Vochysia hondurensis* (Leakey *et al.,* 1990), have also been reported to be relatively insensitive to IBA concentration. In this experiment, IBA concentration was found to have a significant effect on both rooting percentage and the number roots per rooted cutting. The highest rooting percentage was attained at the IBA concentration of 0.4%, which was similar to the optimum IBA concentration of 0.4% reported for *Triplochiton scleroxylon* (Leakey *et al* 1982), but lower than the 1.6% IBA concentration for *Cordia alliodora* reported by Mesén *et al* (1997). In spite of the higher rooting percentage recorded at the 0.4% IBA concentration, the results indicate a range of optimum IBA concentrations, 0.2% to 0.8% for rooting percentage and number of roots per cutting, rather than a single optimum level, as there was no significant difference between the rooting percentages obtained at these concentrations (Table 6.7), thus indicating some similarity in rooting responses between this species and that reported for *Milicia excelsa* by Ofori *et al* (1996). The 8.2±1.7% rooting percentage recorded in the control treatment (without IBA application), though low, would indicate that the species is endowed with some endogenous auxins, making it possible to root without auxin application. However, this response is much lower than responses achieved without exogenous auxin application in *Irvingia gabonensis* (Shiembo *et al.*, 1996), *Milica excelsa* (Ofori *et al* 1996), *Nauclea diderrichii* (Leakey *et al* 1990) and *Vochysia hondurensis* (Leakey *et al.*, 1990), but is comparable with the 10% rooting obtained without IBA application for *Cordia alliodora* by Mesén *et al* (1997). On the other hand, the decline in rooting percentage at the highest IBA concentration of 1.6% would indicate that such high concentrations have inhibitory effects on root initiation, as reported for other species by Leakey *et al* (1990) and Ofori *et al* (1996).

Hartmann *et al* (1990) have pointed out that in many species, the presence of leaves on cuttings exerts a strong stimulatory influence on root initiation. In the rooting of leafy stem cuttings, the practice of trimming the leaf is carried out to minimize water loss while allowing sufficient photosynthesis to occur during propagation to enhance root development (Leakey and Coutts, 1989). As with exogenous auxin application, a number of contrasting results have been reported for the effect of cutting leaf area on the rooting percentage and number of roots per cutting of stem cuttings. While Leakey (1990) and Newton *et al* (1992) report no significant effect of cutting leaf area on the rooting percentages of *Nauclea diderrichii* and *Terminalia spinosa* respectively, cutting leaf area has been found to significantly influence the rooting percentage in a number of species including *Triplochiton scleroxylon* (Leakey *et al.*, 1982; Leakey and Coutts, 1989; Nketia *et al.*, 1998), *Hopea odorata* (Hamzah, 1992), *Irvingia gabonensis* (Shiembo *et al.*, 1996) and *Milicia excelsa* (Ofori *et al.*, 1996), among others. In this study, significantly higher rooting percentages of 54. 3% and 51.6% were recorded in the cuttings in which leaf sizes were reduced to half and one-third their original sizes, as compared to those with untrimmed leaves (42.1%). All the leafless cuttings failed to root (Table 6.8). This result is comparable with the results reported for the above species. The reduction in percentage rooting in untrimmed cuttings may be attributed to water stress due to high transpirational water losses and a consequent reduction in photosynthesis, as pointed out by Leaky and Coutts (1989) and Newton *et al* (1992). The failure of leafless cuttings of *T. tetraptera* to root is comparable to results obtained with leafless cuttings of *Terminalia spinosa* (Newton *et al.*, 1992) and *Irvingia gabonensis* (Shiembo *et al.*, 1996), and emphasizes the importance of the leaf in the rooting process due to its role in the provision of auxins and carbohydrates, as suggested by Leakey and Coutts (1989) and Newton *et al* (1992). It has been reported that leafy cuttings actively photosynthesise, thus providing reflux-soluble carbohydrates which enhance rooting (Leakey *et al.*, 1990; Newton *et al.*, 1992; Newton and Jones, 1993). Haissig (1982) also suggests that leaves are a source of auxins which may direct transport of sugars to the region of root primordia development. However, although leaf size significantly affected rooting percentage, its effect on the number of roots produced per rooted cutting was largely insignificant (Table 6.8), and compares with results reported for *T. spinosa* (Newton *et al* 1992), *T. scleroxylon* (Leakey and Coutts, 1989), *Hopea odorata* (Hamzah, 1992) and *M. excelsa* (Ofori *et al.*, 1996). It also compares with the findings for other species, such as *Accacia mangium*, *Olea spp.* and *Irvingia gabonensis* (Avidan and Lavee, 1978; Darus, 1988; Shiembo *et al.*, 1996) in which leafless cuttings failed to root.

The rooting percentages and number of roots per rooted cutting reported for this study appear to be relatively low, generally, compared with the results obtained in other studies with other species cited above. This is possibly due to a number of factors, among which could be the age and nutritional status of the stock plants from which the cuttings where collected. Cuttings where collected from coppiced plants, of varying ages, growing in the wild. Kantarli (1993) has pointed out that successful rooting from cuttings is affected by the age and the nutrient status of the donor trees, while Smits *et* *al* (1990) also point out that rooting of cuttings generally decreases with the age of the donor trees. A number of studies have also shown that cuttings derived from juvenile stock plants are easier to root than those collected from more mature stock plants (Welander and Snygg, 1987; Berhe and Negash, 1998). The donor stock had been growing in the wild for many years and under varying conditions. The rooting medium has also been shown to significantly influence both rooting percentage and number of roots per rooted cutting as it directly affects moisture and oxygen availability, both of which are crucial for successful rooting of cuttings (e.g. Anderson, 1986; Hartmann *et al.*, 1990; Leakey *et al.*, 1990; Ofori *et al.*, 1996; Shiembo *et al* 1996; Mesén *et al.*, 1997). Thus the results of this study may be considered to be conservative estimates of the rooting ability of this species. The rooting percentage could possibly be improved by choosing more suitable stock plants and rooting medium.

CHAPTER 7

COMPARATIVE GROWTH PERFORMANCE AND COMPETITIVE POTENTIAL OF PLANTED SHADE TREE SPECIES IN FARMERS' FIELDS AND ON-STATION.

7.1. Introduction

7.1.1. Initial growth performance of the planted species

Perennial tree crops are often grown as part of complex multistrata agroforestry systems that incorporate natural vegetation, either through enrichment planting in thinned forest (Preechapanya, 1996), or in rotational systems involving the natural regeneration of secondary forest together with a planted tree component (Gouyon *et al.*, 1993). Both of the above systems of utilizing natural vegetation also occur simultaneously in the cocoa agroforests of West and Central Africa (Gockowski and Dury, 1999). These systems have the potential to contribute to sustainable livelihoods of the rural populations while conserving biodiversity, but there is a critical need to increase their productivity, in order to enhance the living standards of the people who depend on them for a large proportion of their household income (Williams *et al.*, 2001).

In addition to the use of high yielding germplasm to improve productivity (Williams *et al.*, 2001), one way to ensure diversified and sustainable income, as well as improving biodiversity, in the face of the fast dwindling natural forest cover, is the planting of multipurpose shade trees on cocoa farms. Also, the increasingly shorter fallow lengths in the country, caused by increasing population pressure, as pointed out by Obiri (2003), will negatively impact on the regeneration of the shade tree species on fallow lands, putting the tree species in great danger of extinction, especially from farm lands. There is therefore the need for some of these species to be regenerated artificially through planting/enrichment planting. However, it has been pointed out that the selection of species to combine in mixed plantings demands more attention to the compatibility of growth characteristics (Menalled *et al.*, 1998). It is necessary to combine species that differ in such characteristics as height growth, among other characteristics such as shade tolerance, crown structure, phenology or rooting depth. If the species differ sufficiently, they will capture growing space and use resources differently when grown together in mixture. Such species will be able to coexist and are said to have high ecological combining ability (Harper, 1977 cited by Menalled *et al.*, 1998). The intensity of interspecific competition in such mixtures is likely to be less than that of intraspecific competition, and this has been found in some cases to lead to greater overall productivity in the mixtures than in monocultures of the component species – an outcome referred to as the competitive production effect or competitive reduction (Vandermeer, 1989; Kelty 1992; Menalled *et al.*, 1998)

This study was intended as a species screening trial to identify those species, among the selected trial shade tree species, that have the best initial growth potential. It evaluated initial diameter and height growth, as well as mortality, of the planted cocoa and shade tree species two years after planting.

7.1.2. Root structure of selected tree species

Ong *et al* (1996) have stated that the success of agroforestry systems generally depends on achieving complementarity in the capture and partitioning of resources between the tree and crop components. A principal aim of agroforestry is to create interactions between woody perennials, herbaceous crops or pastures, and their biotic and abiotic environments which increase the overall productivity of the land use system and/or its sustainability. To design new agroforestry systems or to optimize existing ones, these component interactions need to be understood (Schroth, 1995). While it has suggested that different rooting depths of trees and crops should increase resource capture without introducing intense below-ground competition (Huxley, 1983), research, in alley cropping systems, has revealed that differences in rooting depth are invariably not found and that competition for water and nutrients, rather than complementarity in their use, may result from combining fast-growing trees with crops in a single system (Daniel *et al.*, 1991; Ong *et al.*, 1991). Investigating water use in multistrata tea agroforestry systems in Malawi, Laycock and Wood (1963) observed that *Grevillea robusta* shade trees produced few superficial lateral roots and that most of its roots were oriented in a predominantly vertical plane. They then suggested that competition with tea for water was lower than that from the other tree species studied, because of this deep rooting habit. As pointed out by Anderson and Sinclair (1993), interactions in agroforestry systems can be divided into above-ground and below-ground processes, and it is evident that much more is currently known about above-ground than below-ground processes.

Although farmers are aware that shade cast by trees can depress crop yield, and they frequently prune branches to limit this, most farmers either have no concept of below-ground competition or simply accept it as an inevitable consequence of combining trees and crops in farmland (Mulatya, 2000). In contrast, however, researchers find that below-ground competition is a major problem in simultaneous agroforestry systems and it has been the focus of much research in recent years (van Noordwijk *et al.*, 1996). Soil water is usually the main constraint to system productivity (Jackson and Wallace, 1999), hence root distribution is an important determinant of tree-crop competition, because it defines the locations of soil water that are accessible to plants (Mulatya *et al.*, 2002). Where tree roots are shallow, they occupy the same soil layers as crops and competition between trees and crops is invariably unavoidable (Ong *et al.*, 1999).

Masi and Maranville (1998) have pointed out that despite the importance of roots, little is understood about their morphology and architecture. They suggested that studies of roots have lagged behind those of shoot because of the tedious and time-consuming labour involved in quantifying and observing roots in their natural arrangement. Fitter and Stickland (1991) have also suggested that traditional methods used to describe root systems, based on root biomass or length distribution in space, have not proven beneficial in quantifying morphology with respect to root branching/architecture and its relation to root function. According to Smith (2001), estimation of root lengths for tree root systems using conventional methods is invariably a difficult and laborious task, and that commonly used methods of determining root lengths are most suited to studies of field crops and it is frequently not feasible to apply them to large trees, because they can require a greater investment in time and labour than is often possible. And while soil coring can provide detailed information on quantities and distribution of roots, it will require large numbers of cores to adequately sample root systems of trees, and this will be constrained by the availability of labour to collect cores, wash root samples, remove debris from samples and measure root lengths (Smith *et al* 1999; Smith, 2001). Van Noordwijk and Purnomosidhi (1995) also highlight the laborious nature of current root research methods in agroforestry and point out that these methods cannot be related to farmers' criteria for selecting and judging the performance of trees. They emphasise that if root research stays in the domain of 'experts', it will not contribute to the development of agroforestry systems in the real world, and that the validity of generalizations about deep- and shallow-rooted trees, competitive and beneficial ones, is likely to be vastly overestimated, unless simple, non-destructive observation tools are developed that can be used to check root development for potentially any tree.

As suggested by Smith (2001), an alternative method is therefore needed to enable routine estimation of the size of tree root systems. This has led to the proposition by van Noordwijk *et al* (1994) that the estimation of the size of tree root systems can be achieved by taking advantage of the fractal characteristics of tree roots to estimate total root lengths from simple branching rules. It has been suggested that root branching has a fractal pattern if the rules governing branching are independent of scale (Eshel, 1998). The fractal dimension refers to the existence of self-similarity arising from repeated iteration of a structural unit (Berntson, 1996) and branching rules are the same for all root sizes (Fitter and Stickland 1992; van Noordwijk *et al.*, 1994; Spek and Van Noordwijk, 1994). Fractal analysis has been found to be useful for providing some information about the branching patterns of root systems for different plant species (Fitter and Stickland, 1992; Lynch and van Beem, 1993; Pagès *et al.*, 1993; Spek and van Noordwijk, 1994; van Noordwijk and Purnomosidhi, 1995; Ong *et al.*, 1999; Smith *et al.*, 1999; Smith, 2001). All these workers emphasis that fractal geometry of roots can potentially be used to classify the intricacy of shape of the root systems. Thus, van Noordwijk and Purnomosidhi (1995) have suggested the use of relations between the root diameter at the stem base (proximal roots) and functionally important root parameters such as the total root length or surface area of the fine roots. They emphasize that if root branching patterns have fractal characteristics, measurement of the proximal root diameter at the stem base and the branching rules as observed anywhere in the root system, would be enough to predict total root length, root diameter distribution and root length per unit dry weight (specific root length).

This study thus saught to investigate the root architecture of the most promising shade tree species and the cocoa, using the non-destructive fractal methods described by van Noordwijk and Purnomosidhi (1995).

7.1.3. Water uptake by selected shade tree species

The presence of deep roots alone does not guarantee complementarity in water use and knowledge of root distribution is of limited value in the absence of corresponding information concerning water and nutrient uptake (Howard *et al.,* 1997). In agroforestry systems it is expected that the components will use water and nutrients from separate soil layers as demonstrated by Howard *et al* (1995) with *Grevillea robusta* in which they found that at least 80% of the water transpired by this species may be drawn from below the crop rooting zone. In the case of simultaneous agroforestry systems, complementarity in root distribution as regards soil water and nutrient availability may be considered as a key to success in plant associations (Ong *et al.,* 1996; van Noordwijk *et al.,* 1996). Studies in dryland agroforestry systems in east Africa led Ong *et al.,* (1999) to conclude that in drylands, competition between trees and crops was most serious below ground and was largely for water. To address the problem of below-ground competition, recent studies have sought to identify trees that have few roots in those shallow soil layers that are occupied by crop roots (Deans and Munro, 2004). A number of workers have, however, pointed out that such indirect attempts to address below-ground competition have failed because while small inter-specific differences in fine root length density in surface agroforestry soils have been found (Odhiambo, *et al.,* 1999), the majority of both tree and crop roots occupy the shallow layer of soil that extends to about 60cm depth (Smith *et al.,* 1997; Odhiambo *et al.,* 1999; Schroth, 1999). Nevertheless, as suggested by Howard *et al* (1997), the degree of competition in multi-species systems is dependent on the partitioning of resources, including water.

However, the respective contribution of species in the interaction for soil resources is not easy to measure. Methods based on the use of non-radioactive tracers (Tofinga and Snaydon, 1992), or natural isotopes of water (Le Roux *et al.,* 1995), although allowing identification of preferential zones of water uptake in plant associations, are destructive and labour intensive. During the last decade sap flow measurements have become increasingly popular especially since several systems have been commercialised. Among these is the heat balance method, which is a continuous method measuring mass flow directly, and has been used by several workers to measure water uptake by various species in different landuse systems (e.g. Fichtner and Schulze, 1990; Howard *et al.*, 1997; Grime and Sinclair, 1999; Jose *et al.*, 2000; Ong *et al.*, 2000; Lott *et al.*, 2003; Deans and Munro, 2004).

Although competition for soil moisture has been reported as the major factor limiting success of alley cropping systems in the semi-arid tropics (Singh *et al.*, 1989; Ong *et al.*, 1991), little of such work has been reported for multi-strata cocoa agroforestry systems. In this study, the heat balance method was used to investigate water uptake by three indigenous forest tree species planted as shade for cocoa in South Formangso, in the Asante Akim South district of the Ashanti region of Ghana.

7.1.4. Hypothesis and study objectives

The main hypothesis of this study is that all the planted shade tree species have faster early growth rates than the cocoa to facilitate early canopy differentiation with the cocoa canopy and ensure above-ground spacial complementarity. It is further hypothesised that all the planted shade tree species have deeper rooting habits, that will be less competitive with that of the cocoa crop, to enhance below-ground complementarity. On these premises, the main objectives of the study were to:

i. determine the initial growth rates of the cocoa and the planted shade trees;

ii. determine the root orientation of the cocoa and the planted shade trees;

iii. determine the rate of water uptake by the planted shade tree species.

7.2. Materials and methods

7.2.1. Initial growth performance

Trials were initiated both on-farm and on-station. The on-farm trials were established on farmers' fields in Gogoikrom in the Atwima district of Ghana. Two on-station trials were established; one in South Formangso in the Asante Akim South district, on one of the field research stations of the Forestry Research Institute of Ghana (FORIG), and the other on a research site belonging to the Ghana Cocoa Growers and Research Association (GCGRA), located in Bontomuruso also in the Atwima district, (see Appendix 7.1 for a diagram of the GCGRA site).

7.2.1.1. On-farm trials

Seedlings of the selected tree species were planted out on farmers' fields to evaluate their survival and initial growth performance under farmers' field conditions. Seven (7) tree species were used for the on-farm trial. These were among the farmer preferred shade tree species for which planting material was available at the time of trial initiation. They included:

i. *Albizia adianthifolia* (Schumach.) Wight
ii. *Entandrophragma angolense* (Welw.) C. DC.
iii. *Entandrophragma utile* (Dawe & Sprague) Sprague
iv. *Khaya anthotheca* (Welw.) C. DC.
v. *Newbouldia laevis* (P. Beauv.) Seeman ex Bureau
vi. *Pericopsis elata* (Harms) van Meeuwen
vii. *Tetrapleura tetraptera* (Schum. & Thonn.) Taub

Single tree plots were used, in which a single individual of each of the 7 selected tree species was represented in a plot on each participating farmer's field; and each farm represented a block. Within each block (farm) the trees were planted at a triangular spacing of 12 m x 12 m. Within each farm 2 seedlings of each species were planted in two separate plots (where possible) to give rise to 2 within block replications. A total of 10 blocks (farms) were established and planting was carried out in the last week of August 2001.

Planting points for the shade tree species were pegged out on each farm in the last week of August 2001 and the species randomly allocated to these points. Randomization was done by assigning numbers to the different tree species and randomly picking these numbers from a box and allocating each number picked to a pegged planting point starting from the first peg.

Farmers were left to plant out their cocoa and other crops according to their usual practice, using the mixed hybrid cocoa variety developed by the Cocoa Research Institute of Ghana (CRIG). Plots were weeded at least 3 times a year by the farmers.

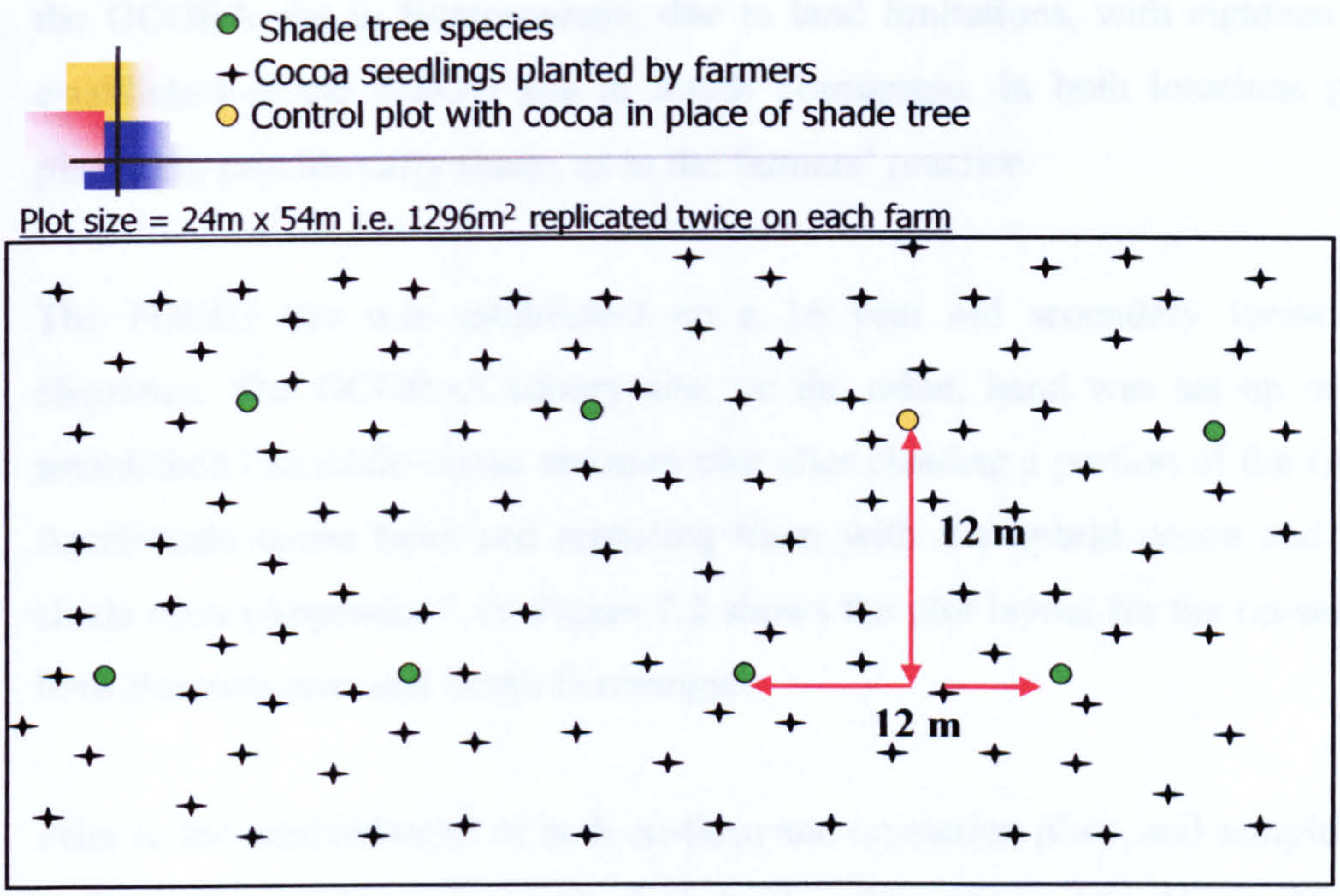


Figure 7.1: Plot layout for on-farm tials. Cocoa is usually planted in irregular pattern by farmers, as depicted in the diagramme above.

7.2.1.2. On-station trials

Five (5) shade tree species were used for both on-station plots at Bontomuruso and South Formangso, in a similar single tree plot design. These were:

i. *Entandrophragma angolense* (Welw.) C. DC.
ii. *Entandrophragma utile* (Dawe & Sprague) Sprague
iii. *Newbouldia laevis* (P. Beauv.) Seeman & Bureau
iv. *Terminalia ivorensis* A. Chev.
v. *Tetrapleura tetraptera* (Schum. & Thonn) Taub

Trees were planted at the same 12 m x 12 m triangular spacing, with the cocoa planted at a regular spacing of 3 m x 3 m. *A. adianthifolia*, *K. anthotheca* and *P. elata* could not be included in the on-station trials due to lack of sufficient planting material, while *T. ivoremsis* was included in the on-station trials alone for the same reason of insufficient seedlings to cover all blocks in the on-farm trials. Five (5) blocks were established on the GCGRA site in Bontomuruso, due to land limitations, with eighteen (18) blocks established at the FORIG site in South Formangso. In both locations plantain was planted to provide early shade, as in the farmers' practice.

The FORIG site was established on a 16 year old secondary forest after forest clearance. The GCGRA/Cadbury site, on the other, hand was set up on an already established *Gliricidia*-cocoa research plot after clearing a portion of the *Gliricidia* and Amelonado cocoa trees and replacing them with the hybrid cocoa and the selected shade trees (Appendix 7.1). Figure 7.2 shows the plot layout for the on-station trials at both Bontomuruso and South Formangso.

Prior to the establishment of both on-farm and on-station plots, soil samples were taken at five random points on each block at depths of 0 – 15 cm, 15 – 30 cm, 30 – 45 cm and 45 – 60 cm, using a soil augur, where possible. Where soils were too stony pits were dug and samples collected accordingly. Samples were air dried and bulked for each stratum. Sub-samples were then taken for laboratory determination of soil physical and chemical properties – texture, pH, organic matter, nitrogen, phosphorus, potassium, calcium, magnesium. Soil analysis was carried out at the Soil Research Institute of Ghana (SRI) in Kumasi, Ghana.

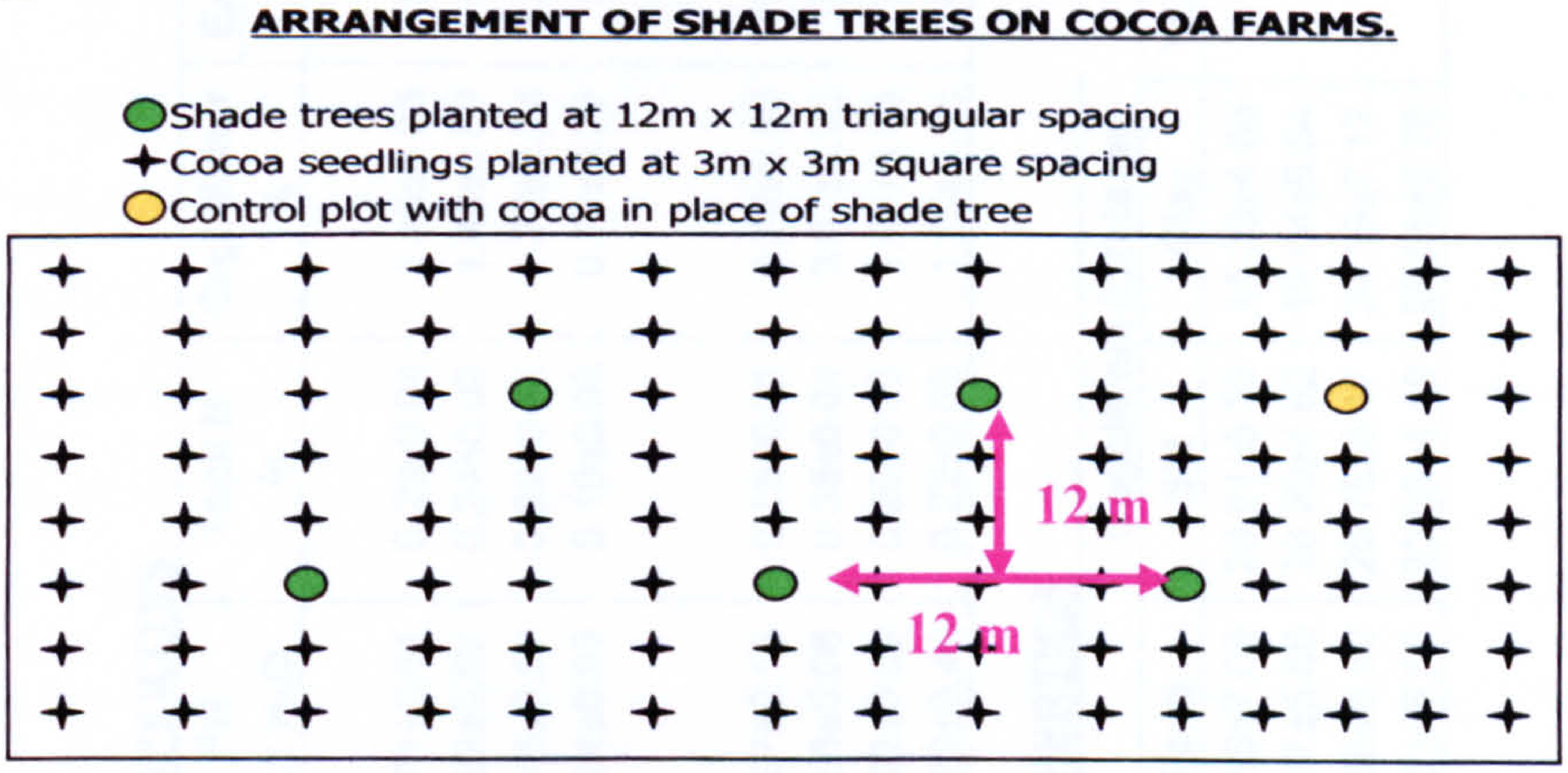


Figure 7.2: Plot layout for on-station trials. Here the cocoa was planted at a regular 3 m x 3 m spacing.

Table 7.1: Soil chemical and physical properties for the on-farm (Gogoikrom) and on-station (South Formangso) plots prior to planting.

CHEMICAL PROPERTIES

Soil Horizon (cm)	PH 1:1 H_2O	Total N %	Org. Matter %	Exchangeable Cations me/100g			Exch. Al (Al + H)	C.E.C. me/100g	Base Sat. %	Available - Bray's	
				Ca	Mg	K				ppmP	ppmK
On-farm											
0 - 15	4.71±0.61	0.29±0.04	2.49±0.86	5.87±1.50	2.07±1.99	0.46±0.16	0.20±0.11	8.74±2.54	96.40±3.21	1.73±0.21	153.05±29.71
15 - 30	4.82±0.62	0.24±0.02	1.48±0.59	5.16±2.20	1.73±1.61	0.33±0.12	0.28±0.09	7.56±2.91	94.11±4.52	1.50±0.16	103.52±21.76
30 - 45	5.15±0.69	0.22±0.02	1.23±0.54	3.77±1.47	1.01±0.70	0.16±0.06	0.49±0.02	5.80±0.91	90.26±3.71	0.10±0.06	67.35±14.95
45 - 60	5.84±0.93	0.19±0.03	0.81±0.29	3.05±1.03	0.66±0.44	0.12±0.04	0.81±0.09	4.48±1.14	81.86±7.64	0.03±0.01	45.79±11.66
On-station											
0 - 15	6.37±0.16	0.39±0.01	4.72±0.36	18.16±2.15	5.19±0.90	0.90±0.07	0.12±0.03	24.66±2.13	99.49±0.25	4.58±0.02	120.92±13.69
15 - 30	6.66±0.06	0.35±0.01	3.67±0.20	15.11±1.26	4.60±0.32	0.84±0.05	0.11±0.01	21.19±1.62	99.42±0.23	1.73±0.01	112.03±9.73
30 - 45	6.92±0.09	0.26±0.05	1.97±0.09	9.57±0.80	2.54±0.09	0.67±0.07	0.10±0.00	13.08±1.79	99.19±0.24	0.14±0.01	84.58±7.70
45 - 60	7.23±0.40	0.22±0.03	1.25±0.05	6.82±0.16	1.94±0.04	0.51±0.03	0.11±0.03	9.64±0.92	98.99±0.18	0	63.54±4.22

PHYSICAL PROPERTIES

Soil Horizon (cm)	Gogoikrom (On-farm)				South Formangso (On-station)			
	Sand	Silt	Clay	TEXTURE	Sand	Silt	Clay	TEXTURE
0 - 15	58.86±7.08	26.81±5.33	14.33±4.86	SL	44.16±3.51	42.78±3.33	13.06±2.77	L
15 - 30	54.67±5.66	26.29±4.62	19.04±5.64	SL	45.88±4.86	39.28±4.37	14.85±2.22	L
30 - 45	49.86±8.50	25.75±5.17	24.39±7.17	SCL	49.58±4.49	34.94±5.18	15.49±2.23	L
45 - 60	47.81±6.56	23.03±4.49	29.56±5.76	SCL	45.78±6.70	28.40±4.92	25.84±3.60	SCL

7.2.1.3. Data collection and analysis

Prior to planting in August 2001, all seedlings (cocoa and shade trees) were assessed for stem basal diameter (at 5 cm above the soil) and height. Survival of the different tree species, as well as growth analysis – i.e. stem basal diameter and height growth were determined yearly for all the species after planting. Stem basal diameter assessment was adopted, instead of diameter at breast height (DBH), to facilitate comparability since a number of the species had not attained heights greater than 1.3 m at the end of the second year. All data was tested for normality, using the Kolmogov-Smirnov test. At year two, basal diameter and height, as well as survival, were compared by analysis of variance (ANOVA), for the different sites and between sites. Arcsin transformation was performed on percent survival data before analysis of variance was carried out. Where the data did not show normality the Kruskal-Wallis test was used to check the results of the ANOVA. An analysis of variance on percentage survival for the species that were common to all three sites – i.e. *T. tetraptera, E.angolense, E. utile* and *N. laevis* was performed, using the General Linear Model (GLM) using percentage survival as the response variable, with species and site as the model variables, and site as the random factor. Treatment means were compared by Tukey's significant difference test, using the Minitab 13 statistical software package.

7.2.2. Competitive potential of shade tree species

This study was conducted on the growth performance trial plots and involved an assessment of the root structure of, and water use by, the shade trees species and the cocoa trees. Assessments were carried out in the on-station (FORIG) site in South Formangso. Assessment of root structure was carried out for *E. angolense, T. ivorensis, T. tetraptera,* which showed the best survival and growth potential within the first 2 – 3 years after planting, and the cocoa; the other shade tree species were not included in this study their poor survival and growth on this site. Measurement of water use was done for all the above species except the cocoa; water use by the cocoa could not be assessed becaused stem diameters were not big enough for the installation of the sapflow gauges available at the time. The other shade tree species were not assessed owing to their poor survival and/or growth performance on the field.

7.2.2.1. Root structure

Entandrophragma angolense, Terminalia ivorensis and *Tetrapleura tetraptera* were selected for this study on the basis of their good initial growth within the first two years of establishment. This study involved an estimation of the structure of the root systems of these selected tree species and the cocoa trees. The techniques described by van Noordwijk et al. (1994) and van Noordwijk and Purnomosidhi (1995) were employed in investigating root architecture and competitivity of the selected tree species and the cocoa. These techniques are based on allometry, fractal branching principles from which simple equations to estimate root variables are derived, and indices of shallow rooting (root competition indices) are estimated.

This was carried out in September 2003 when the study species were 2 years old. The basal part of the roots at the stem base of each selected tree was carefully excavated, in a half sphere of 1 meter radius, using small hand implements. Root diameter and angle from a horizontal plane were measured for all proximal roots (i.e. roots originating from the stem base or as laterals from the top part of the tap root). Five trees per species were assessed.

Stem diameter D_{stem} was measured at breast height or as root collar diameter (which ever was appropriate) and used to estimate stem basal area. Root diameter was measured with a digital calliper and the basal area of roots with an angle from the horizontal plane of less than 45^0 and for those with vertical orientation was estimated from the root diameter measurements. These measurements were subsequently used to calculate an index for root shallowness, as the ratio of the basal area of all horizontally oriented roots and the stem.

7.2.2.2. Data analysis

Stem basal area was calculated as πD^2_{stem}. The basal area of roots with an angle from the horizontal plane of less than 45^0 was calculated as $\pi \Sigma D^2_{hor}$, and for those with vertical orientation as $\pi \Sigma D^2_{vert}$. An index of root shallowness was calculated as $\pi \Sigma D^2_{hor} / \pi D^2_{stem}$, or as ratio of basal area of all horizontally oriented roots and the stem (van Noordwijk and Purnomosidhi, 1995).

7.2.3. Water uptake

Water uptake by three years old trees of *E. angolense*, *T. ivorensis* and *T. tetraptera*, planted as shade for cocoa, was estimated from sap velocity measurements using Thermal Dissipation Probes (TDP) (Delta-T Devices Ltd, UK) (Plate 7.1). The methodology is fully described in the user manual (Dynamax, 1997). Sap velocity measurements were made every 1-minute, and 10-minute mean values stored on a DL2e data logger (Delta-T Devices Ltd, UK). The data were collected from four trees of each species. On each tree, probes were installed at least 0.5 - 1m above the soil surface to minimise any asymmetric influence on sap temperature caused by heat conduction of energy stored in the soil (Weibel and de Vos, 1994). Each probe consisted of a pair of thermocouple needles 80 mm long and 1.65 mm in diameter, each of which was inserted into the sapwood of the tree boles, in a vertical line, with 4 cm distance between the needles (Granier, 1987; Dynamax, 1997). A 12 volt lead-acid battery was used to supply heat to the upper needle. The probe needles measure the temperature difference (dT) between the heated needle above and the sapwood ambient temperature measured by the reference needle below. The dT variable and the maximum dTm at zero sap flow provide a direct and calibrated conversion to sap velocity (Granier, 1987). To protect against solar radiation, wind and rain, the probe on each tree was insulated by covering it with aluminium foil (Plate 7.1). Measurement on each tree lasted for 48 hours before the equipment was moved to the next tree. The mean sap flux density, V, along a radius (m s^{-1}) was calculated, following the equations established by Granier (1987), as:

$$K = 0.0206V^{0.8124} \qquad (7.1)$$

in which

$$K = (T_M - T)/(T - T\alpha) \qquad (7.2)$$

is a dimensionless value and depends on T: T_M, the temperature of the heated probe, obtained when $V = 0$; T, the temperature of the heated probe when $V>0$; and $T\alpha$, the reference temperature of the non heated probe.

As both thermocouples connected in position give the temperature difference between the two probes directly, another expression of K, defined by Granier (1987) can be used:

$$K = (dTm - dT/dT \qquad (7.3)$$

where dT is the measured difference in temperature between that of the heated needle, referenced to the lower non-heated needle, placed at a fixed distance below the heated one, and dTm is the value of dT when there is no sap flow (zero set value). The value of dT is found from the differential voltage measured between the upper and lower thermocouple.

Following from the empirical relation developed by Granier (1987) between sap flow velocity V (cm s^{-1}) and K, represented by:

$$V = 0.0119 \times K^{1.231} \text{ (cm s}^{-1}\text{)} \qquad (7.4),$$

and solving for V, total sap flow (cm^3 h^{-1}) was calculated as:

$$F = VS_A \times 3600\text{(s/h)} \qquad (7.5),$$

where S_A is the cross- sectional area (cm^2) of the sapwood at the heating probe. Since trees were just three years old, sapwood/heartwood differentiation was assumed to be negligible and that the stems were made up of mainly sapwood. Thus stem cross-sectional area under-bark was taken to represent sapwood cross-sectional area. Transpiration rate per tree was therefore calculated from the sap velocity and stem cross-sectional area of each tree species. The sap flow measurements were carried out in September 2004.

7.2.3.1. Data analysis

Interspecific differences in maximum daily rates of sap flow were examined by analysis of variance using Minitab Release 13 Statistical Package.

7.3. Results

7.3.1. Initial growth performance

7.3.1.1. Survival

Figure 7.1 shows the percentage survival of the cocoa shade tree species two years after planting on the FORIG site in South Formangso, the GCGRA site in Bontomuruso and on farmers' fields in Gogoikrom. The first species, *T. ivorensis* was planted on the on-station plots (South Formangso and Bontomuruso) but not in Gogoikrom (on-farm), while the last three species – *A. adianthifolia, K. anthotheca* and *P. elata* – were planted only on the on-farm trials in Gogoikrom, due to limitations on planting material.

In South Formangso, there was highly significant difference (P = 0.001; F = 17.29) in the percentage survival of the different shade tree species two years after planting (Table 7.2). The highest percentage survival (88.9%) was recorded for *T. ivorensis* while *N. laevis* showed the least survival of 0% as none of the planted seedlings of this species grew past the first year after planting at this site. The second highest surviving species was *T. tetraptera* with 77.8%, while survival rates for *E. angolense* and *E. utile* were 55.6% and 38.9% respectively. There was no significant difference (P>0.05) between the percentage survival for *T. ivorensis* and *T. tetraptera* and between *T. tetraptera* and *E. angolense*, but difference in percentage survival was significant between *E. utile* and *N. laevis* and between these two species and the other three species.

Table 7.2: Analysis of variance for percentage survival of cocoa and shade tree species in South Formangso.

Source	DF	SS	MS	F	P
Tree species	5	118436	23687	17.29	0.001
Error	102	139704	1370		
Total	107	258140			

Tree survival (% of original trees planted) in Bontomuruso showed a similar trend to that recorded in South formangso. Here again. *T. ivorensis* showed the highest percentage survival of 80%, with 4 out of the 5 planted seedlings surviving at year 2. Unlike South Formangso, however, the lowest percentage survival recorded here was for *E. utile*, with a value of 20% (i.e. only 1 of the 5 planted seedlings survived) after 2 years. Again, unlike in South Formangso where none of the planted *N. laevis* seedlings survived past the first year, the same species posted a 40% survival, with 2 of the 5 seedlings surviving, after 2 years. *T. tetraptera* posted a 60% survival on this site. Even though percentage survival recorded for the five shade tree species on this site appeard to be higher for some species than others, an analysis of variance showed that there was no significant difference (P>0.05) (Table 7.3) in their percentage survival. This seems quite unusual and may be due to the very low number of blocks (5) used at this site, considering that single tree plots were utilised for the trial.

Table 7.3: Analysis of variance for percentage survival of cocoa and shade tree species in Bontomuruso.

Source	DF	SS	MS	F	P
Tree species	5	14520	2904	1.17	0.351
Error	24	59401	2475		
Total	29	73922			

For the on-farm trials in Gogoikrom, *T. tetraptera* showed the highest percentage survival of 100%, while *A. adianthifolia* and *E. utile* failed completely on all the nine farms monitored. *K. anthotheca, N. laevis* and *E. angolense* showed survival percentages of 88.9%, 77.8% and 66.7% respectively, while *Pericopsis elata* had a percentage survival of only 11.1% (i.e. only one farmer hard one tree of this species still growing on his farm at the end of the second year). Differences in percentage survival on-farm were highly significant (P = 0.000; F = 26.56) (Table 7.4). The Tukey's pairwise comparisons ($\alpha = 0.05$) showed that percentage survival was similar for *T. tetraptera, E. angolense, N. laevis* and *K. anthotheca* but these differed very significantly from *A. adianthifolia*, *E. utile* and *P. elata*, which in turn did not differ significantly from each other.

Table 7.4: Analysis of variance for percentage survival of cocoa and shade tree species in Gogoikrom – on-farm trials.

Source	DF	SS	MS	F	P
Tree species	7	140483	20069	26.56	0.000
Error	72	54407	756		
Total	79	194889			

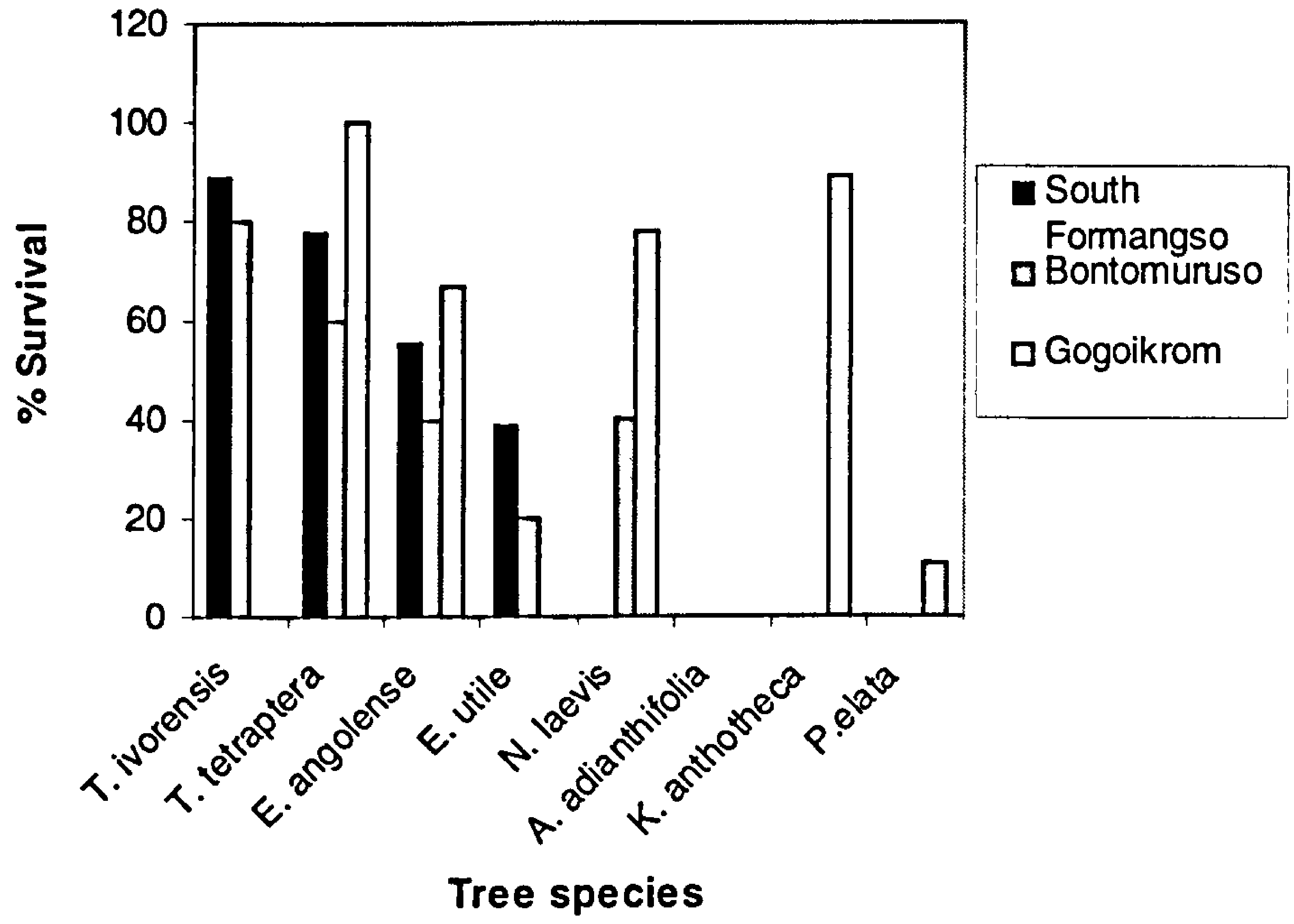


Figure 7.1: Percentage survival of different cocoa shade tree species two years after planting at three different sites in Ghana.

The results of the analysis of variance on percentage survival for the species that were common to all three sites – i.e. *T. tetraptera*, *E. angolense*, *E. utile* and *N. laevis* showed that there was some significant difference (P = 0.043) in percentage survival between the three sites (Table 7.5).

Table 7.5: Analysis of variance for percentage survival of cocoa and shade tree species across the three sites.

Source	DF	SS	MS	F	P
Species	4	24269.4	6067.3	3.32	0.020
Site	2	2993.0	1496.5	0.82	0.043
Error	8	14612.7	1826.6		
Total	14	39875.2			

7.3.1.2. Growth performance

Two years after planting, there were significant inter-specific differences in mean stem basal diameter and mean height between the shade tree species on all three sites. Figures 7.2 and 7.3 show the pattern of mean stem basal diameter and mean total height of the different shade tree species for the three sites.

Mean stem basal diameter showed a very high significant difference between the tree species in South Formangso (Table 7.6). The highest mean basal diameter, was recorded for *T. ivorensis* with a value of 11.52±1.65 cm, which was significantly higher (P = 0.000) than that for all the other species and the cocoa. *T. tetraptera* and *E. angolense* recorded the next highest mean basal diameters of 7.36±1.28 cm and 7.09±1.90 cm respectively, which were significantly smaller than for *T. ivorensis* and significantly bigger than the mean basal diameters of *E. utile* (2.03±1.34 cm) and the cocoa (3.11±0.93 cm) but were not significantly different from each other. On the other hand, mean basal stem size did not differ significantly for the cocoa and *E. utile*.

In Bontomuruso, the pattern of mean stem basal area was somewhat similar to that recorded in South Formangso. *T. ivorensis* trees were bigger in basal diameter than all the other species, with a mean stem basal diameter of 3.89±1.03cm, with *T. tetraptera*, cocoa, *E. uitle*, *N. laevis* and *E. angolense* trees having mean basal diameters of 2.49±0.99 cm, 2.07±0.46 cm, 2.01 cm, 1.83±0.17 cm and 1.72±0.40 cm respectively. Despite these differences in mean stem basal diameter, analysis of variance (Table 7.7) showed that the differences were not significant (P = 0.076).

In the on-farm trials in Gogoikrom, highly significant differences (P = 0.000) were recorded for the mean basal diameters of the cocoa and the shade tree species planted (Table 7.8). Here, *K. anthotheca* was significantly bigger than the rest of the tree species, with a mean stem basal diameter of 6.97±3.05 cm, while the smallest basal diameter (2.03 cm) was found in *E. utile*. *T. tetraptera*, *E. angolense*, *N. laevis*, cocoa and *P. elata* showed intermediate diameters of 3.38±2.73cm, 3.77±1.48 cm, 3.01±2.31cm, 2.73±1.69 cm and 2.19 cm respectively. Stem sizes of *T. tetraptera*, *E. angolense* and *N. laevis* did not differ significantly, but whereas *T. tetraptera* and *E. angolense* differed significantly from the other species, the stem basal diameter of the cocoa did not differ significantly from that of *E. utile*, *N. laevis* and *P. elata*.

For those species common to all the three sites – i.e. *T. tetraptera*, *E. angolense*, *E. utile*, *N. laevis* and the cocoa – analysis of variance showed that the effect of site on mean basal diameters was highly significant (P = 0.002; Table 7.9).

Table 7.6: Analysis of variance for mean stem basal diameter of cocoa and shade tree species in South Formangso.

Source	DF	SS	MS	F	P
Species	4	746.34	186.58	38.26	0.000
Error	60	292.59	4.88		
Total	64	1038.93			

Table 7.7: Analysis of variance for mean stem basal diameter of cocoa and shade tree species in Bontomuruso.

Source	DF	SS	MS	F	P
Species	5	10.855	2.171	6.81	0.076
Error	10	3.187	0.319		
Total	15	14.042			

Table 7.8: Analysis of variance for mean stem basal diameter of cocoa and shade tree species in Gogoikrom

Source	DF	SS	MS	F	P
Species	5	118.140	23.628	53.01	0.000
Error	45	20.060	0.446		
Total	50	138.19			

.

Table 7.9: Analysis of variance for stem basal diameter of cocoa and shade tree species in South Formangso, Bontomuruso and Gogoikrom.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Species	4	2.0506	2.0506	0.5127	1.77	0.228
Site	2	17.7307	17.7307	8.8654	30.64	0.002
Error	8	2.3150	2.3150	0.2894		
Total	14	22.0964				

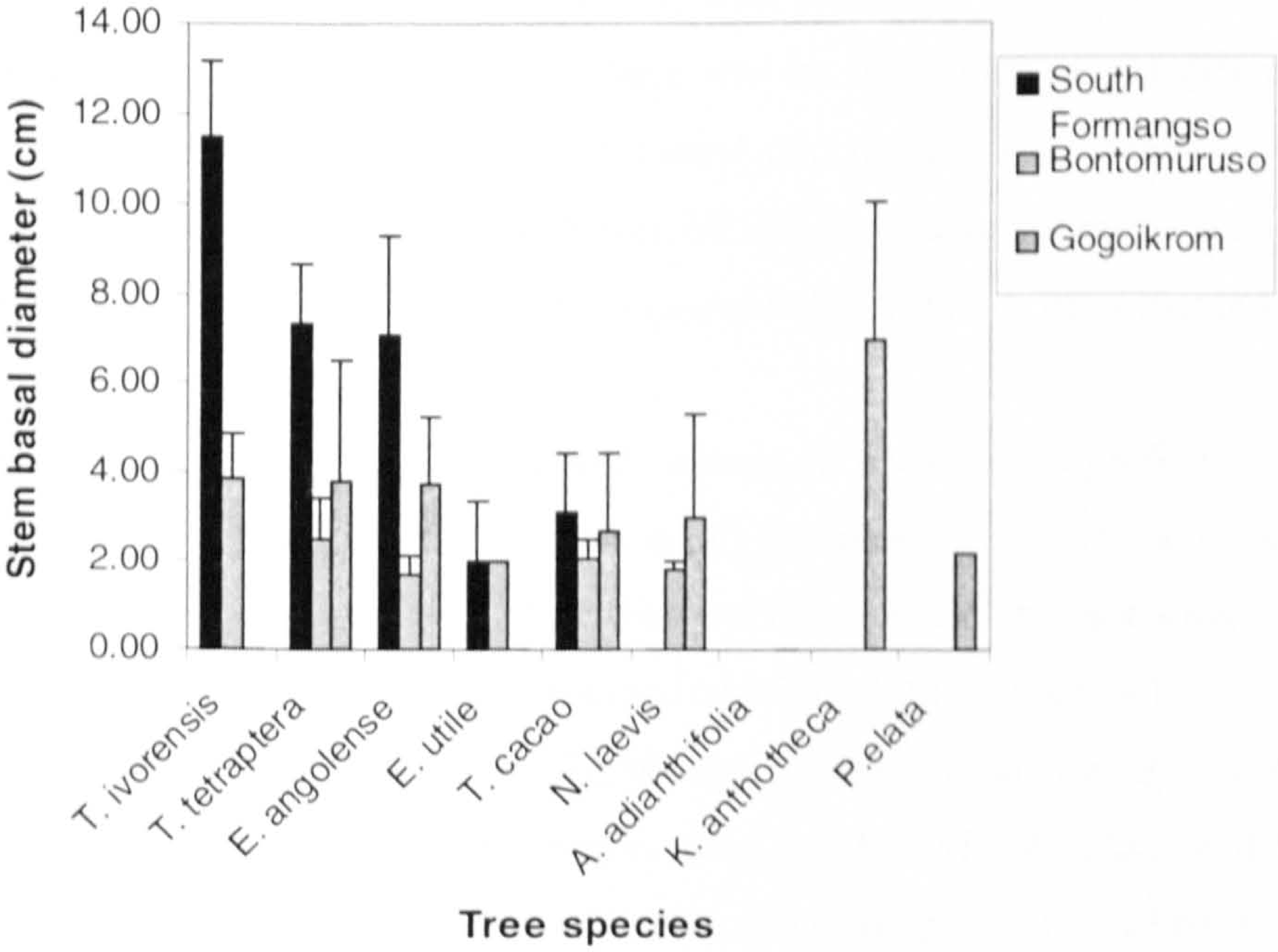


Figure 7.2: Stem basal diameter of cocoa and shade tree species two years after planting at three different sites in the Ashanti region of Ghana.

As with mean stem basal diameters, mean total tree height differed very significantly among the planted shade tree species at the three sites. In South Formangso, differences in mean total height of the species were highly significant (P<0.001; F = 54.86) (Table 7.10). The tallest trees encountered here were those of *T. ivorensis* with a mean total height of some 5.12±0.16 m, which was significantly higher than that for the other species with the exception of *E. angolense* (3.36±1.47 m) which did not differ significantly in height from *T. ivorensis*. *E. utile* was significantly smaller in mean height (0.89±0.68 m) than all the other tree species and the cocoa. *T. tetraptera* trees here had a mean total height of 2.84±0.87 m, which was significantly smaller than for *T. ivorensis* but similar to *E. angolense* and significantly taller than the cocoa and *E. utile* trees. The planted cocoa, however, grew significantly taller (1.34±0.42 m) than *E. utile* trees on this site.

In Bontomuruso, the height growth pattern was somewhat similar to that encountered in South Formangso. Here again, *T. ivorensis* attained the tallest height of 2.73±0.69 m within the first 2 years while *T. tetraptera* trees reached a mean height of 1.96±0.71 m within the same period. Mean total heights recorded for *E. angolense*, *N. laevis* and the cocoa trees were 0.93±0.51 m, 0.82±0.29 m and 0.89±0.43 m respectively. The analysis of variance showed that there was no significant height difference between *T. ivorensis* and *T. tetraptera* trees, but these two species were significantly taller than the cocoa and *E. angolense* and *N. laevis*. Height growth in the cocoa was, however, found to be comparable to that of the *E. angolense* and *N. laevis* trees planted on this site.

In Gogoikrom, *K. anthotheca* and *T. tetraptera* trees grew significantly (P < 0.001; F = 127.58) taller than the other species on all the farms (Plate 7.1), with mean total heights of 4.16±1.01 m and 3.79±1.13m respectively, which did not differ significantly. *E. angolense* and *N. laevis* also recorded similar heights of 2.69±1.73m and 2.24±1.55m respectively, which, though significantly lower than for *K. anthotheca* and *T. tetraptera*, were significantly higher than for *E. utile*, *P. elata* and the cocoa trees. These last three species posted mean total heights of 1.22±0.57m, 1.15 m and 1.61±0.91 m respectively, which were not significantly different from each other.

The effect of site on height growth was significant (P<0.03; P = 5.58) for the species that were common to all three sites, i.e. *T. tetraptera*, *E. angolense*, *E. utile*, *N. laevis* and the cocoa. Where the species survived, height growth of all species was generally significantly higher in South Formangso and Gogoikrom than in Bontomuruso, with the exception of *E. utile* which grew equally poorly in South Formangso and Bontomuruso and did not survive in Gogoikrom (Figure 7.3); *N. laevis* did not also survive in South Formangso. Also *T. tetraptera* and the cocoa were generally taller on farmers' fields in Gogoikrom than in both South Formangso and Bontomuruso.

Table 7.10: Analysis of variance for mean height of cocoa and shade tree species in South Formangso.

Source	DF	SS	MS	F	P
Species	4	150.885	37.721	54.86	0.000
Error	60	41.254	0.688		
Total	64	192.139			

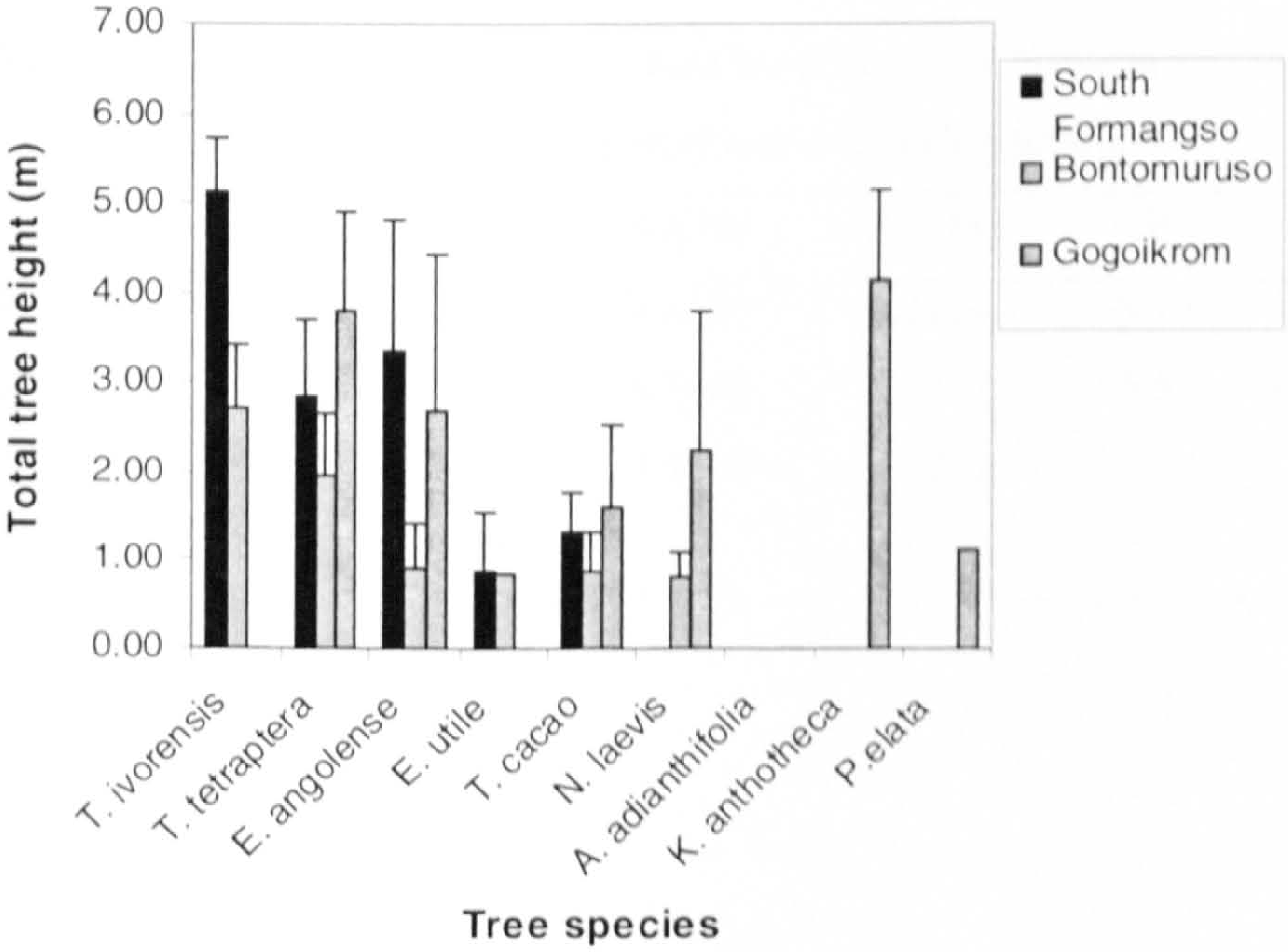


Figure 7.3: Height of cocoa and selected shade tree species two years after planting at three different sites in the Ashanti region of Ghana.

Table 7.11: Analysis of variance for mean height of cocoa and shade tree species in Bontomuruso.

Source	DF	SS	MS	F	P
Species	5	15.9630	3.1926	44.74	0.000
Error	24	1.7127	0.0714		
Total	29	17.6757			

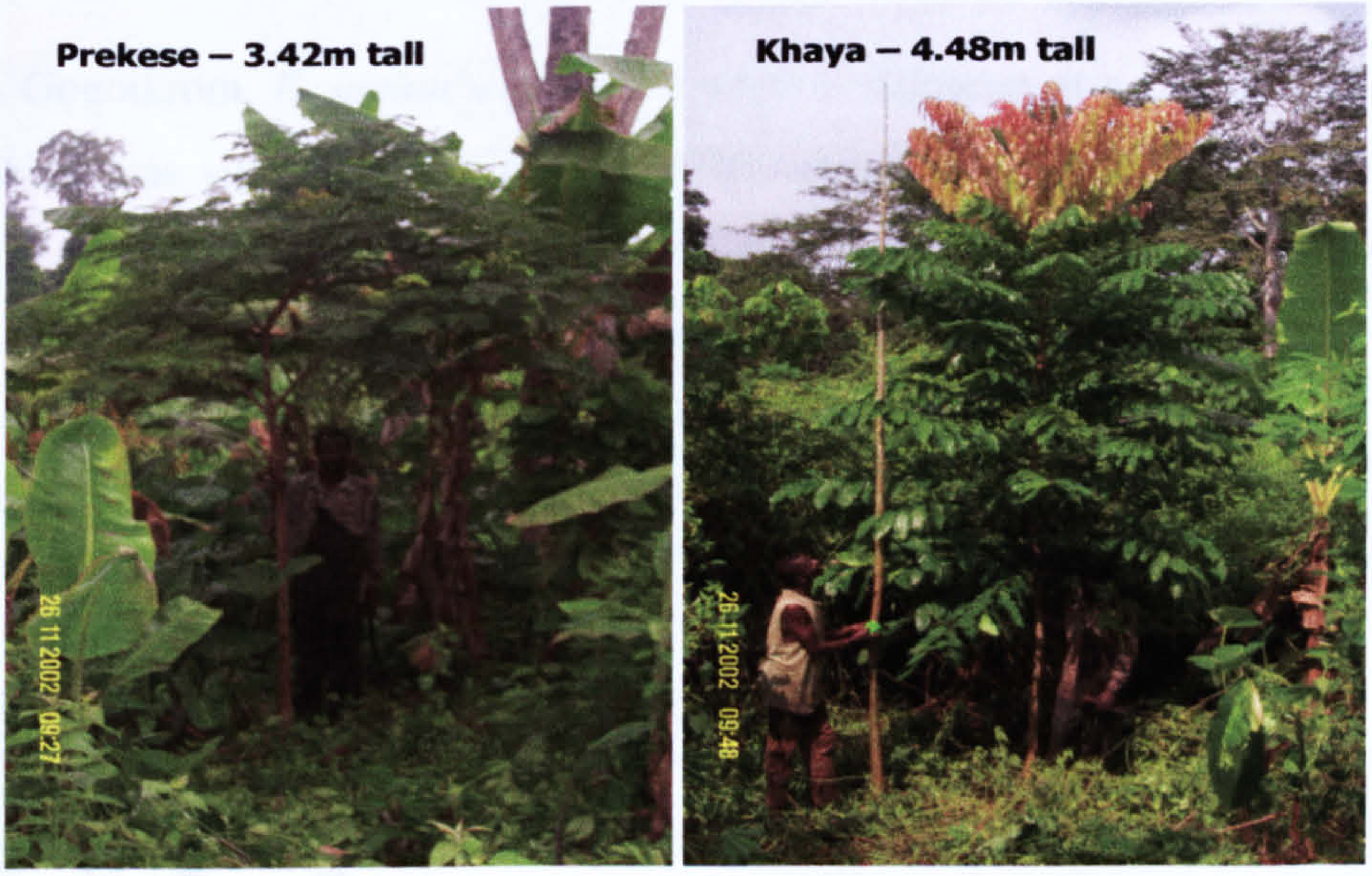
Table 7.12: Analysis of variance for mean height of cocoa and shade tree species in Gogoikrom.

Source	DF	SS	MS	F	P
Species	5	48.1272	9.6254	127.58	0.000
Error	41	3.0933	0.0754		
Total	46	51.2205			

Table 7.9: Analysis of variance for stem basal diameter of cocoa and shade tree species in South Formangso, Bontomuruso and Gogoikrom.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Species	4	8.8656	8.8656	2.2164	5.19	0.023
Site	2	4.7655	4.7655	2.3827	5.58	0.030
Error	8	3.4170	3.4170	0.4271		
Total	14	17.0481				

Plate 7.1: Two-year old *T. tetraptera* (left) and *K. anthotheca* (right) planted on farmers' new cocoa farms in Gogoikrom, Atwima district, Ghana.



Basal stem diameter increments for the different species ranged from 0.86±0.08 to 4.26±0.33 cm yr^{-1} according to species and location. In South Formangso, basal stem diameter growth rate ranged from 1.02±0.04 cm yr^{-1} for *E. utile* to the highest growth rate of 4.26±0.33 cm yr^{-1} for *T. ivorensis*. Basal diameter growth rates for the cocoa and the other tree species were intermediate between this range, with growth rates of 3.68±0.17, 2.87±0.15 and 1.56±0.12 cm yr^{-1}, respectively, for *T. tetraptera, E. angolense* and the cocoa. There was no significant difference ($P<0.05$) between the diameter growth rate of *T. ivorensis* and *T. tetraptera*, and between *T. tetraptera* and *E. angolense*. Likewise, no significant difference was found between basal diameter growth rate for cocoa and *E. utile*. However, *T. ivorensis, T. tetraptera* and *E. angolense* all grew significantly faster in stem basal diameter than *E. utile* and the cocoa on this site (Figure 7.4).

For those species that survived 2 years after planting in Bontomuruso, stem diameter growth rates followed similar patterns as observed for the same species in South Formangso (Figure 7.4). The fastest growing species here was *T. ivorensis*, with a diameter growth rate of 1.95±0.19 cm yr^{-1}, while slowest diameter increment rate of 0.86±0.07 cm yr^{-1} was observed in *E. angolense*. Stem diameters of *T. tetraptera, N. laevis* and the cocoa grew at the rates of 1.25±0.14, 0.92±0.03 and 1.04±0.09 cm yr^{-1}

respectively. The differences in diameter growth rates were however not significant ($P<0.05$).

In Gogoikrom, *K. anthotheca* grew fastest in diameter at a rate of 2.75±0.23 cm yr^{-1}, which was significantly higher ($P<0.05$) than the 1.89±0.22, 1.02±0.02, 1.51±0.18, 1.37±0.19 and the 1.1 cm yr^{-1} diameter growth rates recorded for *E. angolense, E. utile, N. laevis*, cocoa and *P. elata* respectively, but similar to the 1.92±0.31 cm yr^{-1} for *T. tetraptera*. Diameter growth rate for the cocoa on this site was, however, similar to that of all the shade tree species with the exception of *K. anthotheca*.

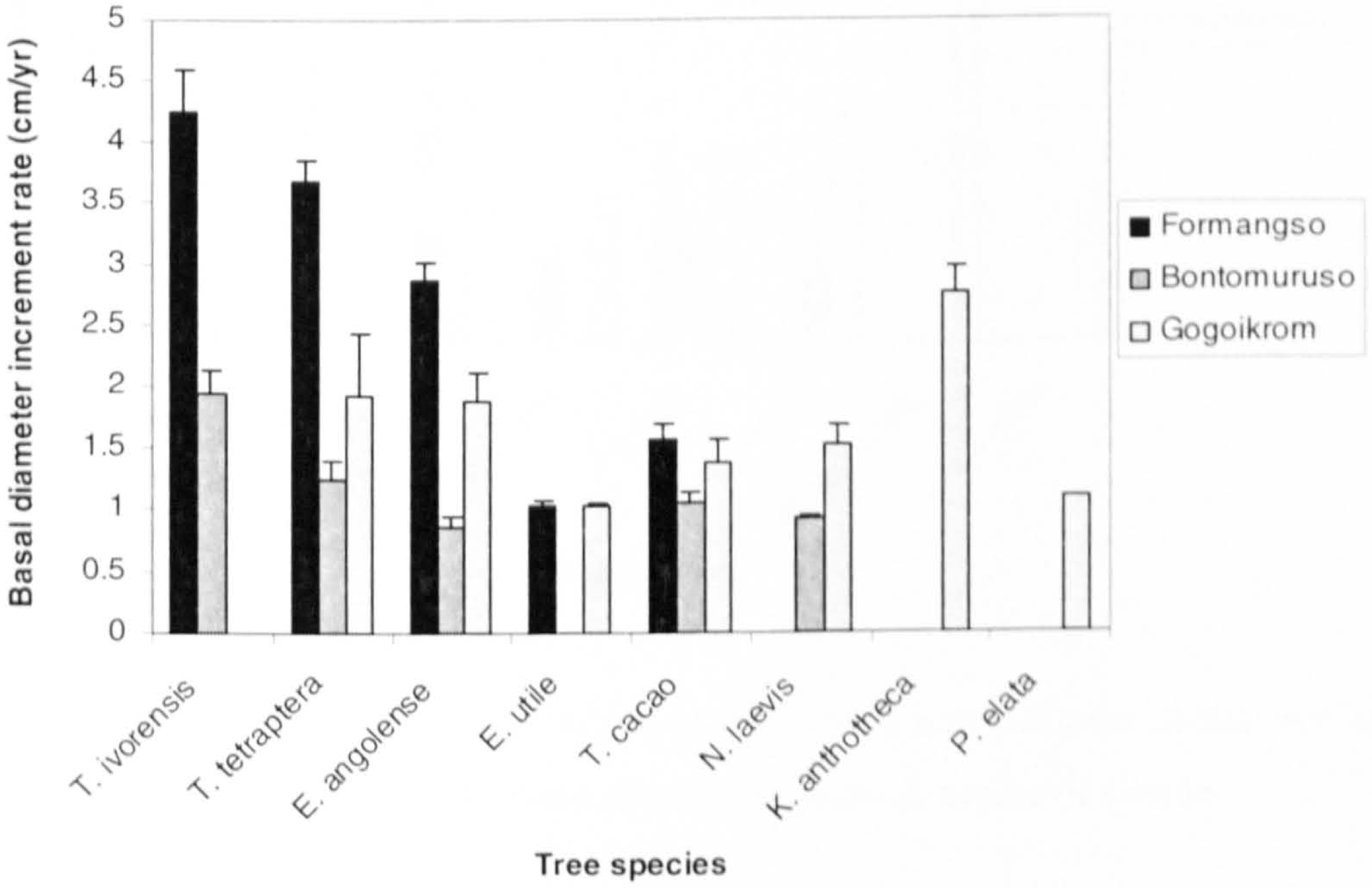


Figure 7.4: Diameter growth rate of two year old cocoa and shade tree species planted at three different sites in the Ashanti region of Ghana.

In terms or relative height growth rates, *T. ivorensis* grew significantly faster than all the other species in both South Formangso and Bontomuruso, where it was planted, with increment rates of 2.49±0.21 m yr^{-1} and 1.37±0.07 m yr^{-1} respectively. *T. tetraptera, E. angolense* and the cocoa had significantly faster height growth rates in South Formangso than in Bontomuruso, with rates of 1.42±0.15, 1.68±0.13 and 0.84±0.07 m yr^{-1} in South Formangso and 0.93±0.09, 0.47±0.05 and 0.45±0.03 m yr^{-1} in Bontomuruso (Figure 7.5). Rate of height growth in Gogoikrom was highest in *K. anthotheca* (2.08±0.14 m yr^{-1}), and this was comparable to that of *T. tetraptera*

(1.71 ± 0.11 m yr^{-1}) on the same site and to that of *T. ivorensis* in South Formangso, but significantly higher than the increment rates for the other species surviving here at year 2. With the exception of *E. angolense*, height growth rates in Gogoikrom were relatively higher than rates for the same species growing in both South Formangso and Bontomuruso (Figure 7.5).

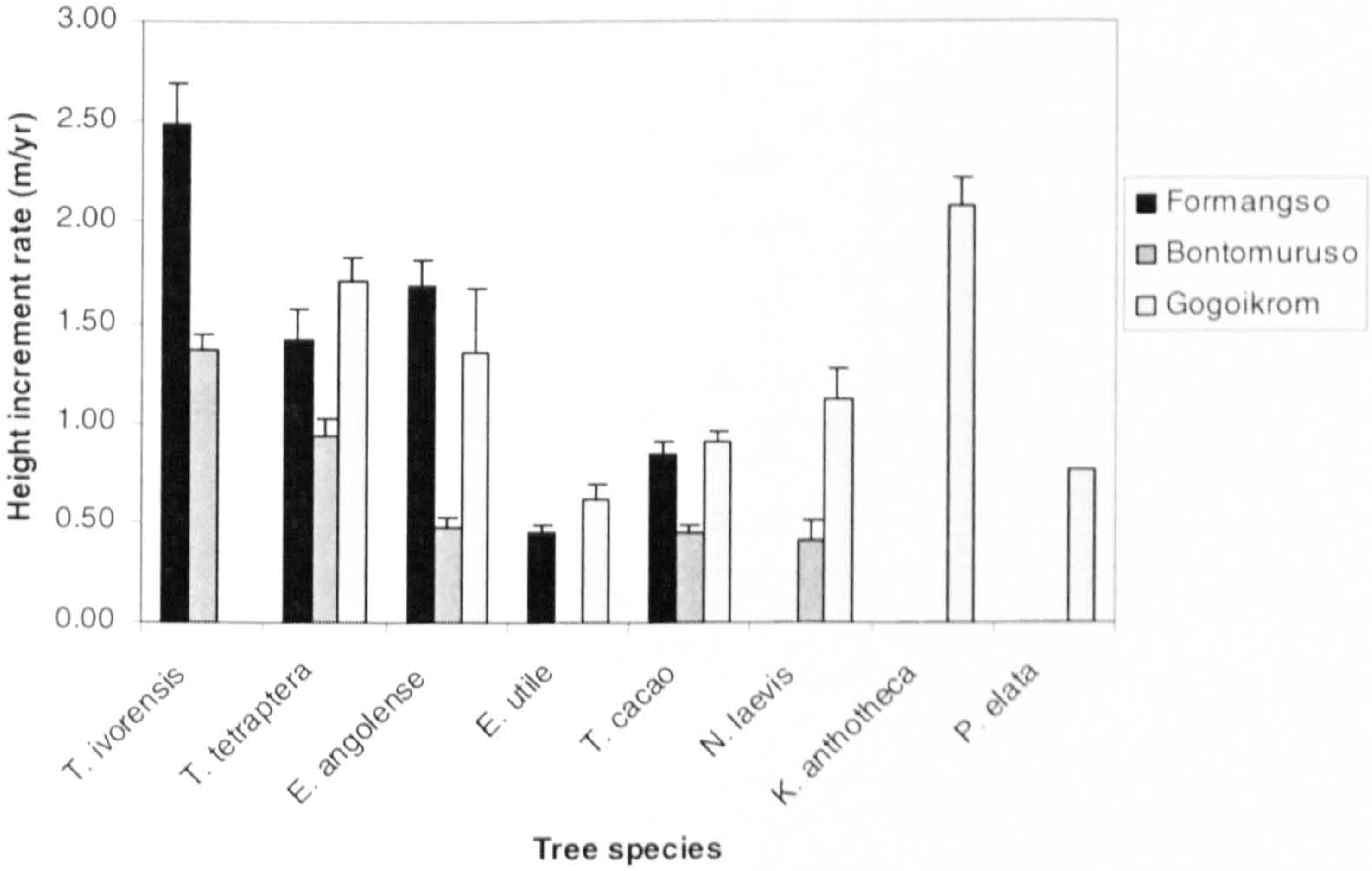


Figure 7.5: Height growth rate two years old cocoa and different shade tree species planted at three different sites in the Ashanti region of Ghana.

7.3.2. Root architecture

Table 7.2 and Figure 7.6 show the calculated indices of root shallowness, or root competitivity indices (CI), for the two (2) years old shade tree species and the cocoa, while Plates 7.2 and 7.3 show the exposed roots of the shade tree species and the cocoa, excavated during the assessment.

Table 7.2: Root basal areas and indices of root shallowness (competitiveness) for cocoa and three shade tree species two years after planting in South Formangso in the Asante Akim South district of Ghana.

Species	**N**	$\pi\Sigma D^2_{hor}$ **(±se) cm^2**	$\pi\Sigma D^2_{vert}$ **(±se) cm^2**	**CI (±se)**
T. cacao	5	1.33 (0.19)	0.15 (0.05)	1.16 (0.34)
E. angolense	5	0.96 (0.03)	2.01 (0.48)	0.66 (0.23)
T. ivorensis	5	2.45 (0.17)	0.46 (0.16)	2.96 (0.27)
T. tetraptera	5	0.28 (0.16)	3.64 (0.48)	0.19 (0.09)

Note: N = number of trees sampled; CI = Competitivity Index (Values are means±se).

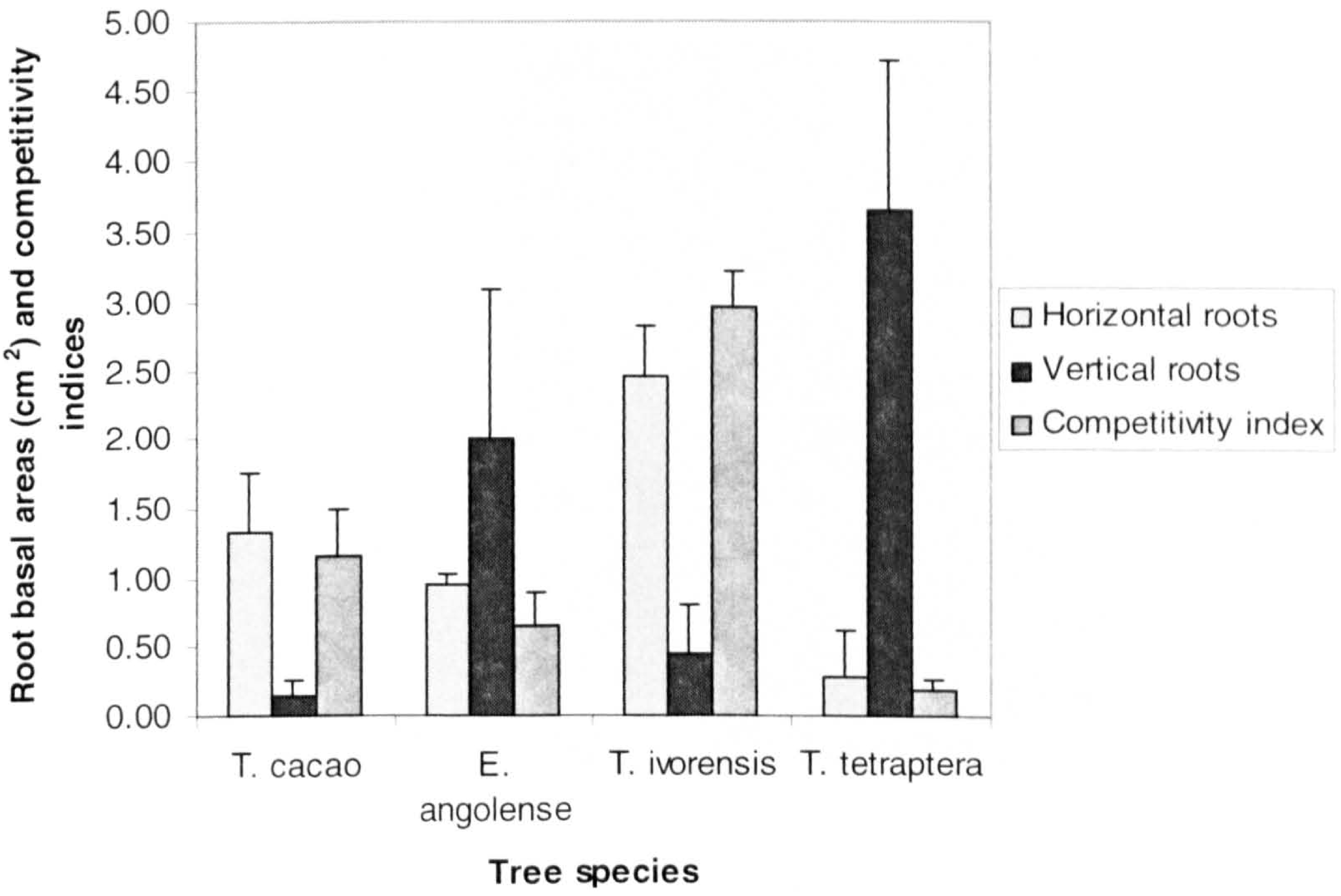


Figure 7.6: Root basal areas and indices of root shallowness (competitiveness) for cocoa and three shade tree species, planted in South Formangso, Asante Akim South district, Ghana.

Plate 7.2: Root structure of 2-year old *T. tetraptera* (left) and *T. ivorensis* (right) interplanted with cocoa at the FORIG research station in South Formangso, Ghana.

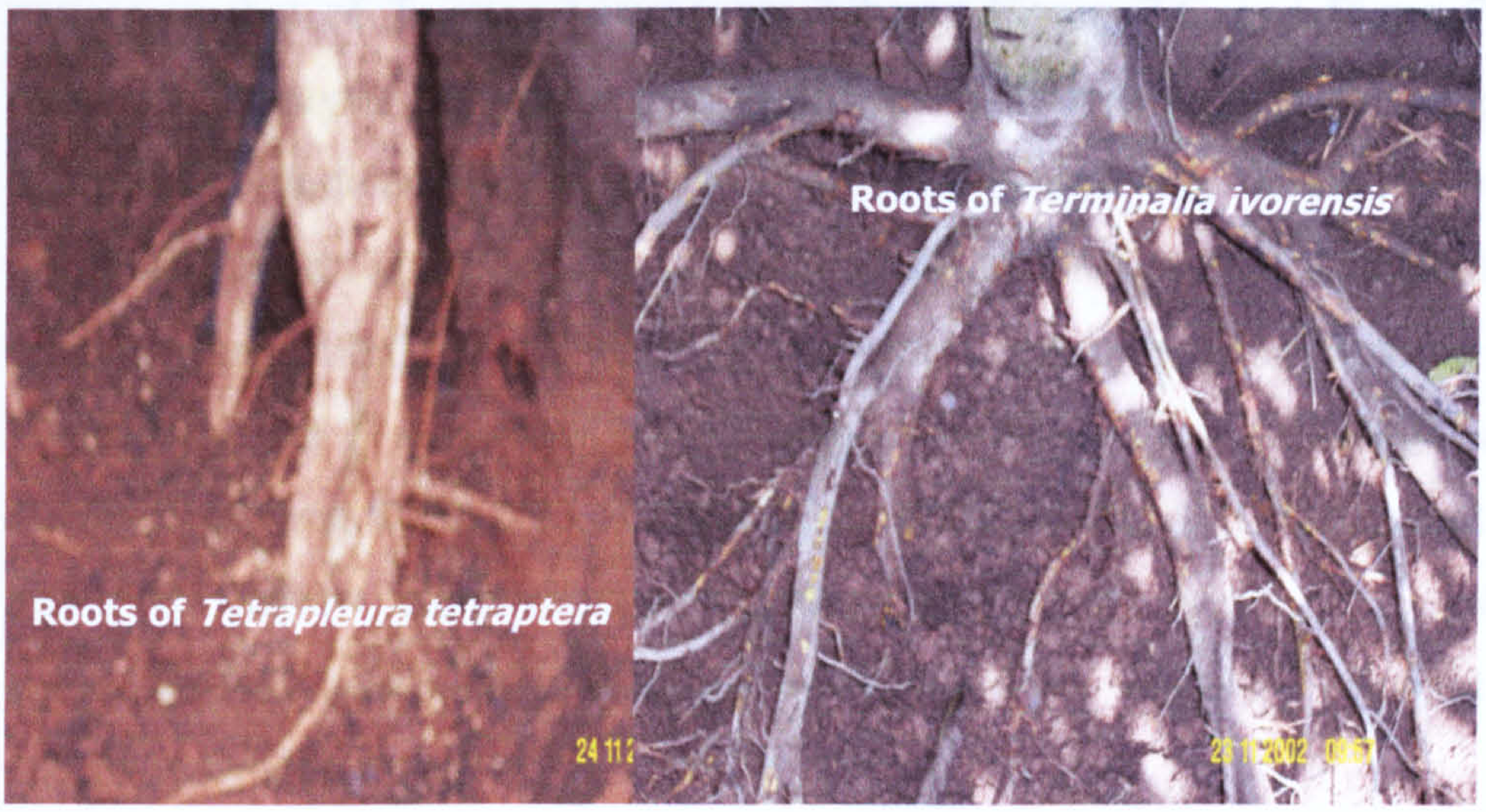
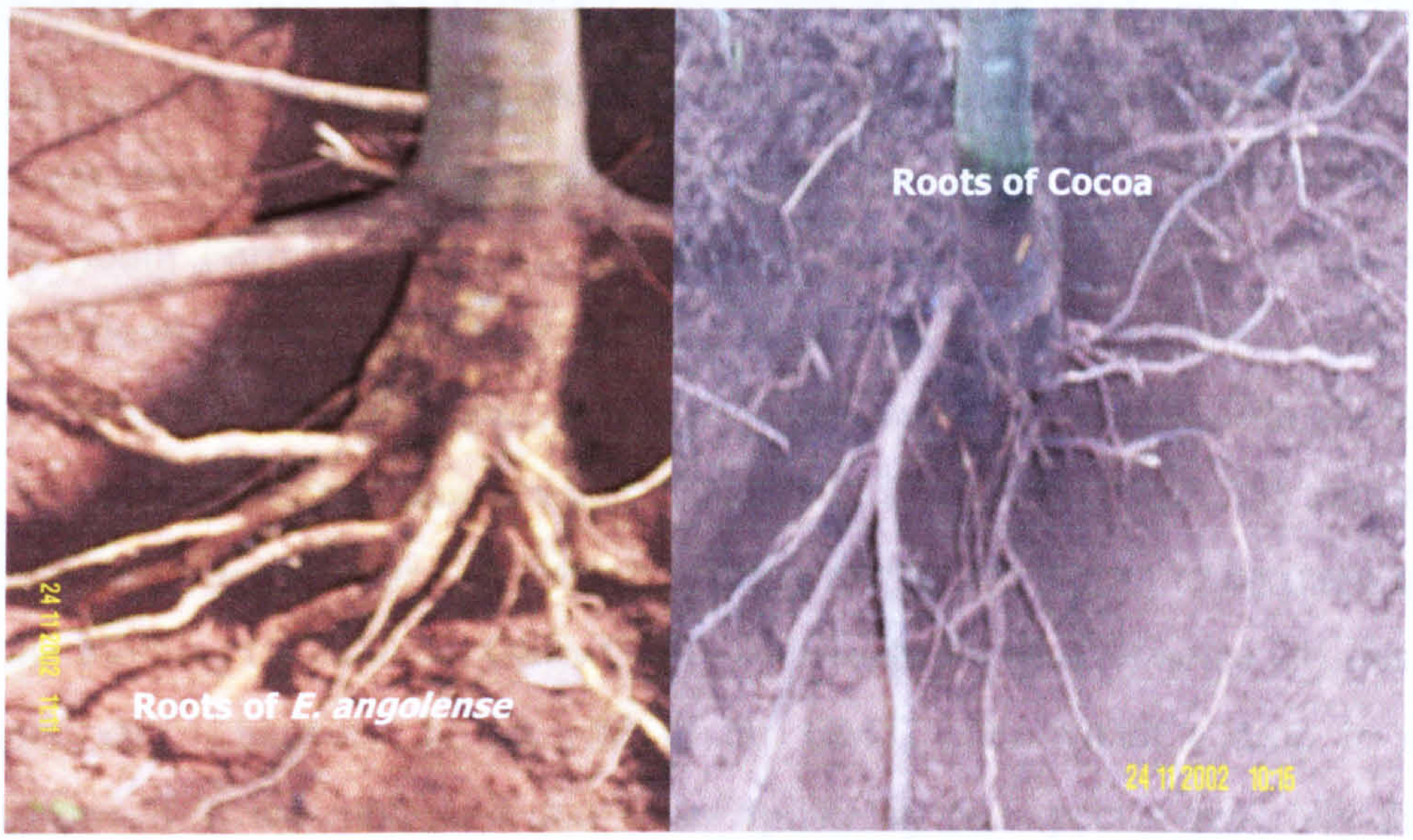


Plate 7.3: Root structure of 2-year old *E. angolense* (left) and cocoa (right) planted at the FORIG research station in South Formangso, Ghana.



T. ivorensis had the highest number of horizontally oriented roots among all the four species studied, with a mean horizontal root basal area of 2.45±0.17 cm^2, while *T. tetraptera* had the least number of horizontal roots, with a mean basal area of 0.28±0.16 cm, in the upper 0 – 40 cm soil horizon, and a greater proportion of its roots (mean basal area of 3.64±0.48 cm^2) oriented in the vertical plane. Rooting depth orientation in cocoa was similar to that of *T. ivorensis*, with more horizontally oriented roots than vertically oriented roots, while *E. angolense* displayed a similar rooting pattern to that of *T. tetraptera* (Table 7.2 and Figure 7.6, and Plates 7.2 and 7.3). Results of analysis of potential competitiveness of tree roots with the cocoa – root competitivity indices (CI), or indices of root shallowness, are shown in the last column of Table 7.2 and Figure 7.6. The values obtained for index of tree root shallowness (CI) ranged from 0.19±0.09 to 2.96±0.27, with the highest value for *T. ivorensis* and the lowest value for *T. tetraptera*. The CI obtained for cocoa was 1.16±0.34 while that for *E. angolense* was 0.66±0.23. Thus indicating that while *T. ivorensis* and cocoa trees had more shallow lateral roots with relatively higher CI values, *E. angolense* and *T. tetraptera* had fewer shallow lateral roots and more vertically oriented roots, with relatively smaller CI's.

7.3.3. Water uptake by shade tree species.

The mean sapwood cross sectional areas for *E. angolense, T. ivorensis* and *T. tetraptera* were 357.27±23.62 cm^2, 477.96±94.15 cm^2 and 335.78±68.30 cm^2 respectively. From the sap velocity data collected and stem sapwood cross sectional areas, mean hourly water uptake rates were calculated for the three shade tree species in South Formangso. Figure 7.7 shows the patterns of mean hourly water uptake (sapflow) by the three tree species. Water use by *E. angolense* was found to be intermediate between those of *T. tetraptera* and *T. ivorensis*, with the latter species drawing significantly more water ($P = 0.010$; $F = 4.96$) (Table 7.3) than *E. angolense* and *T. tetraptera*. For *T. ivorensis*, mean water uptake began to increase quite early in the morning (from about 04hrs GMT) and reached a peak of some 21litres per hour by mid day – between 11 hrs and 14 hrs GMT, after which a drop in sapflow was observed. It was observed that water uptake by this species generally dropped quite appreciably by late afternoon, and by 18 hrs GMT trees of this species were drawing water at the rate of less than 10 l/hr. By midnight and the early part of the morning less than 4 l/hr of water was being used by the young *T. ivorensis* trees on this site.

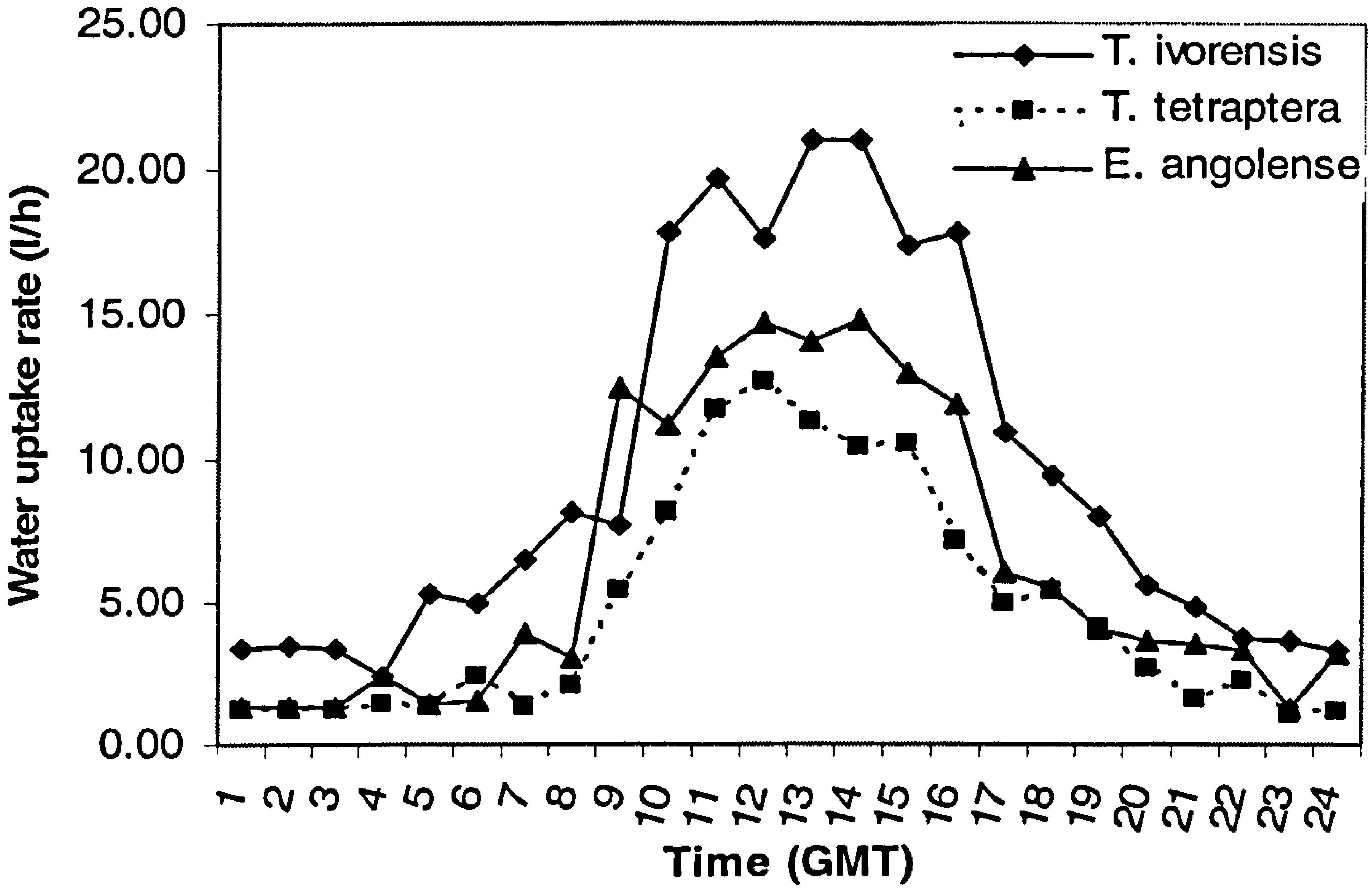


Figure 7.7: Water uptake rates of three indigenous forest tree species planted as shade for cocoa in South Formangso, in the Asante Akim South district of Ghana.

Table 7.3: Analysis of variance for transpiration rate of three cocoa shade tree species three years after planting in South Formangso, Asante Akim district, Ghana.

Source	DF	SS	MS	F	P
Tree Species	2	283.5	141.8	4.96	0.010
Error	69	1973.8	28.6		
Total	71	2257.3			

Plate 7.4: Setup for sapflow measurements on three years old *T. ivorensis* (left) and *E. angolense* (right) trees in South Formangso, Ghana.

T. tetraptera appeared to be drawing less water than both *E. angolense* and *T. ivorensis* on this site. As with *T. ivorensis*, peak uptake period was generally in the afternoon, between 11hrs and 15hrs GMT, with peak mean uptake rates of 12.65 l/hr generally occurring around midday (12hrs GMT) (Figure 7.7) – about an hour earlier than peak uptakes in *T. ivorensis*. The pattern of water use by *E. angolense* was generally similar to that of *T. tetraptera*, and even though it appeared to be drawing more water than the latter, the difference between their mean water uptake rates was not significant (P<0.05). Analysis of variance for mean peak sapflow showed that both species were drawing significantly less water than *T. ivorensis* during the investigation period.

7.4. Discussion

7.4.1. Relative survival and growth performance of cocoa and shade tree of species

Assessment of the field performance of the shade tree species, two years after planting, revealed that *T. ivorensis* and *T. tetraptera* had the best performance, in terms of survival, on the on-station sites in South Formangso and Bontomuruso, and on farmers' fields for, *T. tetraptera*. With 88.9% and 80% survival for *T. ivorensis* and 77.8% and

60% survival for *T. tetraptera* seedlings planted in South Formangso and Bontomuruso respectively, these two species have demonstrated a good potential for use as planted shade. *E. angolense* also registered moderately good survival rates, especially in South Formangso (55.6%). However, *E. utile* and *N. laevis* performed very poorly, in terms of their survival after planting, in South Formangso and Bontomuruso, with *N. laevis* showing 100% mortality in South Formangso.

Across all the three sites, *T. tetraptera* performed best, with 100% survival on farms in Gogoikrom. Comparatively, survival rates were higher for the planted species on the on-farm sites than on both on-station sites, especially for *T. tetraptera, E. angolense, N. laevis* and *K. anthotheca* (Figure 7.1). The higher survival rates recorded for *T. tetraptera* and *N. laevis* (100% and 77.8% respectively) on farmers' fields in Gogoikrom may be attributed to the value of these species to the local farming communities within the project area. The fruits of *T. tetraptera* for instance, locally known as Prekese, are a highly valued and popular spice for the preparation of soups in this area, and indeed the whole of southern Ghana, while *N. laevis* (known locally as Sesemasa) is a medicinal plant, with roots and leaves concoctions widely used in the area for the treatment of various ailments, as recorded within the indigenous knowledge section of this work (Chapter 3). Prekese is also reputed to have high medicinal properties and is reputed to be capable of controlling blood pressure and enhancing breast milk production in lactating mothers. Thus its fruits are popular in markets across south Ghana, and some parts of the north. These attributes would most likely have influenced farmers to take better care of the planted trees of these species, thus resulting in better survival here. This reasoning is supported by Hall and Swaine (1981) who found that even during land clearing for planting, standing trees as well as regenerating saplings of these species are not cut down by farmers. As with *T. tetraptera* and *N. laevis* the relatively high survival of *E. angolense*, as well as *K. anthotheca*, on-farm may be attributed to increased farmer care due to their high timber value, especially in view of the new national forest policy encouraging the private planting and onwnership of valuable forest tree species. Poor survival of *E. utile* and *P. elata* on-farm in Gogoikrom may be due to detrimental competition by intercrops as pointed out by Balandier and Dupraz (1999; citing Frochot and Levy, 1986 and Frochot, 1990). It may also be explained by their inherent poor initial growth rates (Hawthorne, 1995) which could have resulted in their being inadvertently cut during weeding operations, as was noted on a number of farms, in addition to being out-competed and strangled by competing weeds and the planted cocoa and food crops on farmers' fields. Thus, on the basis of survival after planting, the planting of *E. utile* and *P. elata* as cocoa shade may not be recommendable for these sites.

Basal stem diameters and height of the shade tree species and the cocoa, after two growing seasons, ranged from 1.72 – 11.52 cm and 0.83 – 5.12 m, respectively, according to species and location. In terms of growth performance, *T. ivorensis* proved to be the best; registering the highest stem basal diameter (11.52±1.65cm) and height (5.12±0.61m) growth, in South Formangso, compared to any other species on any of the three sites (Figures 7.2 and 7.3). Apart from *T. ivorensis*, *T. tetraptera, E. angolense* and *K. anthotheca* also grew relatively well on all sites, except in Bontomuruso where diameter and height growth of all the planted species were generally poor. These four species registered the best growth rates, within the two years, with *T. ivorensis* posting the highest diameter and height growth rates of 4.26 cm yr^{-1} and 2.49 m yr^{-1} respectively. In comparison with the cocoa, they have significantly faster growth rates; a feature that will ensure early canopy stratification and niche differentiation (Menalled *et al.,* 1998) when grown in mixtures with the cocoa. The high initial growth rates of these species give a good indication of their good ecological combining ability (Harper, 1977 cited by Menalled *et al.*, 1998) with the cocoa crop, as they will ensure good spatial differentiation and reduction in interspecific competition (Vandermeer, 1989; Kelty, 1992; Menalled *et al.,* 1998). On the other hand, the relatively poor growth rates displayed by the other species, especially *E. utile,* and *P. elata* mean that it may not be feasible to plant them with cocoa as shade, and that any use of these species may have to depend on management of already established, naturally occurring trees for the provision of shade. Though naturally regenerating seedlings of *A. adianthifolia* are noted to have a rapid growth (reaching heights of 1 – 2 m in a year) (Taylor, 1960), it failed completely to survive when planted on farmers' cocoa fields in this study. This complete failure to survive is difficult to explain, but may have been due to soil conditions, smothering by weeds and planted cocoa and food crops or failure to properly identify planted seedlings during weeding operations – leading to seedlings being cut off. And although *N. laevis* appeared to be performing relatively well on farmers' fields, its suitability for use as planted cocoa shade is greatly limited by its' rather short bole length and narrow crown, as pointed out in section

5.4.2 of Chapter 5; although it would presumably be retained/cultivated for its medicinal uses.

7.4.2. Root architecture

The data obtained in this study indicate a considerable difference in proximal root orientation between the different tree species two years after planting. At this age, *T. ivorensis* was found to be potentially the most competitive species, with the most extensive shallow proximal roots and, hence, the highest root competitivity index of 2.96±0.27; making it comparable to the competitivity index (2.13) calculated for 4-year old *L. leucocephala* trees in homegarden systems in North Lampung (Indonesia) by van Noordwijk and Purmonosidhi (1995). A higher proportion of the cocoa proximal roots were also located in the topsoil horizon, indicating that at this age there will be considerable interaction (competition) between the roots of the planted *T. ivorensis* shade trees and the cocoa. On the other hand, the root orientation of *E. angolense* and *T. tetraptera* show the former to be moderately deep rooted, with a moderately low competitivity index of 0.66±0.23, while the latter shows a good deep rooting system with a much lower competitivity index of 0.19±0.09. These latter two species thus demonstrated lower competitiveness, and much better below-ground compatibility with the cocoa, based on their calculated competitivity indices, than *T. ivorensis*.

On the basis of these calculated competitivity indices it would seem reasonable to conclude that *E. angolense* and *T. tetraptera* are a better choice for planting as shade for cocoa in this area, due to their low root competitiveness and water uptake. However, it has been shown that competitivity indices of tree species change with tree age (Ong *et al.*, 1999); hence such a conclusion will be too early to draw at this age. In their comparisons of the competitivity indices of 2-year and 4-year old trees of four multi-purpose agroforestry tree species, including *Grevillea robusta, Senna spectabilis, Melia volkensii* and *Gliricidia sepium*, it was shown, for instance, that *Melia volkensii* which had the highest competitivity index (1.19±0.13) at age 2 gave a much lower index of 0.41±0.12 at age 4. On the other hand the competitivity index of *G. robusta* had risen from the lowest comparative value 0.06±0.03 at age 2 to the value of 0.65±0.13 by age 4; thus indicating the substantial variation in competitivity indices with tree age. This, they explained, may be due to the fact that at such an early age (2 years) not all of the structural elements of the root system have been laid down. Tree rooting patterns are also known to be influenced by soil properties (Howard *et al.*, 1997). Thus while serving as a good insight into what the potential relationship/interaction between the shade trees and the cocoa may be, it is not feasible to draw any conclusions on below-ground complementarity of the three shade tree species with the cocoa, and further and more detailed studies, especially a combination of root competitivity and root length density, will be required. Also, Ong *et al* (1999) have suggested that shallow roots, index of shallow rootedness, stem diameter, diameter increment, and combination of these variables, may provide a useful competition index, provided that tree size is always taken into account when making comparisons in the field.

7.4.3. Water uptake

Results of the present study indicate that there is a significant difference in the amount of water used by the three years old trees of the different shade trees in South Formangso. The maximum sap velocities of 41.45 cm h^{-1}, 43.96 cm h^{-1} and 37.67 cm h^{-1}, recorded at midday, for *E. angolense, T. ivorensis* and *T. tetraptera* respectively, indicate that at this age (3 years) these shade tree species are capable of transpiring moderate amounts of water, especially when compared with the typical midday values of 10 to 80 cm h^{-1} reported by Granier *et al.*, (1996) for a nabural rainforest. For all three species, maximum water use was recorded between mid morning and mid afternoon. This period corresponds with the period of maximum incident PAR in this area, as recorded earlier during the phenology and PAR studies (Chapter 5), and compares with the pattern of water use reported by Deans and Munro (2004) for different dryland trees in Senegal, and for *Grevillea robusta* in Kenya by Ong *et al* (1999) and Lott *et al* (2003). Allen and Grime (1995) also observed similar diurnal variation in sapflow, for *G. senegalensis* in Niger, and attributed it to the dependence of transpiration on net radiation and vapour pressure deficit.

Comparatively, *T. ivorensis* trees used significantly more water than both *E. angolense* and *T. tetraptera* trees on the study site. This, as suggested by Bayala (2002) in his study of transpiration patterns by *Parkia biglobosa* and *Vitellaria paradoxa* trees in Burkina Faso, may be due to the larger crown and sapwood cross-sectional area of *T.*

ivorensis compared to the other species. The sapflow rates also followed the trend in growth rates for the three species, with the trend being *T. ivorensis*>*A. angolensis*>*T. tetraptera*, indicating that faster growing species use more water compared to slower growing species. This implies that, even though the use of such fast growing species as *T. ivorensis* will ensure faster spatial differentiation and above-ground complementarity in the use of aerial resources such as light (Menalled *et al.*, 1998), it could also have some negative implications for below-ground complementarity for water and nutrient use.

Although some night time sapflow was recorded for all the species, it was always much less than the corresponding sapflow during the middle part of the day. Cabibel and Do (1991 cited by Green Clothier, 1999) attributed night time sapflow in apple trees, growing in very dry soils, to a recharge of the trees' capacitance. However, as this study was conducted in the rainy season, there was probably sufficient water in the root zone of the trees to maintain favourable water status for the trees so that the trees' capacitance was unlikely to have been strongly depleted during the day (Green and Clothier, 1999). Thus, as pointed out by Green and Clothier (1999), the night time sapflow recorded here, albeit minor, would be more indicative of night time transpiration and less due to a recharge of the trees' capacitance.

As most water was used between mid morning and mid afternoon, it therefore seems more appropriate to limit consideration of data to those obtained around midday when attempting to rank trees in terms of their water use, as pointed out by Deans and Munro (2004). On this premise the indication will be that *T. tetraptera* and *E. angolense* are more conservative water users, and hence potentially less competitive, than *T. ivorensis*. And this indication is further strengthened by the relatively low root competitivity indices of the former species compared to the latter. However, as stated earlier in this section, the stage of growth of the trees is too early to make any conclusive inference from these studies, as evidence has shown that root system dynamics as well above-ground growth parameters change with the age of the tree, and this is likely to change the trend in water use by the species. Nevertheless, the study, and the results obtained, give some useful indication of the competitive potential of these shade tree species and provide a basis for comparison of future trends.

CHAPTER 8

BIOMASS, NUTRIENT DYNAMICS AND CARBON CONTENT OF A COCOA - *GLIRICIDIA* AGROFORESTRY SYSTEM

8.1. Introduction

In many parts of both the humid and dry tropics, forest cover is being cleared or degraded at a rapid rate, mainly to satisfy the subsistence needs of rural communities. Given that over 1.5 billion people in these regions derive at least 90% of their energy requirements from wood and charcoal (NAS, 1983; FAO, 1986), there is pressing need to find new ways to meet present and probably increasing future demands for fuelwood (Jackson *et al.,* 1995) and other wood and non-wood products. Human population growth and the need for agricultural expansion, in conjunction with wood harvesting for fuel and export have led to increasing deforestation rates (Schroeder, 1993). The consequences of all this, as pointed out by Allen and Barnes (1985), are not only reduced soil fertility, but also desertification. Agroforestry is a promising land use practice to maintain or increase agricultural productivity while preserving or improving soil fertility (Schroeder, 1993).

Woody biomass constitutes the major source of energy in the developing countries of the world. It has been reported (FAO, 1986) that about 13% of the world's primary energy is derived from woody biomass. In Ghana, fuelwood shortage has been identified as a pressing domestic problem affecting many households (Otsyina, 1989). The need to establish energy plantations has been recognised. Several multipurpose tree species, including *Gliricidia sepium,* have been recommended in Ghana for use in different landuse systems to reduce or solve the pressing fuelwood problems which face many households in the country (Quashie-Sam *et al.,* 1990), as well as mitigate soil fertility problems and provide valuable fodder for livestock. However, quantitative documentation and information on the growth, dry matter production and nutrient accumulation of these species in Ghana is scarce. Quantitative information on these parameters in a multi-strata tree based production system in Ghana is virtually non-existent. In the system as exists in Bontomuruso, it is expected that the *G. sepium* shade trees will be cut back at some stage to manage the shade level, given the relatively high density 6 m x 6 m shade tree planting distances used, and the wood used for fuel energy. While growth data will help in evaluating the economic rate of development of such multi-strata systems, estimates of tree biomass and distribution are useful in studies of biological productivity and nutrient requirement of such ecosystems. Information on the amount of dry matter and nutrients, and their partitioning at stand level, is therefore essential for developing models of system structure and function in such agroforestry plantations.

Most soils in the tropics are deficient in soil nutrients, especially nitrogen and phosphorus (Sanchez and Logan, 1992). As pointed out by Mafongoya *et al* (1998), many of these soils are acidic, infertile and cannot support sustainable crop production without external inputs of inorganic fertilizers. However, small scale farmers in the tropics have limited access to inorganic fertilizers due to high cost and, in some cases, unavailability of such fertilizers. In these situations, agroforestry systems are considered to be viable and sustainable landuse alternatives because of the benefits of trees in maintenance of soil fertility (Mafongoya *et al.*, 1998). Spatially mixed systems such as coffee and cocoa plantations include upper storey trees that provide nutrients, from litterfall and periodic prunings, as well as the shade provided for the lower storey tree crops (Heuveldop *et al.*, 1988). Two major mechanisms by which trees enhance soil fertility in agroforestry systems are the addition of organic matter through leaf and root decay, and biological nitrogen fixation by leguminous trees (Jose *et al.*, 2000). While decomposition and the rate of nutrient return to upper soil layers through litter decomposition is influenced by the resource quality of the organic material, the environment, and the decomposer organisms present (Swift *et al.*, 1979), it has been pointed out that in the tropics, decomposition rates are controlled to a large extent by the quality of the litter, rather than by the climate (Campbell *et al.*, 1994; Lehmann *et al.*, 1995). Shade trees, by their influence on soil and micro-environmental factors, present an avenue for farmers to achieve sustained yield while increasing diversity of products from their farms. Thus a quantification of the rate of nutrient cycling in cocoa-shade tree agroforestry systems will add to the knowledge of how such systems operate and what their potential benefits are, thereby allowing us to be able to manipulate system composition and configuration for enhanced production.

The Intergovernmental Panel on Climate Change – IPCC - (1995) has stated that carbon dioxide concentration in the earth's atmosphere has increased from 280ppm in the pre-industrial times to 370ppm in 1995, due mainly to human activities. As a result of the increased concentrations of greenhouse gases, the IPCC concluded that the balance of evidence suggests a discernible human influence on global climate (IPCC, 1995). For this reason, it is important to evaluate human activities that have the potential to counteract these effects. It has been pointed out that natural forests, forest plantations and agroforestry plantations are an important reservoir for carbon (Kort and Turnock, 1999). From the perspective of climate change and the global carbon cycle, Schroeder (1993) points out that agroforestry holds an attraction for at least two reasons. The first is that the tree component fixes and stores carbon from the atmosphere. Trees can function as carbon sinks for periods of many years and continue to store carbon until they are cut or die. The second interest in agroforestry is its apparent potential to reduce the need to clear new forest land by providing an alternative to shifting cultivation. Thus a quantification of the carbon content of the components of the cocoa-shade tree agroforestry system will throw more light on the potential contribution of such systems to ecosystem carbon balance and enable us get an idea on the level of contribution of each of these components to this balance.

The primary objective of this study was therefore to provide estimates of the amount of dry matter production and distribution among the components of a cocoa-*Gliricidia sepium* agroforestry system in Ghana. It also sought to quantify nutrient content and distribution within system components, and to investigate mass loss and nutrient release patterns from leaves of *G. sepium* in a litterbag experiment.

8.1.2. Hypothesis and study objectives

The hypothesis for this study is that the inclusion of shade trees in multistrata cocoa agroforestry systems can increase system productivity and contribute to global carbon balance. The specific objectives included:

i. determination of the above-ground dry mass of the system components in a *Gliricidia*-cocoa agroforestry system;

ii. determination litter production by the two components of the system;

iii. determination of litter decomposition and nutrient dynamics within the system;

iv. determination of carbon content of the *Gliricidia* and cocoa trees within the system

8.2. Materials and methods

Biomass production, nutrient cycling and carbon content were estimated for a cocoa-*Gliricidia sepium* shade tree system in Bontomuruso in the Atwima district of Ghana. The study was carried out in November 2002 on a research farm established by the Ghana Cocoa Growers and Researchers Association (GCGRA) in 1996. It consists of Amelonado/hybrid cocoa mixture planted at a regular spacing of 3 m x 3 m, with *Gliricidia sepium* as the shade tree planted at a spacing of 6 m x 6 m. Since establishment the *Gliricidia* has not been cut back and now forms an almost closed canopy above the cocoa crop. Mean stand height was estimated to be approximately 14±2.1 m.

8.2.1. Biomass Production

To estimate biomass for the cocoa and the *Gliricidia* shade a plot 60 m x 60 m was demarcated in a well stocked portion of the farm. Diameter at breast height of 1.3 m (DBH at 1.3 m) of all *Gliricidia* trees and basal diameter (i.e. diameter at 5 cm from the ground, $d_{0.05}$) of all cocoa trees within the plot were measured with a digital calliper. The DBH and $d_{0.05}$ values were tallied into ten diameter classes, with one-tenth of the stand diameter range as the class interval. Stand diameter range for *G. sepium* was 13.74 cm, while that of the cocoa trees was 12. 19 cm. Ten trees, selected to represent as closely as possible the mean size of each of the ten diameter classes, were cut as close to ground level as possible and basal diameter (for *Gliricidia*), total height, bole length (to the first major branching), branch length were measured for each species. Each felled tree was subsequently separated into stems, branches and leaves and weighed fresh on the field. Samples of the stem, branches and leaves were taken, weighed and transported to the laboratory for dry mass and carbon content determination. Sub-samples of the stem, branches and leaves were weighed, dried to a constant weight at 70°C in an oven and reweighed. The dry weight/fresh weight ratios of the various components were used to determine the dry weight of the component parts. The stand biomass was computed as the sum of products of the mean tree values and the number of trees in each of the DBH classes, and expressed on per hectare basis as described by Nwoboshi (1985) and Nolte, et al (2003). Stem volume was computed using the Smalian formula:

$$V = \frac{(S_b + S_t)\,L}{2},$$

where S_b and S_t are basal areas of the butt and top ends of the stem and L is the length of the stem.

The dried samples were ground to pass through a 2 mm sieve and prepared for chemical analysis for Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg), as well as for Carbon (C) content.

8.2.2. Litterfall and Litter Decomposition

To monitor litterfall and litter decomposition the methods of Montagnini *et al.* (1993) and Jose *et al* (2000) were adapted. Fifteen litter traps were randomly placed in a 1 ha plot demarcated in the central part of the cocoa-*Gliricidia* stand. Each trap was made of a 2 mm gauge nylon mesh fitted to stakes fixed 1m x 1m in the ground, ensuring that the base of each net was raised at least 0.5 m from the ground. The traps were emptied fortnightly beginning from November 2002 and continued till October 2003. In the laboratory, the contents of each trap were separated into *G. sepium* and cocoa litter and then dried in the oven at 70°C for 48 hours, pooled into monthly collections and weighed to obtain monthly litterfall data.

Litter decomposition bags, 30 cm x 30 cm in size and made of nylon mesh (mesh size 2 mm^2), were used to monitor decomposition. Twenty grams (20g) of air-dried freshly fallen leaf litter of cocoa and *Gliricidia* was put into each litter bag and the bags stapled at approximately 5 cm intervals. Five groups of 12 litter bags were randomly placed in the 1ha plot demarcated for the litterfall collection. Prior to the placement of the litter bags the area was cleared of ground litter, and the bags were covered with the displaced ground litter after they were placed on the floor. In all 60 litter bags were used.

The litter bags were placed on the plot on 2nd January 2003 and each month one bag was collected from each of the five groups, taken to the laboratory where adhering soil particles were carefully rinsed from the residues with a minimum of distilled water, using a very fine meshed (0.106 mm) sieve, to reduce artificial leaching (Jose *et al.*, 2000). The cleaned residues were then oven dried at 65°C for 48 hours, and weighed to find the change in weight. Mass loss was calculated as the difference between initial weight and the weight remaining at each sampling date. Each month the five decomposition samples were pooled and sub-samples taken for chemical analysis. Samples of the dried freshly fallen litter were also taken, weighed and ground for chemical analysis. Analysis was carried out for N, P, K, Ca and Mg.

Weighed dried samples of the stem and branches of the cocoa and *Gliricidia* collected during the biomass sampling were ground set aside and used for the determination of their carbon (C) content.

8.2.4. Nutrient analysis

Laboratory analysis of the plant material was carried out by technicians in the soil science laboratory of the School of Agricultural and Forest Sciences (SAFS) of the University of Wales Bangor (UWB).

Total C and N were measured using LE02000 CHN analyser (LECO Corp. St. Joseph, MI). All the other elements were digested in concentrated perchloric acid, using 0.2 g of sample and 2 ml of acid. The acid was added and left over night, then heated to 200° C for 4 hours in dry block and left to cool. The solution was made up to 15 ml with distilled water and filtered through a whatman 54 l filter. The solution was frozen until needed. P was determined colourimetrically with ames reagent, with colour intensity determined after 10 minutes at 840 nm with a VESAmax Plate reader (Molecular devices, Sunnyvale, California).

Ca, K and Mg were analysed with a Sherwood Scientific 410 Flame Photometer (Sherwood Scientific, Cambridge, England).

8.3. Data analysis

Regression analysis was performed to determine what easily measured tree parameters were most important in determining aboveground biomass. The results of the regression analysis were used to develop equations by which measured parameters could be used to estimate tree aboveground biomass. All data sets were first tested for normality, using the Kolmogorov-Smirnov test, before futher statistical analyses were performed.

Growth and dry matter production of the *Gliricidia* shade trees and the cocoa were compared using the 2-sample t-test and the Mann-Whitney test. T-test was also performed on the litter decomposition to compare mass loss as a percentage of the initial mass as well as nutrient concentrations for the two species, for each collection. Data on percentage mass and carbon loss was transformed, using arcsin transformation, before analysis of variance was performed. Monthly nutrient release patterns from the decomposing litter of the two species were compared, using the 2-sample t-test for normally distributed data and the Mann-Whitney test for data that was not normally distributed. All analyses were performed using the Minitab statistical software package.

8.4. Results

8.4.1. Dry matter production

The biomass production in the cocoa-*G. sepium* stand in Bontomuruso is shown in Table 8.1. Of the 1111 and 277 trees/ha initial planting density for cocoa and *G. sepium* respectively, survival of the cocoa at the time of the study, 6 years on, was only 34.47%, or 383 trees/ha of the initial stocking, while that of the *G. sepium* trees was 69.07%, or 192 trees/ha, on this site. Quite expectedly, results of the 2-sample t-test showed that the *G. sepium* shade trees had attained significantly taller heights (9.21±1.35 m) than the cocoa (4.39±1.27 m) within the 6 years after plot establishment ($P = 0.000$; $T = 8.21$) (Appendix 8.1).

G. sepium produced significantly higher (P = 0.008; T = 3.28) (Appendix 8.2) dry matter per tree (87.85 kg) than the cocoa (16.46 kg). In terms of biomass distribution per tree, it was observed that as much as 49.54% (or 43.52±3.72 kg) of the total mean tree biomass for *G. sepium* was allocated to the branches and 40.97% (35.99±3.45 kg) to stems, leaving only 9.49% (8.34±0.66 kg) of the the total biomass allocated to the leaves. On the other hand, a comparatively higher proportion of the biomass produced per cocoa tree was allocated to leaves (34.20%) compared to *G. sepium*, though in terms of mass this proportion – 5.63±0.46 kg was only about half of the leaf dry mass/tree produced by the *G. sepium* trees. Unlike in the *G. sepium*, stem dry matter per cocoa tree (36.03% or 5.93±0.96 kg/tree) was higher than branch dry matter (29.77% or 4.90±1.21 kg/tree) (Table 8.1).

With the stocking of 192 trees/ha for the *G. sepium* shade trees, they produced a total stand dry mass of 11.49 t/ha of which stems contributed 4.51 t/ha while branches and leaves contributed 4.74 t/ha and 1.34 t/ha respectively. The cocoa trees on the other hand, at a stocking of 383 trees/ha yielded a total dry mass of 4.51 t/ha with stems, branches and leaves contributing 1.74±0.007 t/ha, 1.29±0.006 t/ha and 1.49±0.005 t/ha respectively (Table 8.1). Apart from stand leaves dry matter for which the Mann-Whitney test at *a* = 0.05 showed no significant difference between the *G. sepium* and cocoa leaves dry weight/ha (*a* = 0.5708), the dry matter production per ha for the other components was significantly higher in *G. sepium* than in the cocoa.

Table 8.1: Above-ground dry matter content and distribution in a 6-year old cocoa-*G. sepium* plantation in Bontomuruso, in the Atwima district of Ghana.

Components	*G. sepium*	%	*T. cacao*	%
	Mass (kg)		Mass (kg)	
Mass of tree components (kg/tree)				
Stem	35.99(3.45)	40.97	5.93(0.96)	36.03
Branches	43.52(3.72)	49.54	4.90(2.21)	29.77
Leaves	8.34(0.66)	9.49	5.63(0.46)	34.20
Total	87.85		16.46	
Stand values (Kg/ha)				
Stocking (trees/ha)	192		383	
Stem (kg/ha)	4739.39(21.77)		1739.92(6.93)	
Branches (kg/ha)	4721.76(17.06)		1293.10(5.63)	
Leaves (kg/ha)	1337.90(5.95)		1485.21(4.75)	
Total (t/ha)	11.49		4.51	

Values presented are means. Standard error of means in parentheses.

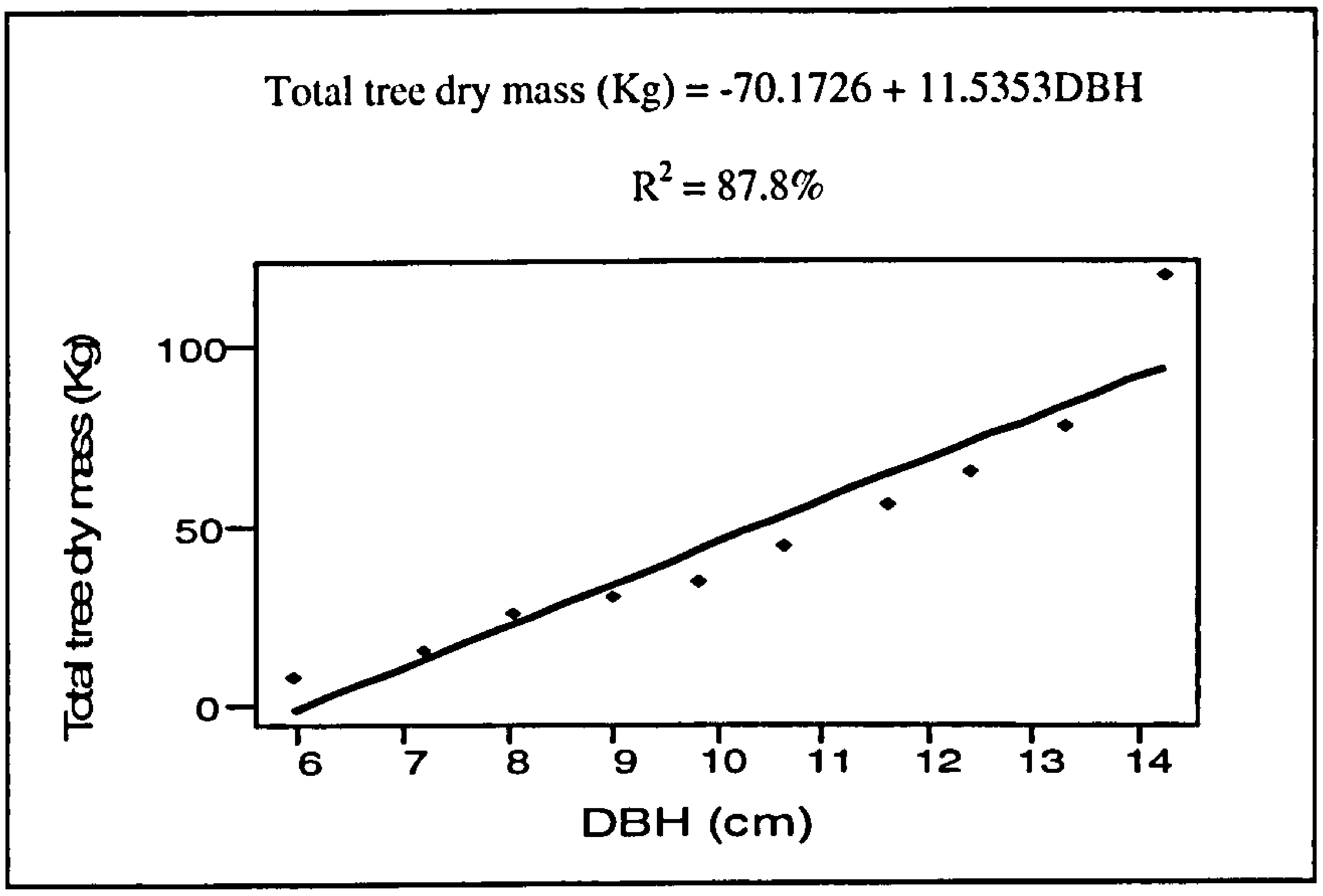


Figure 8.1: Regression between total tree above-ground biomass (kg) and stem diameter at breast height DBH (cm) for *G. sepium* trees planted as cocoa shade in Bontomuruso, Ghana.

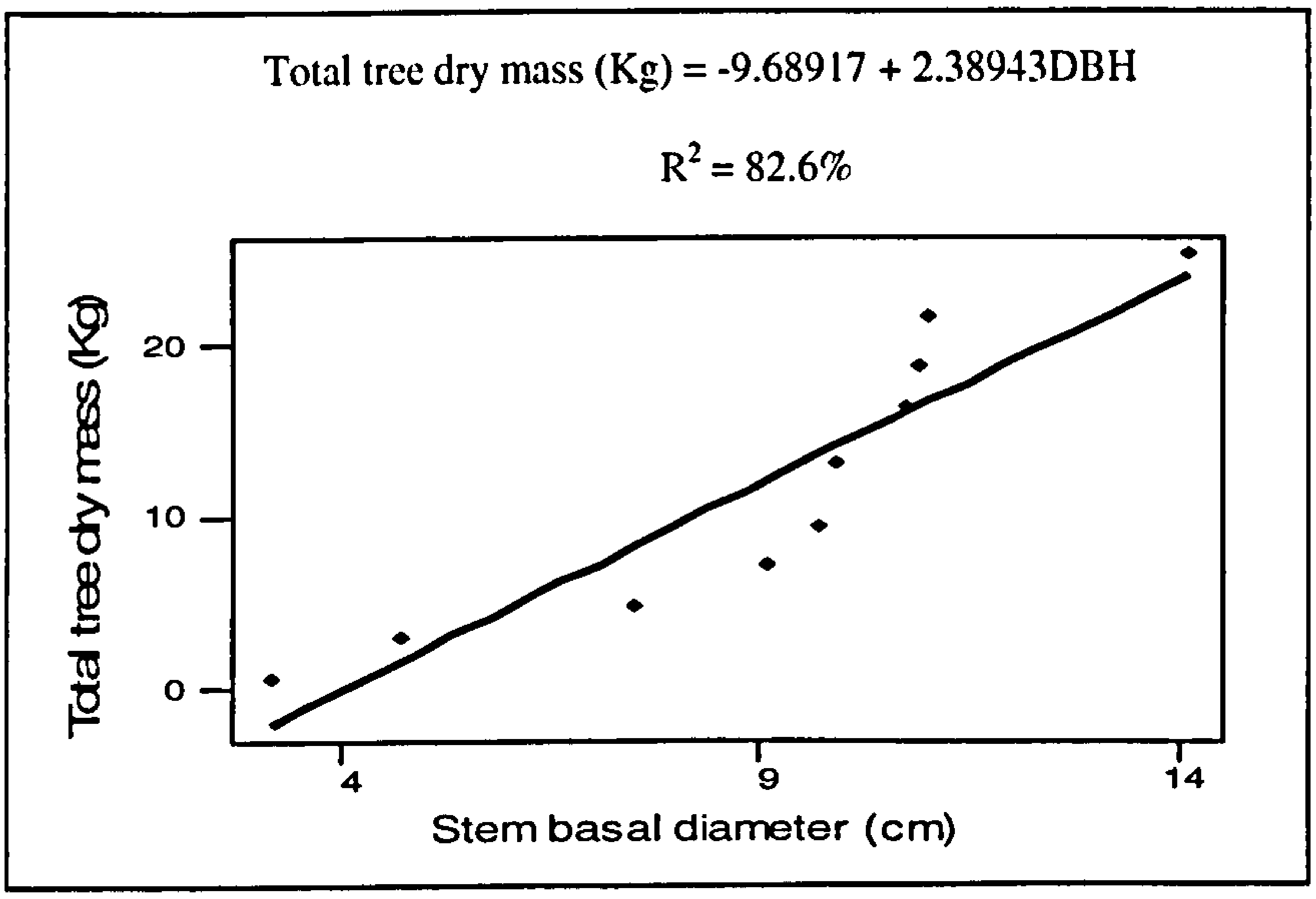


Figure 8.2: Regression between above-ground biomass (kg) and stem basal diameter (cm) for cocoa trees in Bontomuruso, Ghana.

An attempt was made to predict total above-ground biomass per tree using easily measurable parameters such as stem diameter and basal area, measured prior to the destructive sampling. Stem DBH and basal diameter appeared to yield better prediction equations for the *G. sepium* and cocoa, respectively; the regression plots are shown in Figures 8.1 and 8.2 for the two species. *G. sepium* mean tree dry mass was well predicted by DBH with a slope of 11.54 and with 87.8% (R^2) of variation accounted for by the model, while stem basal diameter (at 10 cm from the ground) predicted mean tree above-ground dry mass to a degree of 82.6% (R^2) with a slope of 2.39.

8.4.2. Carbon and nutrient contents

The percentage concentrations of C, N, P, K, Ca and Mg in the two species are shown in Table 8.2. In both species the mean total nutrient concentrations per tree were found to be in the order Ca>N>K>Mg>P. Foliar concentrations of these elements were the highest, on the average, in both species and were in the order N>Ca>K>Mg>P, with N, Ca and Mg showing significantly higher concentrations in *G. sepium* leaves than in the cocoa leaves (Appendix 8.3). However, unlike in the leaves where there was a definate pattern in nutrient concentration in both species, the other tree components – branches and stems – did not show any consistent pattern in both species. For instance, concentration in the branches of *G. sepium* was in the order Ca>N>K>Mg>P while in cocoa, the order was Ca>K>N>Mg>P. It was observed that for all the tree components in both species, P was the least concentrated followed by Mg, while Ca appeared to be the highest concentrated nutrient element, except in the leaves.

Among the various components in both cocoa and *G. sepium*, the average concentrations of these nutrient elements were found to be in the order Leaves>Branches>Stem. The average concentrations in the various components were, however, higher in the *G. sepium* than in the cocoa with the exception of K and Mg which showed relatively higher average concentrations in cocoa.

In terms of carbon content, average concentrations in both species were found to be highest in the stems, while foliar carbon content was lowest, with branch content being intermediate. Per tree, however, the cocoa trees appeared to have higher carbon concentrations than the *G. sepium* trees on this site.

Table 8.2: Percentage nutrient concentration in different tissues of *G. sepium* and cocoa in Bontomuruso, Atwima district (percent in dry mass). Values presented are means±se.

Nutrient element	Plant part	*G. sepium*	*T. cacao*
% C	Leaves Branches Stem	43.51±6.21 44.60±5.73 45.41±7.34	41.30±3.22 44.41±6.94 45.33±6.73
Mean		44.50±0.95	43.68±2.11
% N	Leaves Branches Stem	2.07±1.21 0.91±0.33 0.85±0.16	1.85±1.10 0.79±0.24 0.63±0.21
Mean		1.28±0.69	1.09±0.66
% P	Leaves Branches Stem	0.14±0.11 0.09±0.03 0.07±0.04	0.13±0.10 0.05±0.04 0.04±0.01
Mean		0.10±0.04	0.07±0.04
% K	Leaves Branches Stem	0.76±0.36 0.57±0.32 0.49±0.41	0.81±0.66 0.64±0.39 0.57±0.32
Mean		0.61±0.14	0.67±0.12
% Ca	Leaves Branches Stem	1.78±1.22 0.93±0.74 0.81±0.48	1.33±0.85 0.89±0.39 0.78±0.53
Mean		1.17±0.53	1.00±0.29
% Mg	Leaves Branches Stem	0.18±0.16 0.11±0.05 0.10±0.03	0.33±0.11 0.10±0.07 0.13±0.10
Mean		0.13±0.04	0.19±0.13

Table 8.3: Total nutrient accumulation of *G, sepium* and cocoa trees in Bontomuruso.

Nutient element	Plant part	*G. sepium*		*T. cacao*	
		Mean tree (kg/tree)	Stand value (kg/ha)	Mean tree (kg/tree)	Stand value (kg/ha)
C	Leaves	3.63±2.36	582.12±11.63	2.33±1.22	613.39±9.74
	Branches	19.41±3.13	2105.90±40.63	1.71±089	574.27±12.53
	Stem	16.34±2.67	2151.68±47.33	2.69±1.84	788.71±24.05
Total		39.38±9.40	4839.71±61.64	6.75±2.33	1976.36±94.08
N	Leaves	0.17±0.11	27.69±5.82	0.10±.06	27.48±2.83
	Branches	0.40±0.06	42.97±3.63	0.03±.01	10.22±1.04
	Stem	0.31±0.10	40.28±5.24	0.04±.01	10.96±2.55
Total		0.87±0.61	110.95±14.73	0.17±0.05	48.65±8.26
P	Leaves	0.01±0.01	1.87±1.32	0.007±0.002	1.93±0.41
	Branches	0.04±0.02	4.25±0.77	0.002±0.001	0.65±0.10
	Stem	0.03±0.02	3.32±1.24	0.002±0.001	0.70±0.16
Total		0.08±0.01	9.44±2.88	0.01±0.003	3.27±0.83
K	Leaves	0.06±0.01	10.17±3.32	0.05±0.02	12.03±5.36
	Branches	0.25±0.06	26.91±1.17	0.02±0.01	8.28±2.51
	Stem	0.18±0.09	23.22±2.63	0.03±0.02	9.92±1.44
Total		0.49±0.11	60.31±10.21	0.10	30.22±9.82
Ca	Leaves	0.15±0.01	23.81±4.12	0.07±0.01	19.75±5.82
	Branches	0.39±0.06	42.02±8.21	0.04±0.02	12.03±1.33
	Stem	0.28±0.04	36.97±9.01	0.05±0.01	14.09±1.48
Total		0.82±0.10	102.81±23.77	0.16±0.21	45.87±21.73
Mg	Leaves	0.02±0.01	2.41±0.46	0.019±0.01	4.90±1.16
	Branches	0.05±0.01	5.19±0.29	0.004±0.002	1.29±1.10
	Stem	0.04±0.02	4.74±1.15	0.008±0.001	2.26±0.82
Total		0.10±0.03	12.34±5.61	0.03±0.01	8.46±1.99

The total Carbon content and the different nutrient elements in both species are shown in Table 8.3. As expected, the total content of C, N, P, K, Ca and Mg increased with increasing biomass. For both cocoa and *G. sepium*, the uptake trend in the mean tree (Table 8.3) was in the order N>Ca>K>Mg>P, and was similar to the concentration trend (Table 8.2). It was observed that N and Ca content in each species were virtually the same, especially for the cocoa trees where N and Ca contents were 0.17±0.05 kg/tree and 0.16±0.21 kg/ tree respectively. Since the concentrations of the elements in both species varied with plant parts their uptake and sequestration was closely related to dry weight accumulation. Thus six years after planting, the *G. sepium* shade trees accumulated 110.95±14.73 kg N, 9.44±2.88 kg P, 60.31±10.21 kg K, 102.81±23.77 kg Ca and 12.34±5.61 kg Mg per hectare, with a total C content of 4839.71±61.64 kg/ha. The cocoa trees on the other hand had accumulated a total of 48.65±8.26 Kg N, 3.27±0.83 kg P, 30.22±9.82 kg K, 45.87±21.73 kg Ca and 8.46±1.99 kg/ha, with 1976.36±94.08 kg C/ha in the 6 years. In terms of element distribution among stand components, branches contributed the highest nutrient content per ha for the *G. sepium* shade trees, owing to the higher biomass represented in the stand, with the leaves contributing the lowest and the stems having intermediate content. On the other hand, the highest nutrient content per ha was contributed by cocoa leaves, and was mainly due to the relatively high foliar dry matter content recorded.

However in terms of carbon accumulation on the plot, while the *G. sepium* shade trees accumulated more than double the amount of carbon stored by the cocoa per ha, its disposition in both species was highest in the stem for both species and was generally in the order Stem>Branches>Leaves. On mean tree basis, however, the order was Branches>Stem>Leaves for the *G. sepium* shade trees and Stem>Leaves>Branches for the cocoa, because of the higher biomass of the branches and the leaves components of the *Gliricidia* and cocoa respectively.

8.4.3. Litterfall

The pattern of litterfall in the cocoa-*G. sepium* stand is displayed in Figure 8.3. Total annual litterfall was higher for *G. sepium* shade trees than for the cocoa, in spite of the relatively higher density of the latter. Annual litter production in *G. sepium* was found to be 2.36 t/ha as against the 1.13 t/ha produced by the cocoa trees on this site, with mean monthly litterfall rates of 196.57±29.11 kg/ha and 94.27±8.24 kg/ha respectively for the *G. sepium* and cocoa. Examining the monthly litter production trend throughout the year, it was observed that peak litter production by the *G. sepium* shade trees occurred between December and February, with the highest mean litterfall amount of 416.40±40.53 kg/ha recorded in January. Monthly litterfall pattern followed the pattern of rainfall in the area (Figure 5.3, Chapter 5), except that major litterfall appeared to precede the onset of the major dry season by a month. The *G. sepium* trees here appeared to shed almost all their leaves within four months, starting from October. Between these months – October to January, total litterfall was 1382.27 kg/ha, with a mean of 345.57 kg/ha/month. From February, however, litter production was low and in April there was virtually no litter produced.

Litterfall in the cocoa showed a similar trend to that of the shade trees in that it appeared to be linked to rainfall. Peak litterfall was recorded between October and April.

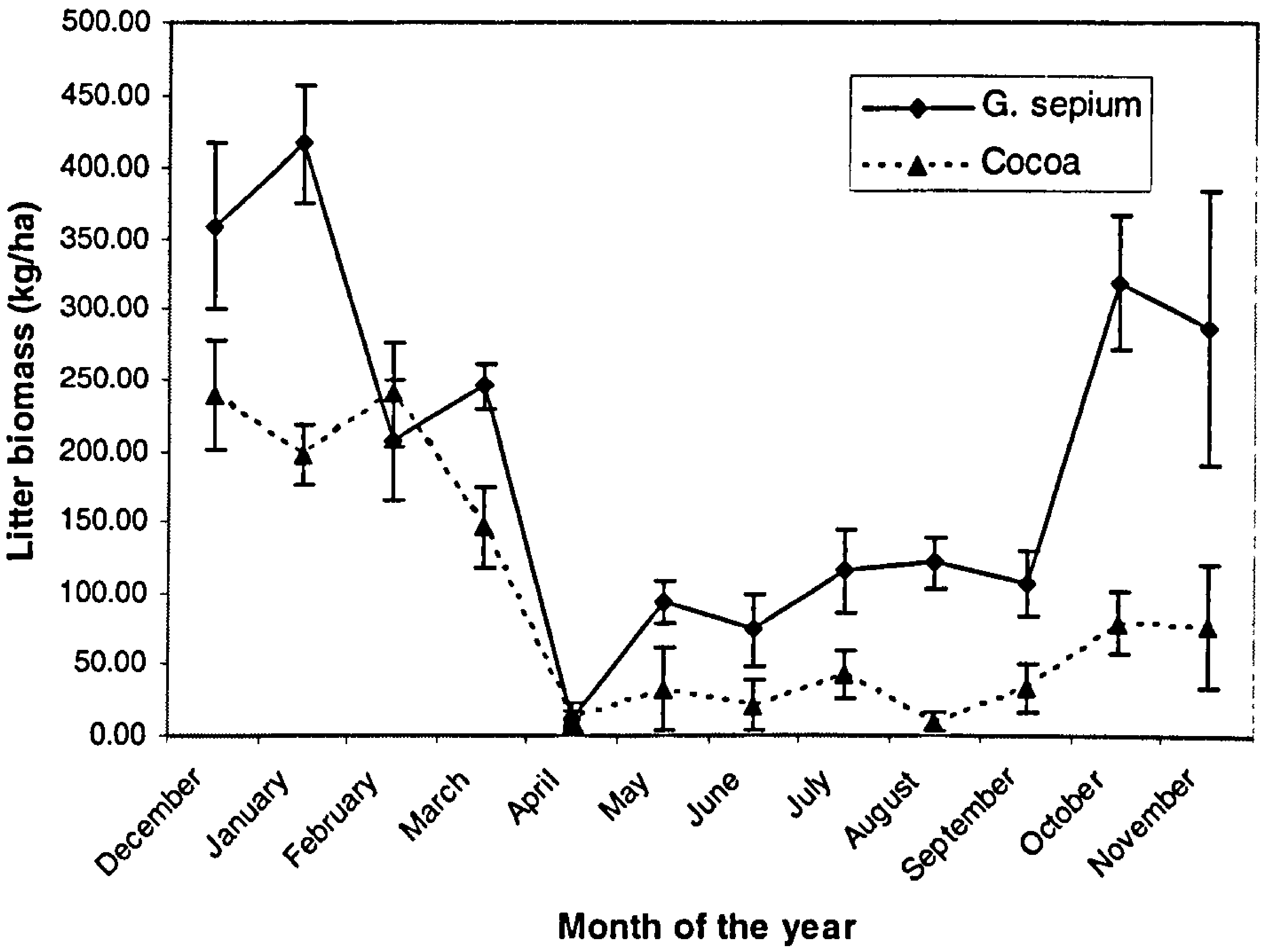


Figure 8.3: Monthly litterfall patterns for cocoa and *G. sepium* in Bontomuruso, Atwima district.

8.4.4. Litter decomposition and nutrient release patterns

8.4.4.1. Decomposition

The leaf litter of the two species exhibited different rates of mass and carbon loss during the incubation period (Figures 8.4 and 8.5). Significant mass loss occurred within a short period in the *G. sepium* leaf litter compared to the cocoa litter. For example, initial decomposition within the first month resulted in a 28.8% mass loss in the *G. sepium* leaves whereas it was only 3.45% in the cocoa leaves (Figure 8.4). The leaf litter exhibited an additional mass loss of 15.25% for *G. sepium* and only 4.75% for the cocoa over the next 30 days. Subsequent mass loss during the rest of the incubation period was significantly more rapid for *G. sepium* leaf litter than for the cocoa ($P = 0.016$; $T = 2.75$), such that by the 4th month virtually all the incubated *G. sepium* leaf litter had decomposed, with only 8.55% of the original mass remaining, whereas only 22.35% of the original mass of the cocoa leaf litter had decomposed within the same period, with as much as 77.65% still remaining.

An analysis of residual carbon showed a similar pattern in carbon loss compared to mass loss, in both species. In general carbon loss was much greater during the first three months of incubation for the *G. sepium* leaf litter but slower for the cocoa (Figure 8.5). The 4th to 5th month after incubation decomposition was virtually completed for *G. sepium* leaf litter, while decomposition of cocoa leaf litter lasted beyond 8 months on this site. As with the mass loss, a 2-sample t-test of carbon loss, at $a = 0.05$, showed that there was a significant difference between the rates of carbon loss in *G. sepium* and the cocoa leaf litter ($P = 0.029$; $T = 2.45$).

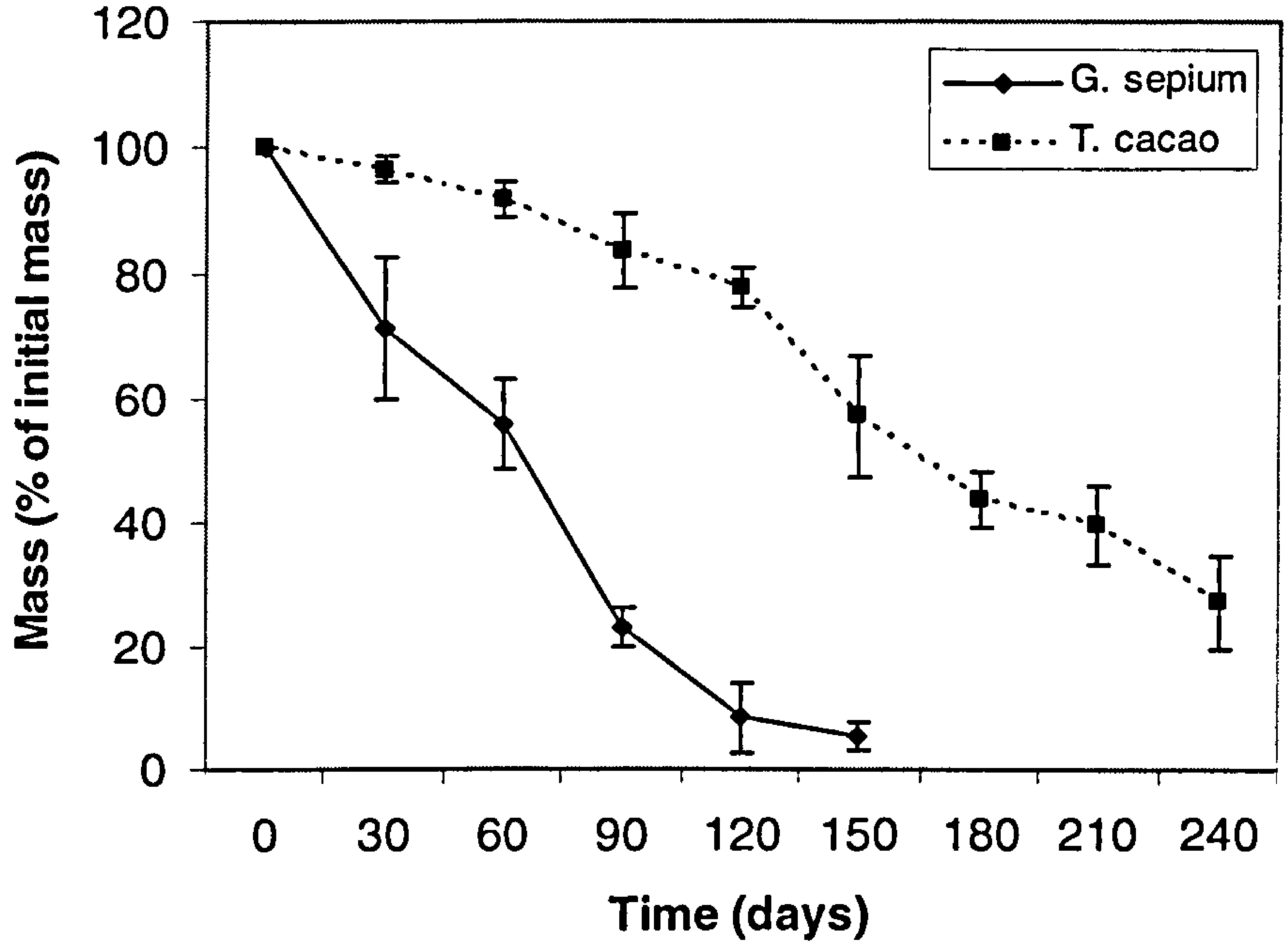


Figure 8.4: Changes in residual mass of *G. sepium* and cocoa leaf litter as percentage of original mass, in a cocoa-*G. sepium* agroforestry system in Bontomuruso. Values presented are means±se.

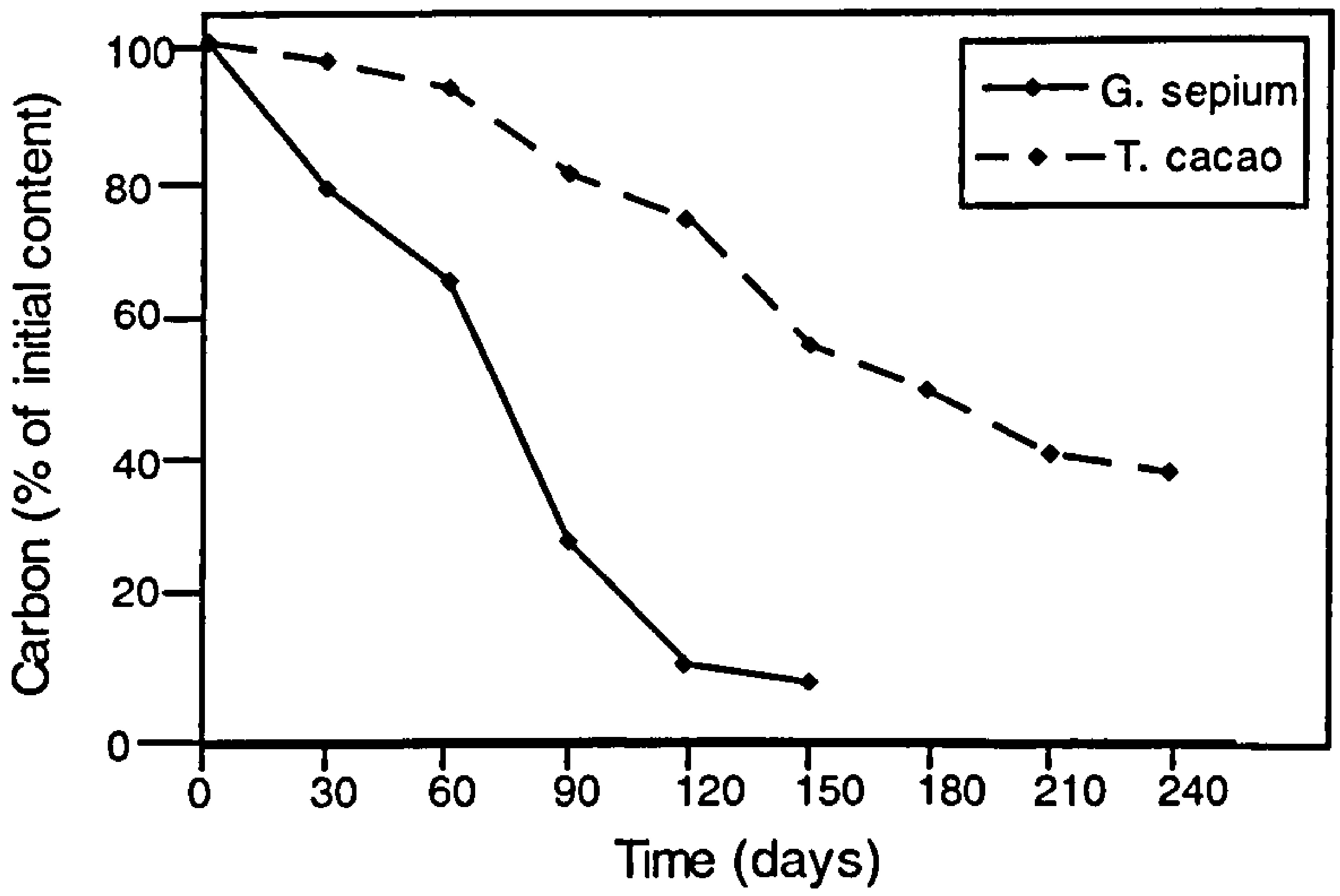


Figure 8.5: Changes in residual carbon of the leaf litter of cocoa and *G. sepium*, as percentages of the original carbon, in a cocoa-*G. sepium* agroforestry system in Bontomuruso.

8.4.4.2. Nutrient release patterns

Initially, *Gliricidia* showed higher nutrient content in its leaf litter than the cocoa, except for P which was more highly concentrated in cocoa leaf litter than that of *Gliricidia* (Table 8.4). In order to analyse both the dynamics of nutrient release and the absolute amounts which were released per unit mass, nutrient release was calculated as residual amounts of the initial concentration; the values for day zero are the initial concentrations (Figure 8.6 a – e).

No net N immobilization was observed during the decomposition of the *G. sepium* leaves, unlike the cocoa leaves in which N appeared to have been immobilized during the first month of incubation. *G. sepium* leaves released most of their N (76.45%) during the first month of incubation, after which release was slowed over the rest of the incubation period (Figure 8.6a). With the cocoa leaves, on the other hand, a slight increase in N concentration (about 6.22%) was observed during the first month, after which N release occurred reasonably fast over the next two months. A t-test of N release from the two species did not reveal any significant difference (P = 0.041; T = 1.85).

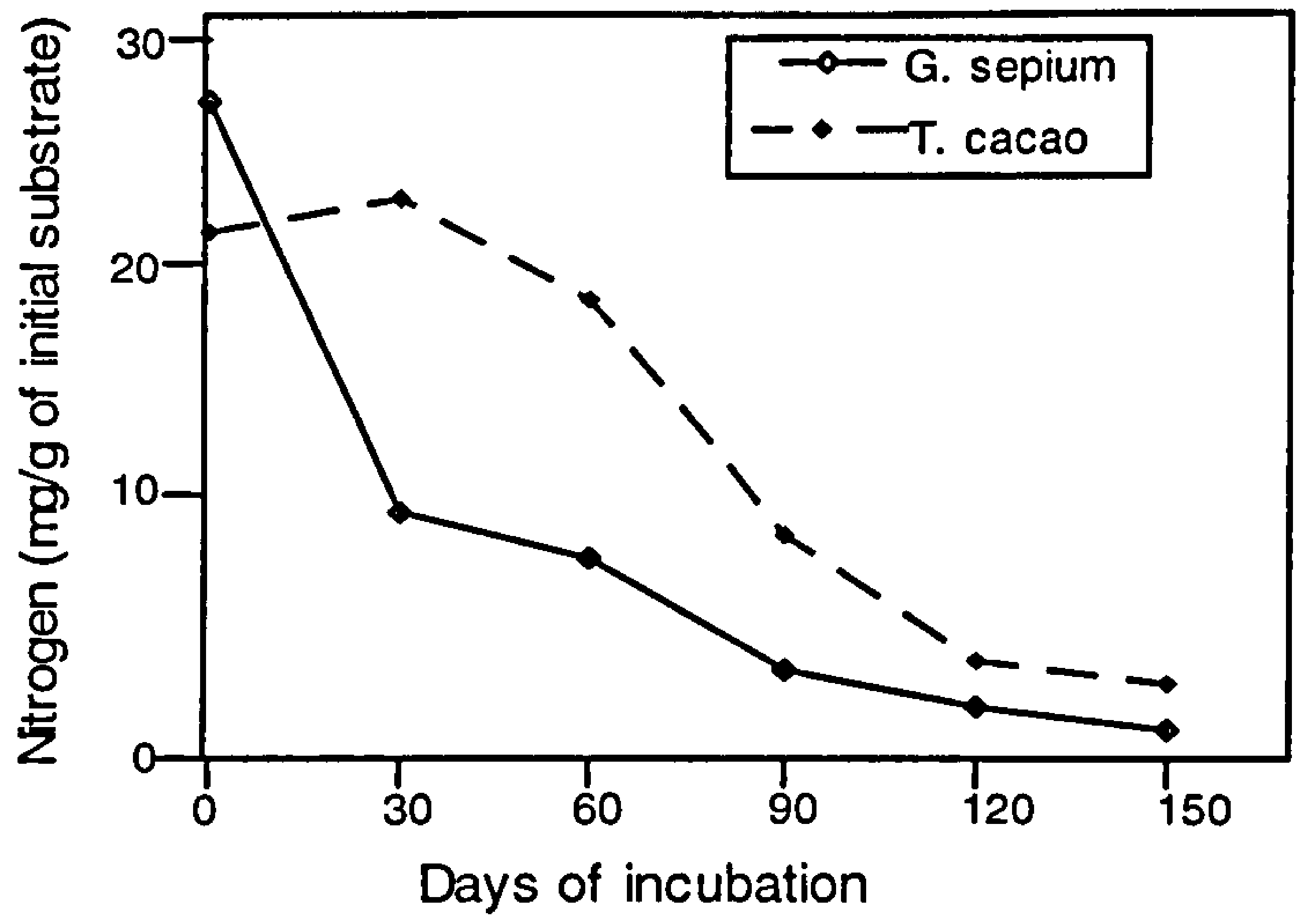
Table 8.4: Initial nutrient composition of the leaf litter of cocoa and *G. sepium* prior to incubation.

	Initial nutrient composition of leaf litter (g/kg)				
	N	P	K	Ca	Mg
G. sepium	26.8±2.11	1.3±0.14	12.8±0.83	17.2±1.24	7.6±0.26
Cocoa	21.4±1.87	1.5±0.09	10.2±1.17	14.9±2.12	3.1±0.11

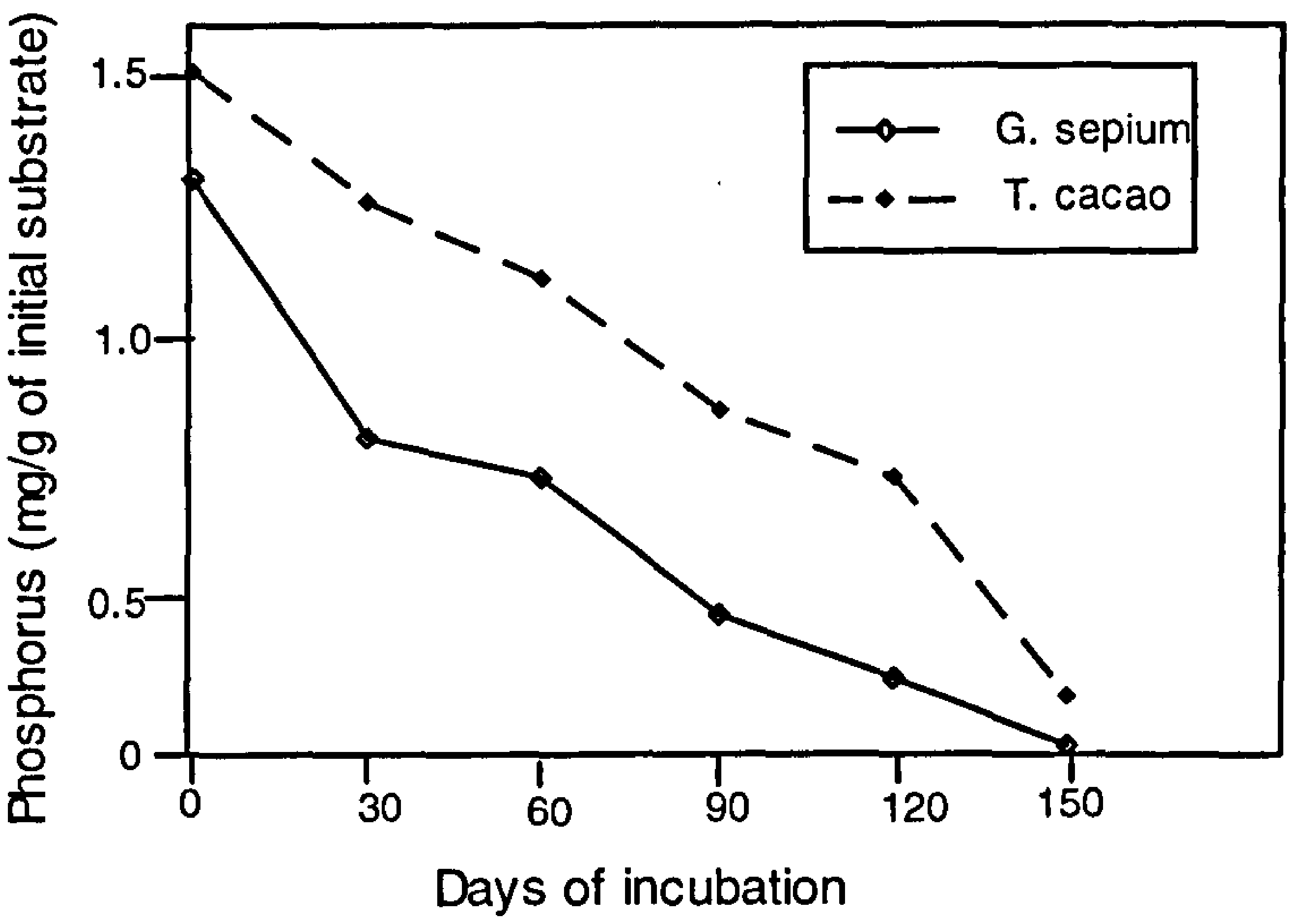
P release occurred fairly uniformly throughout the incubation period for the leaf litter of both species, and appeared to follow a similar pattern. *G. sepium* leaves released almost all their P during the incubation period while the cocoa leaves retained about 20.67% of P beyond the this period (Figure 8.6b). However, from the 2-sample t-test, no significant difference (P = 0.315; T = 1.06) was found between the rates of P release by the two species.

K was released from 90 to 92% from the leaf litter of cocoa and *G. sepium*, respectively, during the first two months of incubation (Figure 8.6c). The Mann-Whitney test showed that there was no significant difference between the rate of K release from the decomposing leaf litter of both species (P = 0.471). However, K release in both species was found to be more rapid than the other nutrients, such that by the end of the third month K was almost completely leached from the litter of the two species (Figure 8.6c).

(a)

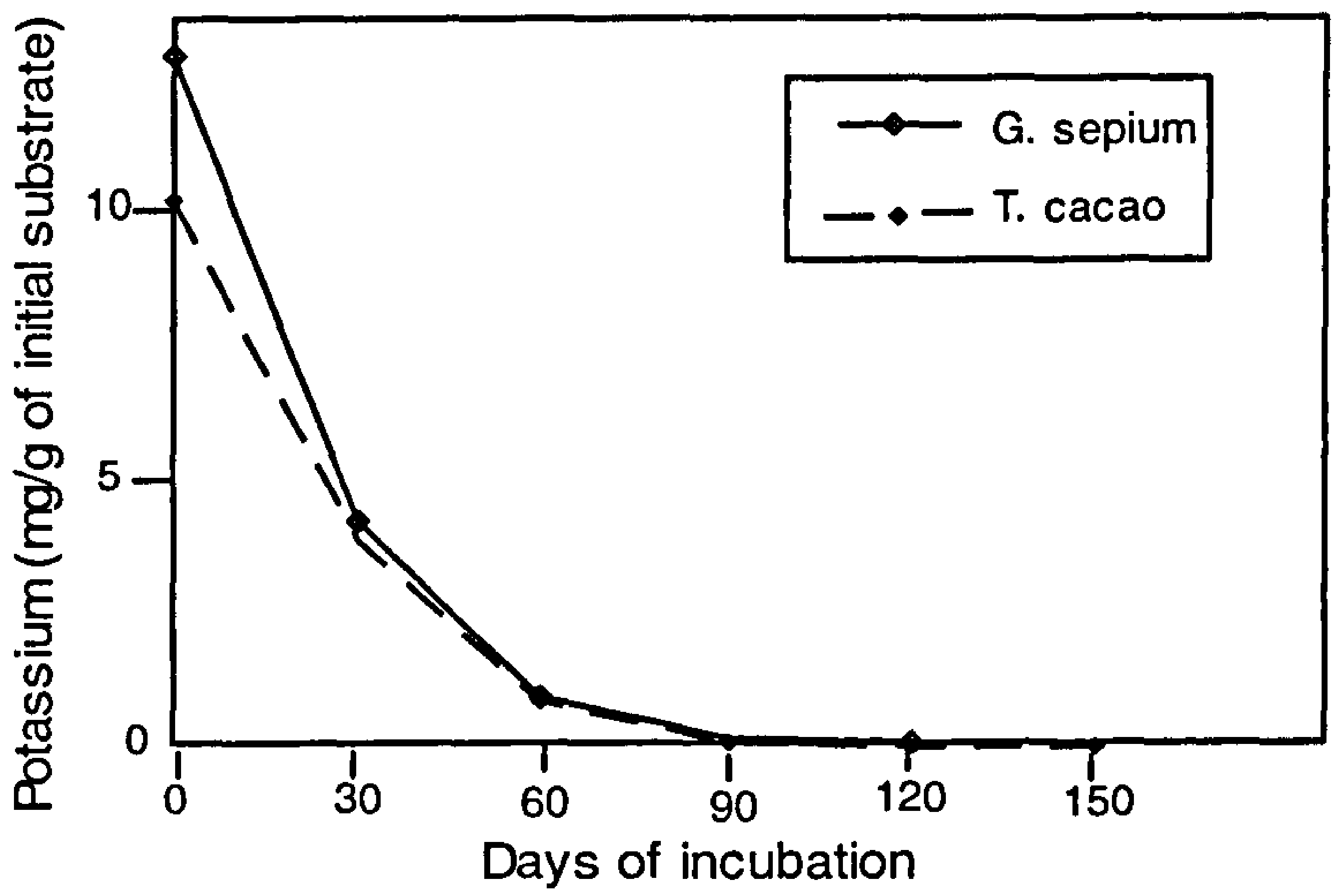


(b)



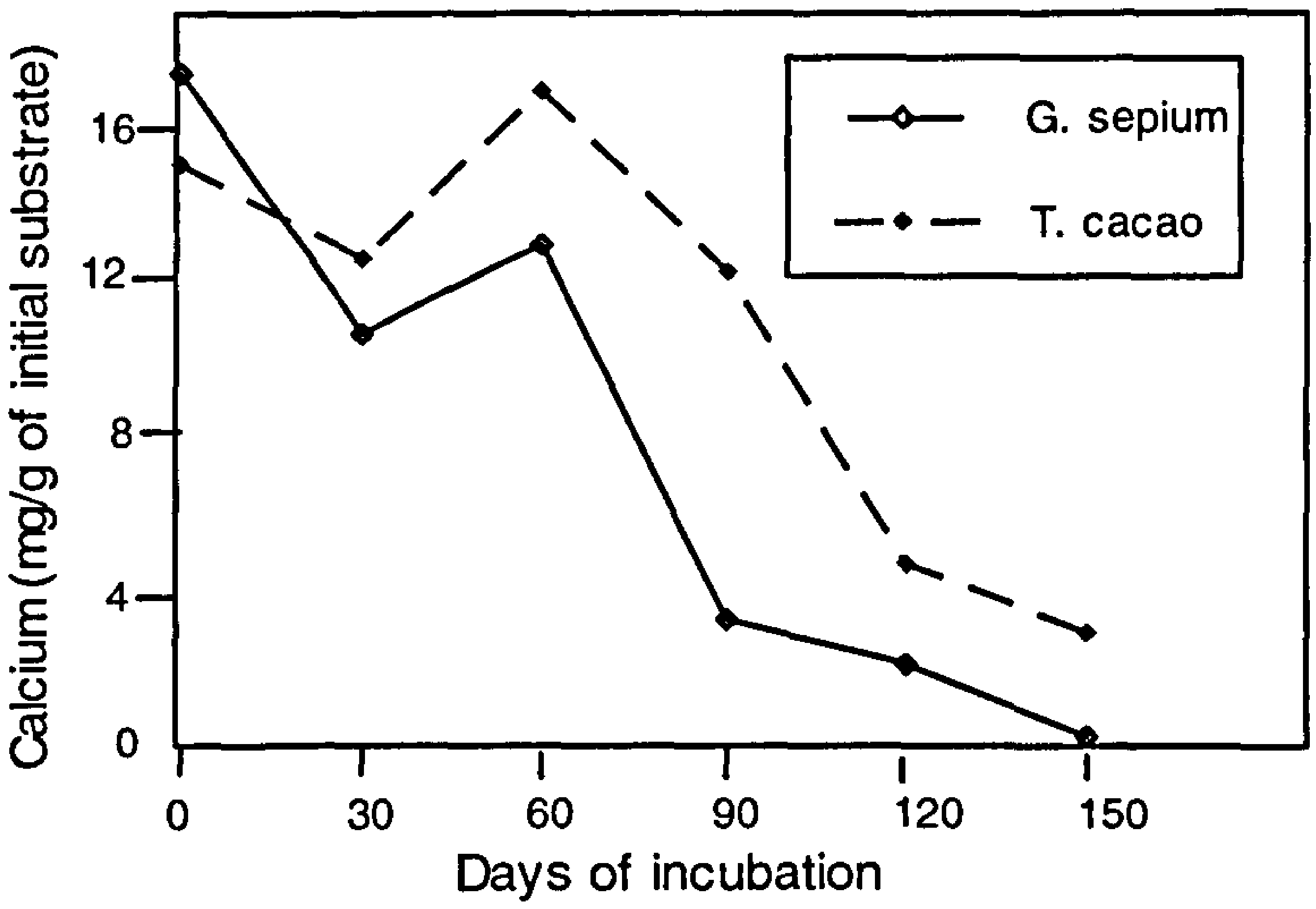
Phosphorus (mg/g of initial substrate)
1.5
1.0
0.5
0
0
30
60
90
120
150
Days of incubation
G. sepium
T. cacao

(c)



Potassium (mg/g of initial substrate)
10
5
0
0
30
60
90
120
150
Days of incubation
G. sepium
T. cacao

(d)



Calcium (mg/g of initial substrate)
16
12
8
4
0
0
30
60
90
120
150
Days of incubation
G. sepium
T. cacao

(e)

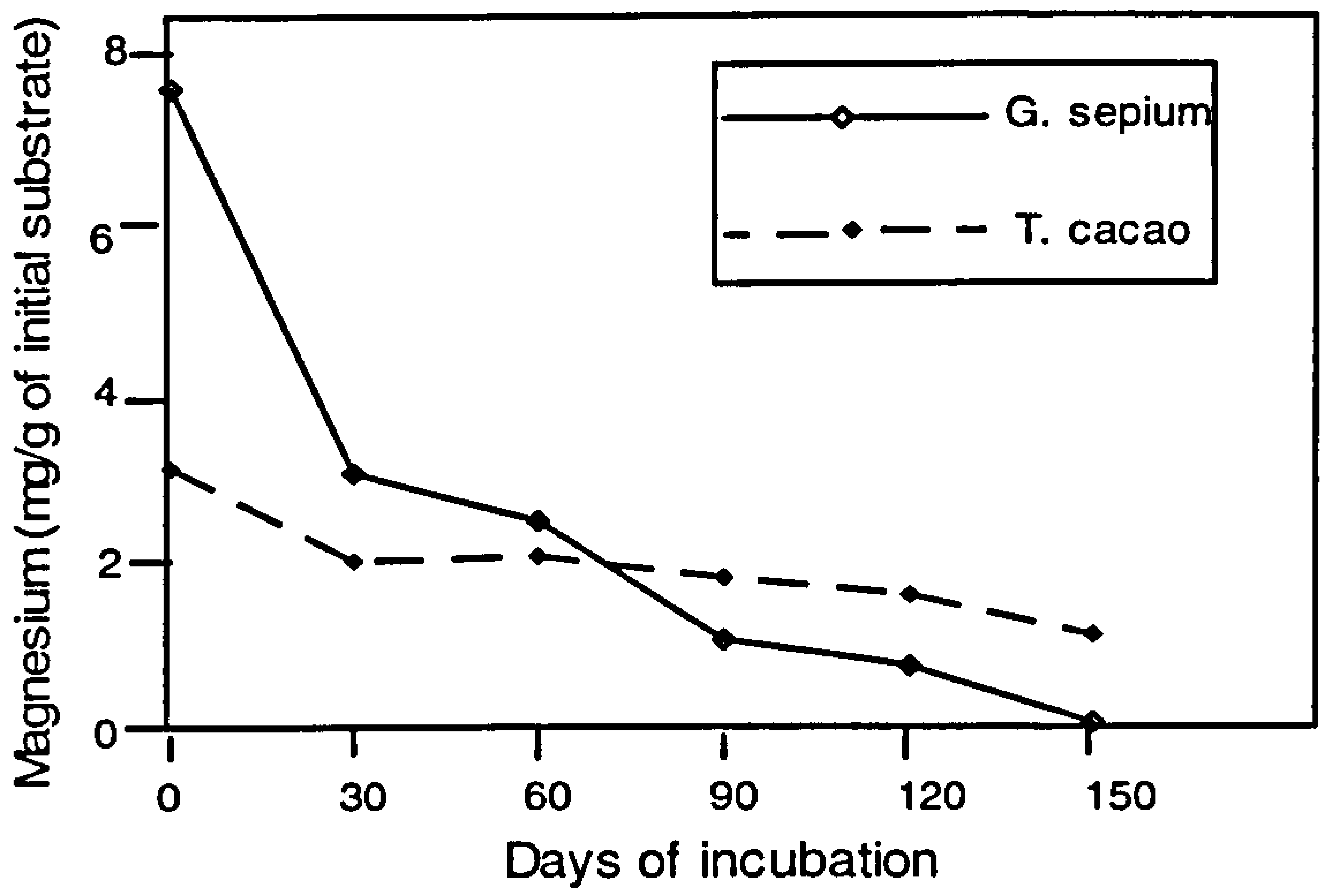


Figure 8.6: Patterns of N, P, K, Ca and Mg release in cocoa and *G. sepium* leaf litter in a cocoa-*G. sepium* agroforestry system in Bontomuruso.

Unlike the other nutrient elements, Ca exhibited a different release pattern in both species. During the first month of incubation, Ca release in *G. sepium* leaf litter was higher than in cocoa leaf litter, with 34.55% Ca released by *G. sepium* as opposed to 16.64% by cocoa leaf litter during this period. However, after this initial release, Ca appeared to be immobilized, in both species, during the second month of incubation (Figure 8.6d). Thereafter, however, rapid Ca mineralization occurred in both species and by the end of the incubation period, Ca was almost completely leached in *G. sepium* while only about 19.93% of the initial Ca remained in the cocoa leaf litter. In spite of the higher initial release of Ca in the *G. sepium* leaf litter, there was however no significant difference (P = 0.433; T = 0.82) in the overall rate of release of this element from both species.

As with N release, Mg release patterns were significantly different for the two species. Rate of release was significantly higher in the *G. sepium* leaf litter than in cocoa (P = 0.047; T = 1.50), with highest release of about 60% of the Mg in the *G. sepium* leaves occurring within the first month of incubation as opposed to only about 34% in the cocoa leaves during the same period (Figure 8.6e). Mg release in the cocoa leaves was relatively slow throughout the incubation period, and by the end of the period as much as 36.77% of the initial Mg still remained unmineralised in the cocoa leaf litter.

8.5. Discussion

8.5.1. Dry matter production

Wood and leaf biomass production is of more significance in the *G. sepium* shade trees than in the cocoa since they are grown primarily for wood fuel and for animal fodder, as well as for soil improvement through litterfall and biological nitrogen fixation. On an individual tree basis, *G. sepium* produced more wood and leaf biomass per tree than the cocoa because of its larger size, which was about twice that of the cocoa. However, on a hectare basis, leaf dry matter production was higher in the cocoa than in the *G. sepium* because of the higher density of the cocoa. The higher leaf dry matter production (5.63 kg/tree) in the cocoa trees, compared to their branches (4.90 kg/tree) (Table 8.1) was mainly due to the highly variable age of the cocoa trees on this plantation. Tree ages ranged between 2 and 6 years, with a greater proportion of trees being in the middle range, and the 2 to 4 years groups made up of the mixed hybrid cocoa variety developed by the Cocoa Research Institute of Ghana and the 5 and 6 year olds being the old Amelonado variety. This would have accounted for a lower branch yield in the lower to middle age trees and an overall lower branches dry weight compared to the leaves.

In the *G. sepium* about half (49.54%) of the total biomass per tree was allocated to the branches, with 40.97% going into the stem and only 9.49% going into leaf formation. Thus about 90% of the growth was partitioned into woody biomass. The greater partitioning of aboveground biomass into branch formation, which may be environmentally controlled, is of particular significance, since this species is grown mainly for fuelwood production. This phenomenon will give a higher fuelwood yield when the shade trees are lopped, pruned or the branches cut back, to control shade levels on the farm. The higher branch biomass in this species is similar to what Nwoboshi (1996) observed in *Eucalyptus alba* planted for fuelwood and charcoal production in the Accra plains in Ghana, in which a greater proportion of their biomass was channelled into branches. Adu-Anning and Anglaaere (1996) observed that species with many small stems and branches constituting a greater proportion of the dry matter are more preferred for fuelwood production than those which have greater portions of the biomass being larger stems. The stand biomass of 11.49 t/ha at this site is, however, lower than the 40.92 t/ha and 39.30 t/ha biomass reported by Mainoo and Ulzen-Appiah (1996) for *G. sepium* and *L. leucocophala*, respectively, though this will be more due to the much higher stand density of 8333 trees/ha for these species, established at the Institute of Renewable Natural Resources farm, Kwame Nkrumah University of Science and Technology, Kumasi.

In terms of carbon storage of the system, the values obtained in this study from the laboratory estimation of C content compared favourably with estimates reported for other pure tropical forest plantations of varying and comparable ages. For example, the total woody carbon content (stem and branches) of 5.62 t ha^{-1} (i.e. 4.26 tC ha^{-1} for *G. sepium* and 1.36 tC ha^{-1} for cocoa) accumulated by this six year old plantation compares well to estimates of 8 tC ha^{-1} reported by Evans (1982) and Pandey (1983) for an 8 year old plantation of *Azadirachta indica*. Without the shade trees, the pure stand of cocoa alone would have accumulated only 1.36 tC ha^{-1}. Thus inclusion of the shade trees more than doubled the carbon storage potential of the system. Although it may be argued that whatever additional carbon is stored in the *Gliricidia* will eventually be released back into the atmosphere when the wood is harvested for fuel, there would still be a net gain in carbon stored, from increase in soil organic matter, as well as from the coppiced stumps of the shade trees. Besides, one useful product that is often suggested in a system like this is the use of the wood as fuel to replace fossil fuel. The carbon benefit, in this case, would then be due to not burning fossil fuel and therefore reducing emissions (Schroeder, 1992). And although burning of the wood will result in carbon emission, the continuous coppice regrowth of the *G. sepium* shade trees wil ultimately result in zero carbon emissions from wood fuel.

8.5.2. Nutrient concentrations

Accumulation of P, K, Ca and Mg was not significantly different between cocoa and *G. sepium* (Table 8.2). Nolte *et al* (2003) found a similar pattern of nutrient accumulation in planted *Calliandra calothyrus* fallows and natural fallows in southern Cameroun, and concluded that this may be an indication that the soil resource is the limiting factor rather than the sink capacity of the species to sequester nutrients. N accumulation was, however, higher in the *G. sepium* trees than the cocoa. This may be explained by the fact that, as a nitrogen fixing tree species, the higher amounts of N would have been acquired through N fixation (Nolte *et al* 2003).

The management implications of the low P and Mg concentrations in all components of both species, though comparable with most agricultural crops, are that these elements constitute the limiting elements and are more likely to be deficient in the near future, with nutrient exports in *G. sepium* pruned and/or lopped branches as fuelwood and successive cocoa harvests. This may lead to a need for nutrient supplementation through fertilization.

Among the various components in both species, the average nutrient concentrations were in the order leaves>branches>stem. The higher foliar nutrient concentrations in both species would seem to indicate some degree of efficiency in nutrient cycling during leaf litter decomposition, and also form a good index of the nutitional status of the trees (Nwoboshi, 1985). Similar trends of higher foliar nutrient concentrations were observed by Adu-Anning *et al* (1995) in some fuelwood species planted in the Sudan Savannah zone of Ghana, and by Nolte *et al* (2003) in Calliandra and natural fallows in southern Cameroun.

In this study, *G. sepium* accumulated 110.95 kg N ha^{-1}, 60.31 kg K ha^{-1} and 102.81 kg Ca ha^{-1} compared with the 48.65 kg ha^{-1}, 30.22 kg ha^{-1} and 45.87 kg ha^{-1}, of N, K and Ca, respectively, accumulated by the cocoa (Table 8.3). This implies pruning the shade trees could potentially add some 70.66 kg of N ha^{-1}, 37.08 kg of K ha^{-1} and 65.83 kg of Ca ha^{-1} in branch and leaf material if there is no export of prunings from the system either as fuelwood or fodder – though this will ultimately depend on the level of immobilization and recalcitrance of the different nutrient elements in the plant material. Conversely, it would also mean that in the event of export of pruned and/or lopped branches as fuelwood, which is common practice in this area, substantial amounts of nutrients could be lost from the system. Even in such a situation, nevertheless, the higher foliar nutrient concentrations imply that 24.96%, 16.86% and 23.15% of the total biomass N, K and Ca will be potentially available to the cocoa crop through the *G.*

sepium litterfall and decomposition, as it is a deciduous tree. The impact of these rates of nutrient uptake on the soil nutrient reserves depends largely on their distribution and the residence times in the different components of the stand, and these will in turn influence the rate of nutrient cycling in the ecosystem (Nwoboshi, 1985). However, as pointed out by Heuveldop (1988), the upper storey trees of such spatially mixed systems as this cocoa plantation provide nutrients, from litterfall and periodic prunings, as well as shade to the lower storey crops.

8.5.3. Litterfall

The rate of leaf litterfall of the cocoa was significantly lower than that of the shade trees, and, at 1.13 t/ha/yr, was generally low overall. This is due to the fact that cocoa generally has an evergreen habit, compared to the deciduous *G. sepium* shade trees. Nevertheless, the litterfall pattern in this species demonstrates the sensitivity of the cocoa trees to soil moisture content, with comparatively higher rate and amount of litter production in the dry season – December to March – and very little litter production between April and August, when rainfall is at its highest in this location.

The rate and amount of litterfall of the *G. sepium* (2.36 T/ha), on the other hand, was comparable with values reported for species grown, at similarly low densities, for shade in agroforestry systems in humid and sub-humid climates, which range between 2 and 4 t/ha (Young, 1989). At a planting density of 277 trees/ha, and a current stocking of 192 trees/ha, the annual litterfall rate of 2.36 t ha^{-1} yr^{-1} is comparable to litterfall rates ranging between 8.02 – 11.02 t ha^{-1} yr^{-1} reported by Montagnini *et al* (1993) for four indigenous species in the Atlantic lowlands of Costa Rica. Beer (1988) also reported comparatively similar annual litterfall rates of 2.9 – 3.3 t ha^{-1} for *Cordia alliodora*, 6.9 t ha^{-1} yr^{-1} for *Inga jinicuil* and 5.3 t ha^{-1} yr^{-1} for *Inga leptoloba*, all grown as shade trees for crops in the humid tropical regions of Latin America, at comparable densities of 185 – 278 trees ha^{-1}. As with the cocoa trees, litterfall from the *G. sepium* trees was closely related to seasonality. However, unlike the cocoa, which remained evergreen through out the year, litterfall in *G. sepium* commenced just before the onset of the main dry season, and within the next four months – October to January, most of the trees had dropped their leaves and were leafless (Figure 8.3). As explained by Reich and Borchert (1984) and Reich (1995), this pattern of leaf litterfall in response to soil moisture status is the tree's strategy for reducing moisture (water) demand through the dry months. And as pointed out in section 5.4.1.1 (Chapter 5), this pattern of litterfall has positive implications for temporal complementarity of resource use between the cocoa and the *G. sepium* shade trees. Maximum litterfall (and virtual leaflessness) in the dry season, when soil moisture is low, will greatly reduce soil moisture extraction by the shade trees, thereby reducing competition with the cocoa trees for water and nutrients during this period, as pointed out by Broadhead et al., (2003a and b). The high litter production in the dry season also has positive implications as it will ensure soil cover and protection from the excessive heat of the dry season and from erosion during the rainy season, as well as maintaining nutrient cycling, as highlighted by Montagnini *et al* (1993). However, it also implies that shade provision will be minimal during this period.

8.5.4. Litter decomposition

The leaf litter of the cocoa and *G. sepium* exhibited different rates of mass loss during the incubation period (Figures 8.4). The rate of mass loss was faster for the *G. sepium* leaf litter than for the cocoa. The rate of mass loss was faster during the first month of incubation, for the *G. sepium* litter (28.8%) compared to the cocoa (3.45%). This rapid mass loss during the early phase of the decomposition process in this study is similar to trends observed by Melillo *et al* (1989) and Jose *et al* (2000) for red pine needles and for black walnut and red oak trees in alley cropping systems. Rapid mass loss during the early phase of decomposition may be related to microbial utilization of highly labile components of the substrate, such as non-structural carbohydrates. When these are depleted, the rate of mass loss is also decreased (McClaugherty and Berg, 1987). In field studies, Prescott *et al* (1993) reported that the labile fraction of litter was rapidly metabolised by microorganisms, or lost through leaching. Parsons *et al* (1990), however, explained that although some of the labile material may be water soluble, microorganism metabolism rather than leaching is responsible for the greatest part of mass loss. Carbon loss in the *G. sepium* leaf litter also followed similar patterns as those of mass loss and was much greater during the first three months (Figure 8.5), as observed by Jose *et al* (2000) in their study in a temperate alley cropping system in the USA, suggesting a rapid depletion of the labile carbon sources by microorganisms.

The difference in decay rates between the *G. sepium* and cocoa litter will be due largely to differences in substrate quality, as suggested by a number of workers (Swift *et al* 1979; Palm, 1995; Mafongoya *et al* 1998; Jose *et al* 2000). It has been pointed out that the rate of decomposition and nutrient release of organic materials is determined, to a large extent, by the chemical composition of the material (Palm, 1995; Mafongoya *et al* 1998), with rapid decomposition and nutrient release being associated with high quality and immobilization or slow release associated with low quality (Swift *et al* 1979). Lignin and cellulose (plus hemicellulose) content have been identified as some of the greatest determinants of litter decomposition rates (Mafongoya *et al* 1998), but these were not measured in this study. However, litter N content, as well as the C:N ratio of the litter material, have also been known to be major determinants of litter quality, and hence decomposition rates (Palm, 1995: Girisha *et al* 2003). It has been pointed out that nutrient quality is usually measured in terms of net N or P mineralization patterns, and that materials with N concentrations greater than 20 mg g^{-1} or P concentrations greater than 2.5 mg g^{-1} are considered of high quality (Mafongoya *et al* 1998). It has also been pointed out that in many cases the litter N content is a good predictor of initial decomposition rates, though apparently the amount of fibre, lignin and polyphenolic compounds play a significant role in the release of N and P from decomposing litter in tropical ecosystems (La Caro and Rudd, 1985; Palm and Sanchez, 1990; 1991). Thus the higher decomposition rate recorded for the *G. sepium* is due to its relatively higher N concentration, and lower C:N ratio, compared to the cocoa leaf litter. Similarly fast decomposition rates of litter of *G. sepium* have also been reported by a number of workers, who found this to be a result of such litter quality parameters as low to moderate C:N ratio, relatively low lignin and polyphenol content and a low protein-binding capacity, all of which influence decomposition rate (Palm and Sanchez, 1991; Tian *et al* 1992a and 1992b; Handayanto *et al* 1994; Handayanto *et al* 1997).

8.5.5. Nutrient release patterns

It has been explained that different nutrients in decomposing litter have different patterns of release over time and that nutrients are retained with different strengths in the litter structures (Girisha *et al* 2003). One mechanism for this, according to Rutigliano *et al* (1998), is microbial immobilization. The status of a nutrient, whether it is limiting or non-limiting to microbial growth, determines its release dynamics. The nutrients which are in limiting amounts – where the carbon:element ratio is above the critical level – will be retained resulting in immobilization, whereas, elements in surplus – where the C:element ratio is below the critical limit – will be released during decomposition (Berg and Staaf, 1981).

Nutrient release and turnover are further influenced by the nature of chemical bonds that attach the elements to the organic matter (Girisha *et al* 2003). The various nutrient elements generally exhibited some differences and similarities between the species (Figures 8.6a – e). In contrast to the leaf litter of the cocoa, which showed relatively slow release of N, the release of N in *G. sepium* leaves was quite fast. Within the first month of incubation some 54.74% of the initial N content in the litter was mineralized. This falls well within the reported range of 35 – 60% N released by decomposing litter of *G. sepium* within the first month (Palm and Sanchez, 1991; Tian *et al* 1992a and 1992b; Handayanto *et al* 1994; Handayanto *et al* 1997) and 30 – 70% N released by decomposing litter reported by Palm (1995). This rapid release of N is possibly due to the relatively high N content of the leaf litter and their generally low lignin and polyphenol contents as outlined by these authors. Mafongoya *et al* (1998) have pointed out that *G. sepium* leaves have high N contents but are low in lignin and polyphenols and therefore decompose very quickly, releasing a large proportion of their N. In comparison, there appeared to be a net immobilization of N in the cocoa leaf litter within the first month of incubation, with a small increase in N concentration observed in the incubating litter. Thus in the first month no N was mineralised or released from the cocoa litter. Similar patterns of initial net N immobilization in decomposing litters of a number of species have been reported. For instance, Palm (1995) reported initial N immobilization in *Senna siamea*, lasting up to 6 weeks before net mineralization occurred, *Dactyladenia barteri*, a nonlegume, showed net immobilization throughout the incubation period. This phenomenon of delayed N release is thought to be controlled by the %N content of the litter material and the %lignin (L) and %polyphenol (PP) contents, as well as the PP:N and (L + PP):N ratios, as indicated by a number of workers (Palm and Sanchez, 1991; Tian *et al* 1992a; Handayanto *et al* 1994).

P release was faster from *G. sepium* leaf litter than from the cocoa, but appeared to be, generally, more evenly distributed throughout the incubation period than the N release, in both species. However, with its limited concentration in the leaf litter of both species, decomposition is unlikely to be able to supply sufficient quantities of P to meet nutritional requirements of the cocoa. The advantage, though, is that in addition to the limited amounts of P released from the decomposing litter the increased soil organic matter, from the litter, has the potential to reduce the P fixation capacity of the soil (Palm, 1995), thereby making more P available to the crop.

Unlike the other nutrient elements, K release was rapid in both species, and followed virtually the same pattern. Within the first month 67.34% and 61.76% of the K were mineralized from the *G.sepium* and cocoa leaf litter respectively, and by the end of the second month almost all the K (over 90%) was released. This rapid release in both litter types is possibly attributable to the fact that as a non-structural component of plant cells, K is highly susceptible to initial leaching losses, as suggested by Staaf (1980). The implication of this pattern of release is that sudden flushes of K in the soil will occur at certain periods of the year, in tune with litterfall pattern, and the benefits would depend on the fine root activity patterns of the cocoa trees.

Ca exhibited the most complicated release pattern of all the nutrients, in both species. For both species a high release of Ca was recorded in the first month, though this was higher in *G. sepium* than in the cocoa. In the second month, however, Ca was immobilized in both species and actually increased in concentration. Thereafter, rapid mineralization was observed over the next 2 – 3 months. The increase in concentration could possibly be due to soil contamination of litter material, since it was virtually impossible to wash off all soil material from the decomposing litter material without the danger of leaching. On the other hand, as pointed out by Cromack *et al* (1975) Ca could have been transported actively by the hyphae of fungi into the litter bags, resulting in the increased concentrations.

Mg release pattern in *G. sepium* was markedly different from that of the cocoa litter. Within the first month *G. sepium* litter release about 60% of its total Mg as against only 34% by the cocoa litter. After this period, however, Mg mineralization from *G. sepium* slowed quite substantially, while there was virtually no further release by the cocoa litter throughout the remaining period of incubation (Figure 8.6e). While the rapid initial Mg release in the *G. sepium* might have been due to leaching, as it is a non-structural element, its virtual immobilization in the cocoa litter is not quite clear. It is quite possible, as put forward by Girisha *et al* (2003), that it was probably the limiting element to the decomposer community.

CHAPTER 9

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

9.1. Introduction

Tropical deforestation for agriculture continues to be a major contributor to the worldwide loss of biodiversity (Bryant *et al* 1997). The rapid rate of deforestation has resulted in a race among conservationist to protect the remaining forested tracts. Plantation forests and agroforestry systems in developing countries play an important role in the restoration of vegetation cover, and help to meet the increasing demands for fuel wood and other wood and nonwood products. The concepts, strategies and policies associated with agroforestry are rapidly evolving towards the creation of sustainable land uses that enhance farmers' livelihoods, provide commodities for global markets and mitigate global concerns about environmental degradation (Leakey and Tchoundjeu, 2001). The techniques for the domestication of indigenous trees for the agroforestry production of non timber forest products (NTFPs) also are evolving rapidly and should produce further benefits in terms of income generation for agricultural inputs and household welfare. Diversification may increase as farmers develop and apply domestication strategies to a wider range of species (Leakey and Tchoundjeu, 2001). As pointed out by Rice and Greenberg (2000), the economic and social values of diversification are illustrated by evidence from cocoa agroforests in Cameroun, but to date there is only limited data to indicate whether or not there are ecological benefits that might confer greater sustainability.

Cocoa has been cultivated by small holders in the shade of primary or secondary forest trees for generations throughout the tropics (Purseglove, 1968). Research suggests that shade grown tree crops provide small scale farmers with a number of advantages over full-sun grown crops. Shade-grown tree crops tend to maintain productivity for longer periods of time, and are less prone to insect and disease losses. They require less capital and labour inputs, such as fertilizer, insecticides, and weeding, than full-sun monocultures (Purseglove, 1968; Young, 1989). Furthermore, shade-grown tree farms are likely to contain other valuable products, such as fruits, fibre, medicinal products, and timber, which can be harvested as needed, such as when market prices of cocoa are low. Consequently, households cultivating shade-grown trees, and especially those not using intensive systems involving purchased inputs (as happens with the majority of cocoa farmers in Ghana) are generally less affected by market fluctuations than farmers cultivating full-sun high input crops (Collier *et al* 1994); Thrupp, 1998). Shade-grown tree crop systems also provide biodiversity and ecosystem functions that benefit farmers as well as the system as a whole (Perfecto *et al* 1996; Lenne and Wood, 1999). Quite expectedly, shade grown crops tend to be cultivated by smallholders who lack the capital to convert to technified, full-sun systems (Belsky and Siebert, 2003).

There is potential to further enrich these agroforests and to enhance their profitability and thus their potential to alleviate poverty. Most of the trees in the cocoa agroforests are wild or undomesticated land races, and were not selected on the basis of their genetic quality (Duguma *et al* 2001). There are several high value fruit and medicinal tree species in the humid forests of West Africa, being exploited only from the wild. These species are reported to have tremendous potential for domestication and inclusion in the cocoa-based and perhaps other multi-strata agroforests of the region (Duguma *et al* 1990; Okafor and Lamb, 1994; Leakey, 1998). However, not all indigenous forest trees with socio-economic value are suitable for inclusion in multi-strata cocoa agroforestry systems either because they are alternate hosts to cocoa pest and diseases or because of their unfavourable growth characteristics or adverse competitive features.

Although the use of shade trees in the cultivation of cocoa has been a subject of much controversy, the inherent low soil fertility status, particularly the low cation exchange capacity, and the characteristic nitrogen deficiency associated with Acrisols – the bulk of soils on which cocoa is cultivated in Ghana – justifies the inclusion of shade trees in the cocoa plantation system of Ghana. The traditional cocoa growing areas in Ghana are in many places denuded and have been abandoned. Re-establishing cocoa in these areas has proven difficult due to low soil fertility, bush fires, diseases and pest, and inappropriate vegetation cover to provide shade for young cocoa (Ayanjala, 1983). The incorporation and management of shade trees in these degraded sites with low organic matter content is crucial for the maintenance and restoration of soil fertility. Through nutrient pumping and litter production, trees recycle nutrients and maintain soil fertility by means of the maintenance of the soil cation exchange capacity (Szott *et al.,* 1991).

This study was designed as a combined on-station and participatory on-farm field research carried out with farmers to investigate farmers' knowledge on indigenous forest tree species considered suitable for use as shade on cocoa farms, and to evaluate the field performance of some of the identified/preferred species when planted with cocoa. A number of research activities were carried out to achieve these goals, including an exploratory indigenous knowledge acquisition and documentation, to aid the identification of potential cocoa shade trees and the subsequent selection of a number of them to screen for their field performance and competitive/compatibility potential with the cocoa.

9.2. Farmers' knowledge about shade trees and cocoa-shade tree interactions

Farmers' knowledge of above- and below-ground interactions between cocoa and shade trees was based largely on an understanding of the relative effects of shade on cocoa caused by different shade tree species. A number of attributes were recognised, including leaf size; crown density; crown size; tree height; the depth and spread of the roots; rate of litter decomposition and their variability between species. The depth and spread of roots was said to influence the extent of competition between the cocoa and the shade trees for soil moisture and nutrients.

An increase in any of the above-ground tree attributes was believed to increase the intensity of shade, resulting in more intense tree-cocoa interactions. Shade is a word loosely used to describe modification of the microclimate beneath the shade trees in a number of ways; principally the effects on the amount of light, the temperature and humidity beneath the shade tree canopy. From the results of the indigenous knowledge acquisition, it can be surmised that farmers recognised that light interception by shade trees was determined by the canopy structure. Though the effect of the radiation regime, in terms of direct and diffuse components of the solar tract, which is known to affect shade (Iqbal, 1983) did not come out clearly in the farmers' knowledge, this is more likely because the interviews were not structured adequately to capture this, rather than a lack of knowledge by the farmers.

Attributes of the tree canopy that affected shade were recognised by the farmers at two levels; that of the individual tree crown and that of the individual leaf. Tree crown was described in terms of both size and density. In terms of size, tree height and crown size (which principally referred to crown width) combined to influence the area affected by shade, while crown density affected the intensity of the shade that is cast within this area. This contrasts with most scientific treatments of light extinction by plant canopies that have considered continuous agricultural crop or forest canopies without confining foliage within envelopes associated with individual plants (Campbell and Norman, 1989). There has, however, been modelling of canopy discontinuity with respect to orchards (Jackson and Palmer, 1979) and isolated plants (Mann *et al.*, 1979; Norman and Welles, 1983). The amount of leaf area and, more recently, the spatial distribution of leaf area density, vertical and horizontal dimensions within tree crowns have also been considered (Wang and Jarvis, 1990). However, despite simulation models for statistical description of canopy structure (Ross, 1981), few data are available on the actual variation of leaf area density in plant stands and random or uniform distributions are generally used as approximations (Campbell and Norman, 1989). It is unclear to what extent farmers' perceptions of crown density referred to the total amount of foliage within the crown as opposed to the grouping of foliage elements, but it is likely that it was the overall effect of these two factors combined that corresponded to the differences in crown density recognised by the farmers.

The consideration of leaf size by farmers contrasts with the emphasis of most scientific research. While passing mention has been made that the size of individual leaves may influence the absorption of radiation (Wang and Jarvis, 1990), the turbid medium analogy, which involves treating leaf area as a statistical density function within a given volume or layer rather than the individual leaf surfaces being represented, has been adopted since the work of Monsi and Saeki (1953 cited by McCrady and Jokela, 1998). Farmers' knowledge about the effect of leaf inclination angle on shade was not captured, but they recognised trees as having leaves which either pointed upwards or downwards, or were horizontal, and that horizontal leaves were associated with more intense shade than those that were vertically oriented. This is quite consistent with the scientific observation and theoretical explanation that planophile canopies intercept a higher proportion of incident light than erectophile canopies (de Wit, 1965).

The knowledge articulated by farmers on the relationship between tree root architecture and competition for soil moisture and nutrients corresponds closely with the statement made by Vandenbeldt *et al* (1990) that tree roots often exploit the crop root zone for nutrients and water because of the proliferation of fine roots in the upper soil layers. This may be particularly so for tree species whose roots are shallow with horizontal distribution. Vandenbeldt *et al* (1990) have indicated that the simplistic model portrayed in most agroforestry literature of trees as complementary and uncompetitive with annual crops be used with caution. Research has shown that a great variation in rooting pattern both within and between species can occur, which may be influenced by several factors including silvicultural manipulations and environmental factors. However, literature also suggests that mixtures of trees and crops may exhibit more extensive niche differentiation than would be expected from their rooting patterns in monoculture because of responses to reduced water and nutrient availability in upper soil layers as a result of resource consumption by companion crops (Sinclair *et al.*, 1994).

The conclusion therefore is that farmers' knowledge can add to and support knowledge derived from formal scientific research domains. For instance, farmers' knowledge of different tree species increasing soil moisture around them provides new research avenues for investigating below-ground interactions of tree roots. It is also concluded that farmers' proxies for ecological criteria can aid species prioritization and selection for agroforerstry interventions.

9.3. The potential of indigenous forest tree species for use in cocoa agroforests

The future of shade grown cocoa in Ghana will depend largely on the extent to which suitable shade tree species can regenerate naturally, especially in fallows since these eventually get re-converted to cocoa farms; and this will also be influenced, to a large extent, by the length of the fallow periods. The results from the study of the population structure of the different shade tree species revealed that, in contrast with the findings of Swaine (1992), the Meliaceaes - *Entandrophragma spp* and *Khaya spp* - have a rather poor regeneration potential in the surrounding natural forest, resulting in subsequent poor regeneration of these species in the fallows due to poor seed rains. The implications of this are that these species which are highly valued for their timber, medicinal and other service products, are gradually being eroded from the agricultural landscape. The remaining four species, on the other hand, demonstrated good potentials to regenerate naturally in the fallow, with steep SCD slopes showing high seedling densities and intermediate sapling populations, as indicated by Lykke (1998). However, the increasingly shorter fallow lengths in this area, as in all other parts of the country, caused by increasing population pressure, as pointed out by Obiri (2003), will negatively impact on the regeneration of these species on fallow lands. Thus the species are in great danger of extinction, especially from farm lands, and therefore need to be regenerated artificially through planting/enrichment planting.

Apart from regeneration potential, there is a need for some amount of temporal complementarity, in above- and below-ground resource use, between the cocoa and the shade tree species, as explained by Ong and Black (1994). Above-ground resource use is controlled by the phenological pattern of the trees, as well as the light interception pattern which is in turn influenced by tree crown characteristics among other factors.

The results of the study show that, with the exception of three of the species – *N. laevis* and *T. ivorensis* and to some extent *K. anthotheca* – the remaining four species displayed leafing patterns which were negatively correlated with seasonal rainfall patterns, and hence with soil moisture regimes. As observed in other tropical forest tree species by a number of workers (Frankie *et al.*, 1974; Lieberman, 1982; Okullo *et al.*, 2004), these species shed most of their leaves in the dry season and developed full canopies in the rainy season, in response to soil moisture content. They thus displayed strong temporal complementarity in the use of light and water as the reduction in leaf cover reduces transpirational water loss and water uptake by the species (Reich and Borchert, 1984; Broadhead et al., 2003a & b). On the other hand, the absence of leaves on these species in the dry season, when the intensity of the sun is higher, will provide little shade for the cocoa crop at this time of the year and could lead to sun scorching, especially for young cocoa. The evergreen habit of *N. laevis* is possibly due to the tree's relatively narrow, compact and generally small crown, resulting in low whole canopy transpiration, as explained by Reich (1995). It is also possible the species has deep rooting habit which, in combination with the above crown characteristics will result in a minimal water deficit in the trees (Reich, *opp cit*), and hence low water stress. *T. ivorensis* was the only species that did not show a clearly defined pattern in its leafing phenology as individual trees of this species, growing in the area, were generally asynchronous in their leafing pattern. Correlation between leaf shedding and rainfall was weak, suggesting that other factors other than rainfall influence leafing phenology in this species. Leafing phenology in this species is possibly facultative and, as suggested by a number of workers (Borchert, 1980; Reich and Borchert, 1984; Broadhead et al., 2003a & b), may be controlled more by a combination of endogenous factors than by environmental factors such as rainfall.

For *A. adianthifolia, E. angolense, E. utile* and *T. tetraptera,* the reduction in their leaf cover in the dry season implies low soil water extraction by these shade tree species, and reduced competition with the cocoa crop during the dry season when soil moisture is limiting, as explained by Broadhead et al., (2003b), but will also mean minimal shade provision for the cocoa. On the other hand, maintenance of full leaf cover throughout the year, especially in the dry season, as exhibited by *N. laevis,* and to a large extent, *K. anthotheca,* will result in competition between these species and the cocoa for the limited dry season water and nutrients. It is therefore necessary to strike a balance between competition for below-ground resources and shade provision. *T. ivorensis,* with its asynchronous leafing phenology, seems to offer this balance more than any of the other shade tree species, on the basis of their patterns of leaf fall and leaf formation.

The amount and quality of light (PAR and R/FR) received beneath the canopy of each shade tree species was generally higher in the dry season than in the rainy season and was possibly due to higher irradiances usually received by tree canopies during the dry season as a result of reduced cloud cover (Chazdon and Fletcher, 1984; Rich *et al.,* 1993) and deciduosity. The R/FR ratios found beneath the canopies of these shade tree species (0.3 – 1.16) are generally comparable to values reported by Varlet-Grancher *et al* (1993). An attempt was made to establish a relationship between light transmission, in terms of quantity (PAR) and quality (R/FR), through the canopies of the different shade tree species and their crown properties – leaf cover, crown depth and crown diameter. The results showed that only leaf cover was strongly correlated with PAR and R/FR transmission; and the correlations were negative, indicating that more light penetrates through the crowns as leaf cover reduces. The correlation between crown depth and crown diameter, on one hand, and PAR and R/FR transmission on the other hand were generally weak, negative and not significant. This is similar to the results of Bello and Nair (2003) who found a weak negative correlation between crown diameter and PAR transmission in a shaded perennial agroforestry system in Costa Rica. Similar influence of leaf cover on light transmission has been reported for Sitka spruce by Wang and Jarvis (1990), who explained that the total area of leaves and their spatial distribution within a tree crown are far more important than crown shape or leaf inclination angle distribution of the crown in their influence on light transmission. As indicated by Broadhead et al., (2003a & b), the dry season patterns of lower leaf cover and higher PAR and R/FR transmission will imply reduced below-ground and above-ground competition between the shade trees and the cocoa for water and nutrients and for light. It therefore means that *A. adianthifolia*, *T. ivorensis* and *T. tetraptera*, with their lower overall leaf cover and higher PAR and R/FR transmittance in the dry season, coupled with their larger crown areas, appear to be more temporally complementary with the cocoa, especially in the dry season. But this will also mean minimal shading for the cocoa during this period. Therefore the more appropriate recommendation will be the use of a combination of different species with different leaf phenological patterns.

The results of seed pre-treatment effect on germination of *T. tetraptera* seeds indicate that concentrated H_2SO_4 treatment is the most effective means of breaking seed dormancy, and corresponds with the findings of Odoemena (1988) for the same species in Nigeria, as well as those of Masamba (1994) for four African *Acacia* species in Niger. The highest germination response obtained with the longest treatment time of 20 minutes also corresponds with similar results obtained by Bhagat *et al* (1992) for seeds of *Indigofera gerardiana* in the northwest Himalayas, and appears to indicate seed coat dormancy in this species. However, in spite of the high germination response obtained with this method of pre-treatment, it is not of practical use to local farmers owing to the difficulties in obtaining H_2SO_4 and the dangers involved in handling and working with it. Thus the alternative and more practical method of scarifying seeds with citric acid which is easily obtainable from locally grown *Citrus jambhiri*, and which gave a moderate germination response, presents a more practical means of treating *T. tetraptera* seeds to enhance germination.

As widely published in literature, the use of rooting hormones (IBA), as well as leafy stem cuttings were found to be effective in rooting cuttings of *T. tetraptera*. While the results of the effect of IBA concentration on rooting showed general similarity to results obtained with other species (e.g. Ofori *et al.*, 1996; Mesén *et al* 1997), they also contrast with results reported for other tropical forest tree species in which rooting of cuttings was found to be insensitive to IBA concentration (e.g. Leakey *et al.*, 1990; Shiembo *et al.*, 1996). However, the rooting percentages and number of roots per rooted cutting obtained in this study appears to be relatively low compared to the results reported in other studies for a number of tropical forest species, and could be due to a number of factors including the age of the stock plants from which the cuttings were collected, as this has been shown to have a significant effect on rooting of stem cuttings (e.g. Welander and Snygg, 1987; Berhe and Negash, 1998). It would also possibly be due to the rooting medium (washed river sand alone) used in this study, since rooting medium has also been shown to significantly influence both rooting percentage and the number of roots per rooted cutting as it directly influences moisture and oxygen availability, both of which are crucial for successful rooting of cuttings (e.g. Anderson, 1986; Hartmann *et al.*, 1990; Leakey *et al.*, 1990; Ofori *et al.*, 1996; Shiembo *et al.*, 1996; Mesén *et al.*, 1997). The conclusion from this study, then, is that the estimates of the rooting percentage as well as the number of roots per rooted cutting of this species are quite conservative and could possibly be improved by collecting cuttings from more suitable stock plants, instead of from plants growing in the wild, and by finding a more suitable rooting medium.

With regards to performance of the tree species after planting on the field *A. adianthifolia*, *E. utile* and *P. elata* showed very poor ability to survive, while the poor initial growth rates recorded for them agrees with Hawthorne's (1995) ascertion that these species have inherently poor initial growth rates. Their poor survival could be due to detrimental competition from intercrops as explained by Frochot and Levy (1990, cited by Balandier and Dupraz, 1999). Therefore, it will not be very appropriate to recommend these three species for inclusion on farmers' fields as planted shade, due to their poor survival and poor initial growth performance. Any consideration of these species for shade on cocoa farms will have to be based on managing already existing natural regeneration found on fallows during land preparation. If there is a need for enrichment planting due to absence of, or low, natural regeneration, then a better option will be to plant and manage the trees for at least two years prior to the establishment of the cocoa crop, as *E. utile* in particular is noted to grow quite fast after the slow initial growth period (Hall and Swaine, 1981; Hawthorne, 1995).

The remaining five species - *E. angolense*, *K. anthotheca*, *N. laevis*, *T. ivorensis* and *T. tetraptera* – demonstrated moderate to good potential for use as planted shade for cocoa on farmers' fields, with moderate to high survival rates and good initial growth rates on the field. In comparison with the cocoa, these species have significantly faster growth rates; a feature that will ensure early canopy stratification and niche differentiation (Menalled *et al.*, 1998) when grown in mixture with the cocoa. Their high initial growth rates also give an indication of their good ecological combining ability (Harper, 1977 cited by Menalled *et al.*, 1998) with the cocoa, as they will ensure good spatial differentiation and reduction in interspecific competition, as explained by a number of workers (Vandermeer, 1989; Kelly, 1992; Menalled *et al.*, 1998). The suitability of these species, with the exception of *N. laevis*, is further strengthened and recommended, based on the good clear bole lengths and crown characteristics obtained for their mature trees on fallows. Despite its short bole length and rather narrow crown, inclusion of *N. laevis* as a companion species will still be recommended due to its socio-economic value to the local population as a highly valued medicinal plant.

Results of the evaluation of the rooting habits and water use potential of the cocoa and some of the best growing shade trees on the field revealed that cocoa and *T. ivorensis* have more or less similar rooting habits, with a good proportion of their proximal roots oriented in a horizontal plane, and consequently high competitivity indices. *T. ivorensis* demonstrated particularly high root competitiveness, at 2 years of age, comparable to the competitivity index obtained for 4-year old *L. leucocephala* trees by van Noordwijk and Purmonosidhi (1995). On the other hand, *E. angolense* and *T. tetraptera* had low competitivity indices and thus demonstrated lower competitiveness, and much better below-ground compatibility, with the cocoa, based on these calculated competitivity indices, than *T. ivorensis*. On the basis of the competitivity indices obtained for the species in this study it appears reasonable to conclude that *E. angolense* and *T. tetraptera* are a better choice to plant as cocoa shade, compared to *T. ivorensis*, due to their low root competitiveness. However, results from studies on other agroforestry tree species indicate that competitivity indices of tree species change with age (Ong *et al.*, 1999), hence such a conclusion will be too early to draw at this early age. Tree rooting patterns are known to be influenced by soil properties (Howard *et al.,* 1997). Thus while giving an insight into the potential below-ground interaction between the various shade trees and the cocoa, it is not feasible to draw any definite conclusions on below-ground complementarity of the three shade tree species with the cocoa, and further more detailed studies will be required as the trees age.

In terms of water use by the shade tree species, maximum water use was recorded between mid morning and mid afternoon and coincided with the period of maximum incident PAR in this area. This pattern of water use was generally similar to results reported for some dryland trees in Senegal (Deans and Munro, 2004), and for *Grevillea robusta* in Kenya (Ong *et al.,* 1999; Lott *et al.,* 2003) and also for *G. senegalensis* in Niger (Allen and Grime, 1995). *T. ivorensis* trees, at three years, used comparatively more water than *E. angolense* and *T. tetraptera* trees of the same age, and was possibly due to the larger crown and sapwood cross-sectional area (Bayala, 2002) of the *T. ivorensis* trees. Sapflow rates generally followed the trend in growth rates for the three species, with the trend being *T. ivorensis>E.angolense>T. tetraptera*; indicating that faster growing tree species tend to use more water than slower growing species. The implications of this are that, even though the use of such faster growing species will enhance faster spatial differentiation and above-ground complementarity in the use of aerial resources, as explained by Menalled *et al* (1998), it could also have some negative implications for below-ground complementarity for water and nutrient use. These results of sapflow in the three shade tree species suggest that *E. angolense* and *T. tetraptera* are more conservative water users, and hence potentially less competitive, than *T. ivorensis.* This conclusion is further strengthened by the relatively lower root competitivity indices of the two species compared to the latter. However, the stage of development of the trees is too early (3 years) to draw conclusions from these results, as evidence has shown that root system dynamics as well as above-ground growth parameters change with the age of the tree; and this will most like change the trend in water use by the species. Nevertheless, the results obtained in this study give some useful indication of the competitive potential of these shade tree species and provide a basis for comparison of future trends.

Results of the accumulation of above-ground dry matter and nutrient dynamics in the cocoa-*Gliricidia* agroforestry system indicated that the inclusion of the *G. sepium* shade trees increased the above-ground dry matter of the system by as much as 73.70%, and a greater proportion of this biomass was contained in the branches of the shade trees. The higher branch biomass of the *G. sepium* shade trees is similar to results reported by Nwoboshi (1996) for *Eucalyptus alba* in the Accra plains of Ghana in which branches constituted a greater proportion of their total above-ground biomass. This pattern of dry matter distribution makes the species appropriate for growing as a fuelwood species in agroforestry systems.

The inclusion of *G. sepium* also increased carbon capture by some 4.84 t ha^{-1}, over the sole cocoa carbon content of 1.98 t ha^{-1}, to a total of 6.82 t ha^{-1}. Even though this may not seem very high, it does compare well with figures reported for 8 year old plantations of *A. indica* (8 t C ha^{-1}) by Evans (1982) and Pandey (1983), and demonstrates that multi-strata cocoa agroforestry systems present substantial potential for capturing and storing atmospheric carbon, especially where the shade tree species are large sized trees grown for long rotations, as the indigenous species investigated in this study.

Leaf litter contribution by the shade trees was more than double that produced by the cocoa alone, and generally compared favourably with litterfall figures reported for other multi-purpose shade tree species elsewhere (e.g. Beer, 1988; Young, 1989; Montagnini *et al.,* 1993). And while the pattern of litterfall in *G. sepium* was closely related to season of the year, with higher litter production in the dry season, that of the cocoa was less affected by season. This pattern of higher litterfall in the dry season, possibly in response to reduced soil moisture levels, humidity and higher temperature, would imply reduced water extraction by the shade trees thereby reducing competition with the cocoa for water and nutrients during this period of the year (Broadhead et al.,., 2003). The higher litter production at this time of year will also ensure increased soil protection from excessive heat of the dry season and from soil erosion in the rainy season, as well as ensure improved nutrient cycling (Montagnini *et al* 1993).

The generally faster decomposition rates and nutrient release patterns recorded for the *G. sepium* leaf litter compared to the cocoa litter in this study indicate that the inclusion of the *G. sepium* shade trees improved the overall cycling of nutrients within the system. Litter quality, as determined by its N content, as well as the C:N ratio of the litter, appeared to have an influence on both litter decomposition rates and nutrient release patterns. Hence the *G. sepium* leaf litter with higher N content and lower C:N ratios decomposed faster and generally release the nutrients in the decomposing litter faster than the cocoa. However, apart from N and Mg, nutrient release patterns were generally similar in both species. Nitrogen immobilization was observed in the cocoa leaves due to their low N content, and this seems to contrast with the report of Palm and Sanchez (1990) who made a general statement that N immobilization may be the rule in the tropics.

Thus the short term results and conclusions outlined above clearly demonstrate that native forest tree species have a considerable pontential for use in an agroforestry context.

9.4. Farmers' knowledge versus scientific knowledge

Examination of the farmers' knowledge base enables a number of comparisons with some of the field experimental findings to be made, though this is limited, at this stage, to the above-ground attributes of the trees and their effect on microclimatic conditions on cocoa farms. In terms of height of the different shade tree species used for the field trial, there appeared to be agreement between the farmer's classification of tree height and the actual height measurements recoreded in the field. Comparing Table 3.8 (Chapter 3) and Table 5.5 (Chapter 5), *E. angolense, E. utile, K. anthotheca* and *T. ivorensis* were classified by farmers as tall trees while *A. adianthifolia* and *T. tetraptera* were described as medium height trees, with *N. laevis* being described as short. The field measurements of total height corresponded witht this classification except for *E. utile* and *K. anthotheca* for which field measurements revealed short to medium heights of 9.5 m and 12.7 m respectively. However, as explained in chapter 5, trees of these species measured in the field were mainly juveniles and their heights did not reflect the actual heights of mature trees of these species. Description of crown shape by farmers, which was classified as either narrow or wide, also corresponded with field assessment of crown diameter/area of the individual species.

In terms of shade provision farmers classified trees according to how much sunlight passes through the crown; this can be compared with PAR transmission beneath the canopies of the individual species. From the farmers' knowledge, *A. adianthifolia* and *T. tetraptera* are said to provide light shade, allowing a lot of sunlight through their canopies, while the *entandrophragmas* and *K. anthotheca* are said to provide heavy/excessive shade, with low light transmission. Results of the PAR measurements on the field correspond with this assessment. *A. adianthifolia* and *T. tetraptera* were found to be transmiting relatively higher PAR to below-ground arrays than the other species while the Meliaceaes where among the heavier shade casters (Figure 5.11; Chapter 5). The only controversy here appeared to be with *N. laevis* for which the farmers classified shade cast by the species as "light" and light transmission as "medium" whereas the field PAR measurements revealed the species to be the heaviest shade caster with the least transmitted PAR. This, however, appears to do with the crown shape/area of the species, which is inherently narrow/small thus rendering effective shade cast on the cocoa crop to be minimal.

9.5. Limitations of the study

Althought the results of this study demonstrates the potential for the use of native forest tree species in planted cocoa agroforestry systems, there are a number of limitations which, if overcome, could have improved some of these findings.

In the assessment of light transmission (PAR and R/FR light) through the canopies of the individual shade tree species, the use of the hand held AccuPAR and Skye 110/100 measuring systems for PAR and R/FR light measurements, respectively, meant that above-canopy and below-canopy light were not taken at the same time. The small time lag introduced between measuring light in the open and moving the instrument to take readings under the tree canopies could introduce some error in the calculation of net light transmitted to below-canopy arrays, which is calculated as the difference between above- and below-canopy readings. This is because, between taking the two readings cloud movement could alter the amount of insolation reaching the tree canopies. The ideal situation would be to take the two measurements simultaneously with two sets of instruments, and connected to a data logger.

The moderate rooting responses obtained in the vegetative propagation study, compared to results from other studies, was possibly due to the use of only one rooting medium – washed river sand – as well as the use of cuttings collected from wildlings instead properly prepared stock plants. The rooting percentages as well as the number roots produced by the rooted cuttings could possibly have been improved by choosing more suitable stock plants and testing different rooting media.

The study on root architecture and potential competitivity and/or complementarity between the planted shade trees and the cocoa was limited to an evaluation of competitivity indices for the different species. This was mainly due to logistical problems, mainly in terms of equipment. Although competivity indices give an idea of the potential complementarity of belowground resource use between the trees it does not give a full picture of the root system structure. The method did not allow the estimation of tree root lengths and root length densities as well as the distribution of fine roots, all of which enable the determination of root activity patterns. The results of this study could have been improved by complementing it with an evaluatution of root distribution patterns, through soil/root coring at different distances from each tree, and at different soil depths, as outlined by several workers (e.g., Rao *et al.*, 1993; Akinnifesi *et al.*, 1998; Jama *et al.*, 1998; Jones *et al.*, 1998; Mekonnen *et al.*, 1999; Odhiambo *et al.*, 1999; 2001; Rowe *et al.*, 2001; Smith, 2001). Nevertheless, the results presented in this study give us an idea of root orientation and potential competitivity and /or complementarity for the study species.

With regards to water uptake by the different shade tree species, it was not possible to measure water use simultaneously on all combinations of species, due to equipment limitations imposed by cost. This renders interspecific comparisons of the water uptake rates obtained in this study less practicable, though an attempt was made to minimise variations caused by fluctuations in environmental conditions by reversing the sequence of interspecific measurements. As pointed out by Deans and Munro (2004), sapflow is dependent on numerous environmental variables including soil water content and the atmospheric environment. It responds rapidly to fluctuations in the latter, particularly solar radiation. Thus the better option would have been to measure sapflow on all three species simultaneously, as well as carry out simultaneous recording of environmental variables such as air temperature, relative humidity and photosynthetically active radiation (PAR).

9.6. Recommendations

1. Although the farmer's ecological knowledge elicitation and documentation in this study was basically exploratory and not detailed, it did reveal a great potential for understanding farmers' perceptions of various production issues, and give a clearer understanding of the factors that contribute to farmers' decision making processes. It is therefore recommended that local farmers' knowledge elicitation and documentation be incorporated into project formulation and development processes, to enhance communication and ensure effective cooperation and participation by farmers.

2. With the general decline in forest cover over the last few years, and the increasing threat from illegal felling of trees for timber, there is an urgent need for artificial regeneration of forest cover through enrichment planting. Judging from the good initial growth performance of some of the planted species, it is recommended that active planting of cocoa shade trees, using indigenous forest tree species that have some value to the local communities be encouraged.

3. Since the shade tree species generally have different leaf phenology patterns and different below-canopy PAR and R/FR regimes, as well as exhibiting different below-ground complementarity, the planting of a mixture of tree species for cocoa shade is recommended, rather than the planting of one or two species.

4. Since the germination of *T. tetraptera* seeds have been shown to improve with the treatment of locally available and cheap citric acid, it is recommended that this method of seed pre-treatment be improved for use by farmers to produce seedlings of this species for planting.

9.7. Further research

Although some advances have been made by this study, a number of issues still require further investigation in order to gain a fuller understanding of the mechanisms involved in resource capture and utilization in multi-strata cocoa agroforestry systems. Two years after planting tree crops was certainly too short a time to obtain definite conclusive data on various aspects of above- and below-ground interactions between the cocoa and the planted shade trees. Thus while recommending that the various aspects of this study will need to be monitored over a long time period, the following specific aspects need highlighting.

1. A more detailed elicitation and documentation of farmer's ecological knowledge on multi-strata cocoa agroforestry systems is required.

2. Below-canopy PAR and R/FR transmittance were found to be linked to leaf cover. However, PAR and R/FR measurements were made only on particular days and time of day. It will be more informative to carry out continuous PAR and R/FR light assessment over the whole year or at least over whole seasons.

3. To investigate the link between PAR and R/FR light regimes and cocoa productivity, with the view to developing light saturation curves cocoa and determining optimum shade levels/light requirements for cocoa to enhance optimum production.

4. Further research is required to further improve the germination of *T. tetraptera* seeds using locally applicable seed pre-treatment methods, such as citric acid or other such methods.

5. Since the results of this study indicate modest success of rooting *T. tetraptera* leafy shoot cuttings, further research is needed to find out if this could be improved with use of different rooting media and improved stock plants, in place of the wildlings used in this study.

6. There is a need to carry out a more detailed investigation of rooting patterns, such as rooting depth, root length density and root activity patterns of cocoa and the shade tree species to gain a clearer understanding of below-ground resource sharing. This will better inform the choice of appropriate shade tree species to plant with cocoa. This will need to be to carried out periodically over a number of years to determine root development patterns as the trees age.

7. Tree growth habits are known to change as they grow, and this is likely to alter their water requirements. It is therefore necessary to continue to monitor water uptake by the cocoa and the different shade trees to identify their various water and nutrient uptake patterns as they develop.

8. These short term results of this study have revealed that there is considerable potential for the use of native forest tree species in an agroforestry context. It is therefore recommended that more species be screened for use in planted multi-strata cocoa, and other perennial as well as annual crop, agroforestry systems.

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Appendix 3.1: WinAKT definite clause grammar

The definite clause grammar. Terms in bold are reserved terms in the grammar (i.e. words reserved for use by the system); terms starting with a capital letter are variables; =:> means 'can take the form of'.

FormalSentence => Statement **if** FormalConditions

FormalSentence => Statement

Statement => Cause Causes Effect
where Causes is an element of the set: {causes] way,causes2way}

Statement => AttributeStatement

Statement => not(AttributeStatemenn

Statement => link(intluence Thin2.Thin2)

Statement => link(Link Object Object)

Statement => link(Link ProcessBit.ProcessBit)

Statement => link(Link,ProcessBit.Obiect)

Statement => comparison(Attribute.Object.Comparison.Object)

FormalConditions => FormalConditions and FormalConditions

FomlalConditions => FormalConditions or FormalConditions

FormalConditions => Statement

FormalConditions => ActionBit

FomlalConditions => ProcessBit

AttributeStatement => att value(Obiect,Attribute, Value)

AttributeStatement => att value(ProcessBit,Attribute, Value)

AttributeStatement => att value(ActionBit.Attribute.Value)

Cause => AttributeStatement

Cause => ProcessBit

Cause => ActionBit

Cause => Object

Cause => not(Cause)

ActionBit => action(Action.Object,Object)

ActionBit => action(Action.Object)

ActionBit => action(Action)

Effect => AttributeStatement

Effect => ProcessBit

Effect => ActionBit

Effect => not(Effect)

Process bit => process(Process)

Process bit => process(Object.Process)

Process bit => process(Object.Process.Obiect)

Thing => Object

Thing => ProcessBit

Attribute => atom

Process => atom

Link => atom

Object => atom

Object => part(Object,Object)

Action => atom

Comparison => Atom
where Atom is an element of the set: {2reater than, less than, same as, different from}

Value => Atom
Where Atom is an element of the set: {increase, decrease, chan2e, no chan2e}

Value => Atom

Value => Number
Where Number is either a tloating point number or an integer

Value => range(Value,Value)

Appendix 3.2: Sample statements recorded in the knowledge base for Atwima.

1: the fertility of afonywie is low if the volume of rainfall is low
2: hyire texture is hard if the level of moisture is low
3: the fertility of asaase_tuntum is high
4: the fertility of asaase_kokoo is high
5: the water_holding_capacity of asaase_tuntum is high
6: the water_holding_capacity of asaase_kokoo is high
7: odum shade for cocoa crop is good
8: sesemasa shade for cocoa crop is good
9: akuakuoninsuo shade for cocoa crop is good
10: wama shade for cocoa crop is good
11: emire shade for cocoa crop is good
12: ofram shade for cocoa crop is good
13: kakapenpen shade for cocoa crop is good if cocoa crop is young
14: odoma_fufuo shade for cocoa crop is good
15: odoma_kokoo shade for cocoa crop is bad
16: esan shade for cocoa crop is good
17: onyina shade for cocoa crop is bad
18: wawa shade for cocoa crop is bad
19: pepediawuo shade for cocoa crop is good if cocoa crop is young
20: akonkodie shade for cocoa crop is good
21: okro shade for cocoa crop is good
22: the breakage of nyamedua branch is high
23: the medicinal_properties of kakapenpen is high
24: esan firewood_properties is good
25: esan stem pestle_quality is good
26: esan ash for tobacco_mix quality is good
27: the breakage of wawa branch is high
28: the timber_quality of emire is high
29: the timber_quality of ofram is high
30: the timber_quality of odum is high
31: the timber_quality of wawa is high
32: the timber_quality of onyina is high

33: the weed_growth_rate of asaase_kokoo is high

34: the incidence of akate is low if the presence of shade_tree is high

35: cocoa yield is poor if cocoa_sasabro presence is positive

36: the quality of opam shade cocoa is high

37: the quality of bawdie shade cocoa is high

38: soil fertility is good if atooto presence is dominant

39: soil fertility is good if nsonywea presence is dominant

40: soil fertility is good if nyanya presence is dominant

41: soil fertility is good if nsaasun presence is dominant

42: amiemfosamina shade for_cocoa crop is good

43: pampena shade for_cocoa crop is good

44: nyamedua shade for_cocoa crop is good

45: otie shade for_cocoa crop is good

46: esia shade for_cocoa crop is good

47: fruntum shade for_cocoa crop is good

48: sesemasa shade for_cocoa crop is good if cocoa crop is young

49: fotie shade for_cocoa crop is good

50: sesea shade for cocoa crop is good

51: konkroma shade for cocoa crop is good

52: asoma shade for cocoa crop is good

53: prekese shade for cocoa crop is good

54: kusia shade for cocoa crop is good

55: edinam shade for cocoa crop is good

56: besebuo shade for cocoa crop is good

57: onwamdua shade for cocoa crop is good

58: kokrodua shade for cocoa crop is good

59: baku shade for cocoa crop is good

60: esakokoo shade for cocoa crop is good

61: the presence of cocoa_sasabro is high causes cocoa death is certain

62: the presence of nkrampan is high causes cocoa death is certain

63: the presence of afonywie is high causes cocoa growth_rate is poor if the level of moisture is low

64: the presence of hyire is high causes cocoa growth_rate is poor if the level of moisture is low

65: cultivating of frequently causes a decrease in fertility of soil

66: absence of trees causes a decrease in fertility of soil

67: the presence of trees is high causes soil temperature is cool

68: the population of weeds is high causes a decrease in fertility of soil

69: fallow length is short causes the population of weeds is high

70: nyankyereni causes opro presence is positive

71: nyamedua causes opro presence is positive

72: opro presence is positive causes the destruction of cocoa_pod is high

73: the destruction of cocoa_pod is high causes the yield of cocoa is low

74: okro branch breakage is positive causes cocoa_tree destruction is positive

75: nyamedua branch breakage is positive causes cocoa_tree destruction is positive

76: cocoa_tree destruction is positive causes the yield of cocoa is low

77: odoma_fufuo causes the level of soil_moisture is high

78: wama causes the level of soil_moisture is high

79: odoma_kokoo causes the level of soil_moisture is low

80: the level of soil_moisture is high causes the yield of cocoa is high

81: the level of soil_moisture is low causes the yield of cocoa is low

82: cocoa growth_rate is poor causes the yield of cocoa is low

83: fallow length is short causes cocoa growth_rate is poor

84: fallow length is short causes esre growth is dominant

85: esre_growth causes a decrease in fertility of soil

86: okro causes the level of soil_moisture is high

87: wawa causes the level of soil_moisture is low

88: odoma fruits decomposition is positive causes an increase in fertility of soil

89: shade_tree leaves decomposition is positive causes an increase in fertility of soil

90: an increase in fertility of soil causes an increase in yield of cocoa

91: nfofokwae_growth causes an increase in fertility of soil

92: fallow length is long causes nfofokwae growth is dominant

93: cocoa_shade_tree height is tall causes cocoa ventilation is good

94: cocoa ventilation is good causes the incidence of cocoa_disease is low

95: the incidence of cocoa_disease is low causes the yield of cocoa is high

96: cocoa_shade_tree height is tall causes cocoa_canopy sunlight_availability is good

97: sunlight penetration is good causes the yield of cocoa is high

98: sunlight penetration is good causes the incidence of cocoa_disease is low

99: the presence of nkrampan is high causes the yield of cocoa is low

100: akate presence is positive causes the destruction of young_cocoa is high

101: nfofo_kwae presence is positive causes fallow stage is mature

102: fallow stage is mature causes the fertility of soil is high

103: adjoguo stage is beginning causes not cutting of trees

104: decay of vegetation_debris causes an increase in fertility of soil

105: cracking of ateche causes soil_suitability_for cocoa_cultivation is negative

106: an increase in intensity of trees shading cocoa causes a decrease in yield of cocoa

107: an increase in density of trees causes an increase in intensity of cocoa shading trees if cocoa stage is mature

108: the intensity of shading of cocoa is high causes a decrease in density of weeds

109: trees shading soil causes an increase in enyunnu of soil

110: nsonywea height is short causes the intensity of nsonywea shading cocoa is low

111: shade_tree competition soil water is resource causes a decrease in yield of cocoa

112: decomposing of tree fruits causes an increase in fertility of soil

113: decomposing of tree leaves causes an increase in fertility of soil

114: decomposing of odoma fruits causes an increase in fertility of soil

115: decomposing of domini fruits causes an increase in fertility of soil

116: the fertility of soil is low causes cocoa growth_rate is poor

117: an increase in fertility of soil causes cocoa growth_rate is good

118: cocoa growth_rate is good causes cocoa yield is good if cocoa yarie is absent

119: cocoa yarie is absent causes cocoa yield is good if the fertility of soil is high

120: spraying of cocoa activity is positve causes cocoa yarie is absent

121: etwre presence is positive causes cocoa death is certain

122: asaase_paeye occurence is positive causes cocoa death is certain

123: etwre presence is positive causes asaase_paeye occurence is positive if hyire presence is dominant

124: nkanka presence is pronounced causes cocoa death is certain

125: drought occurence is positive causes nkanka occurence is pronounced

126: cocoa growth_rate is poor causes cocoa yield is poor

127: cocoa death is positive causes cocoa yield is poor

128: cocoa_leaves yellowing is positive causes cocoa yield is poor

129: the fertility of soil is low causes cocoa_leaves yellowing is positive

130: cocoa yield is poor causes the level of poverty is high

131: the fertility of asaase_tuntum is greater_than asaase_kokoo
132: the fertility of soil of nfofokwae_fallow is greater_than acheampong_fallow
133: the fertility of soil of acheampong_fallow is greater_than esre_fallow
134: the yield of hybrid_cocoa is greater_than tetteh_quashie
135: the disease_susceptibility of hybrid_cocoa is greater_than tetteh_quashie
136: the shade_requirement of hybrid_cocoa is less_than tetteh_quashie
137: the fruit_initiation_time of hybrid_cocoa is less_than tetteh_quashie
138: the clearing_ease of fallow acheampong is greater_than fallow nfofokwae
139: the weed_density of acheampong fallow is greater_than nfofokwae fallow
140: the fertility_loss of afonywea is greater_than asaase_kokoo
141: the soil_under of nfofo_kwae is same_as kwae
142: the fertility of nfofo_kwae fallow is same_as acheampong fallow
143: susumansa is_found_on fertile_soil
144: esre is_found_on infertile_soil
145: anansetrumuhuma is_found_on infertile_soil
146: twinta is_found_on infertile_soil
147: atooto is_found_on fertile_soil
148: cocoa_sasabro is_caused_by ants
149: poor_cocoa_yield can_be_caused_by anunum
150: anunum_incidence is_caused_by overshading
151: anunum_incidence is_also_caused_by excessive_rains
152: nkrampan is_caused_by birds
153: nkrampan causes poor_cocoa_yield
154: nkrampan can_be_removed_with cutlass
155: kookoo_sasabro is_controlled_by removal of diseased trees
156: anunum is_controlled_by chemical spraying
157: nkrampan can_also_be_removed_with prune

Appendix 3.3: Tree species identified on farmers' fields in Gogoikrom, Atwima.

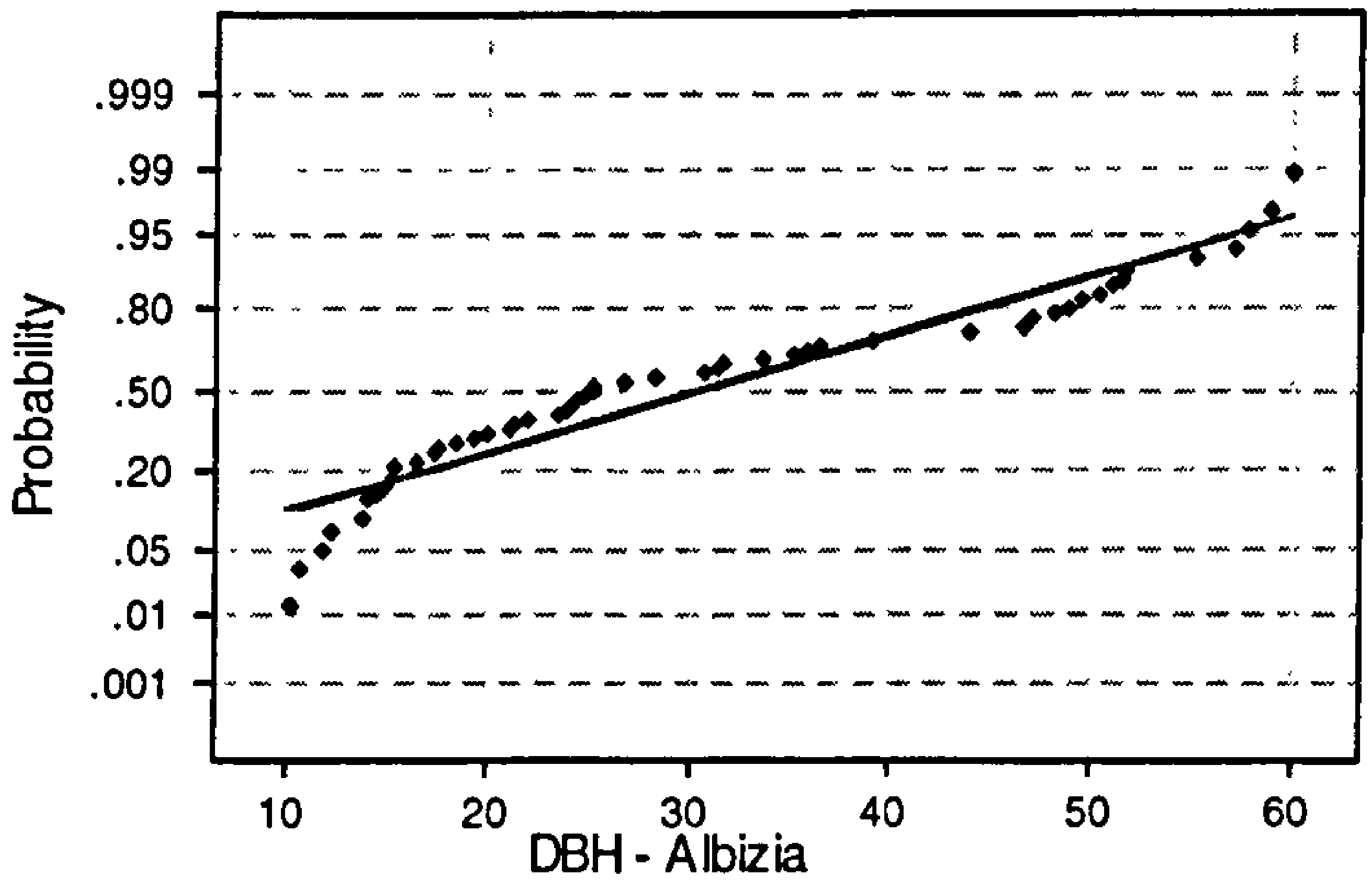
Tree species	Family	Local name	Remarks
*Albizia Adianthifolia***	Mimosaceae	Pampena	Good for cocoa, light crown but shallow roots; good timber
Albizia ferruginea	Mimosaceae	Awiemfosamina	Good for cocoa, deep roots, light crown; good timber
Albizia zygia	Mimosaceae	Okoro	Good for cocoa but branches brittle; shallow rooting; good timber
Alstonia boonei	Apocynaceae	Nyamedua	Good for cocoa but branches brittle; wood used for carvings.
Bombax buonopozense	Bombacaceae	Akata/Akonkodie	Bad for cocoa
Ceiba pentandra	Bombacaceae	Onyina	Bad for cocoa, branches brittle, host to cocoa pest; good timber, kapok used for pillows and mattresses.
Celtis mildbreadii	Ulmacaceae	Esa	Good for cocoa; good for fuelwood and pestles
Celtis zenkeri	Ulmacaceae	Esakokoo	Good for cocoa
Cola gigantean	Sterculiaceae	Watapuo	Bad for cocoa; fruit and seed edible; good fuelwood; found on sandy soils
*Entandrophragma angolense***	Meliaceae	Edinam	Good for cocoa, deep rooting, dense shade but high crown; valuable timber.
Entandrophragma cylindricum	Meliaceae	Penkwa/Sapele	Good for cocoa, valuable timber.
*Entandrophragma utile***	Meliaceae	Utile	Good for cocoa; valuable timber.
Ficus capensis	Moraceae	Odoma/Nwamdua	Good for cocoa; good timber tree.
Ficus exasperate	Moraceae	Nyankyereni	Bad for cocoa, takes too much water and nutrients from soil.
Funtumia africana	Apocynaceae	Okae	Good for cocoa; good timber tree.
Funtumia elastica	Apocynaceae	Fruntum	Good for cocoa; valuable timber tree; gum used for mending bicycle tyres, etc.
Grewia mollis	Tiliaceae	Kyapotoro	Good for cocoa, deep rooting; bark used in local brewery.
Hannoa klainniana	Simaroubaceae	Fotie	Good for cocoa; valuable timber tree.
Irvingia gabonensis	Irvingiaceae	Besebuo	Good for cocoa; seeds used as spice for soup.

Lannea welwitschii	Anacardiaceae	Kumanini	Bad for cocoa, host for cocoa pest; fruits edible.
*Khaya anthotheca***	Meliaceae	Kruba	Good for cocoa; valuable timber tree
Khaya ivorensis	Meliaceae	Dubini	Good for cocoa, but heavy crown; valuable timber tree
Lophira alata	Ochnaceae	Kaku	Good for cocoa, deep rooting, high crown; valuable timber tree
Maesopsis eminii	Rhamnaceae	Onwamdua	Good for cocoa, deep rooting; used for timber; seeds processed for edible oil.
Milicia excelsa	Moraceae	Odum/Iroko	Good for cocoa, high crown; very valuable timber.
Milicia regia	Moraceae	Odum-nua/Iroko	Good for cocoa; good timber tree.
Morinda lucida	Rubiaceae	Konkroma	Good for cocoa, deep rooting, high crown; medicinal value.
Morus mesozygia	Moraceae	Wonton	Good for cocoa, deep rooting, but compact crown.
Musanga cercropioides	Moraceae	Odwuma	Bad for cocoa, shallow rooting, draws too much water from soil; branches brittle; medicinal value.
Myrianthus arboreus	Moraceae	Nyankumabere	Good shade for cocoa, fuits edible.
Myrianthus libericus	Moraceae	Nyankumanini	Good shade for cocoa, deep rooting
*Newbouldia laevis***	Bignoniaceae	Sesemasa	Good early shade for cocoa, narrow crown; valuable medicnal plant.
Parkia bicolour	Mimosaceae	Asoma	Good shade tree for cocoa, but shallow rooting.
*Pericopsis elata***	Papiloinaceae	Kokrodua	Good for cocoa; valuable timber species.
Petersianthus macrocarpus	Lecythidaceae	Esia	Good shade for cocoa, high crown, deep rooting.
Piptadeniastrom aficanum	Mimosaceae	Dahuma	Good cocoa shade, high wide crown, but shallow rooting; valuable timber tree.
Pycnanthus angolensis	Myristicaceae	Otie	Good cocoa shade, high crown, deep rooting, but branches brittle. Valuable timber tree.
Rauvolfia vomittoria	Apocynaceae	Kakapenpen	Good early shade species; valuable medicinal plant.

Ricinidendron heudelotti	Euphorbiaceae	Wama	Good for cocoa, deep rooting, heavy but high crown; branches brittle; good timber tree.
Solanum erianthum	Solanaceae	Pepediawuo	Good early shade for cocoa.
Spathodea campanulata	Bignoniaceae	Akuakuo-ninsuo	Good shade for cocoa, deep rooting, high and wide crown; keeps soil moist.
Spondias mombin	Anacardiaceae	Atoa	Good shade for cocoa, deep rooting.
Sterculia rhinopetala	Sterculiaceae	Wawabima	Good shade for cocoa, high crown.
Strombosia glaucescens	Olacaceae	Afena	Good shade for cocoa, deep rooting; good for roofing rafters and transmission poles.
*Terminalia ivorensis***	Combretaceae	Emire	Good shade for cocoa, high wide crown; valuable timber tree.
Terminalia superba	Combretaqceae	Ofram	Good shade for cocoa, high wide crown, valuable timber tree.
*Tetrapleura tetraptera***	Mimocaceae	Prekese	Good shade for cocoa, light crown; spice and medicinal value.
Tieghemella heckelii	Sapotaceae	Baku/Makore	Good shade for cocoa; valuable timber tree.
Treculia aficana	Moraceae	Brebretim	Good early shade for cocoa, short tree, deep rooting.
Trema orientalis	Ulmaceae	Sesea	Good early shade for cocoa, small tree.
Triplochiton scleroxylon	Sterculiaceae	Wawa	Bad for cocoa, draws too much water from soil, branches brittle, habours pests; valuable timber.
Turreanthus africanus	Meliaceae	Avodire/Apapaye	Good shade for cocoa, but low branching, deep rooting, very valuable timber.

** Species selected for field trials.

Appendix 4.1: Analysis of variance for mean size (DBH) of trees found in the three landuse systems in Atwima, Ghana.



Average: 30 5556
StDev: 15.3628
N: 54

Kolmogorov-Smirnov Normality Test
D+: 0.155 D-: 0.113 D : 0.155
Approximate P-Value < 0.01

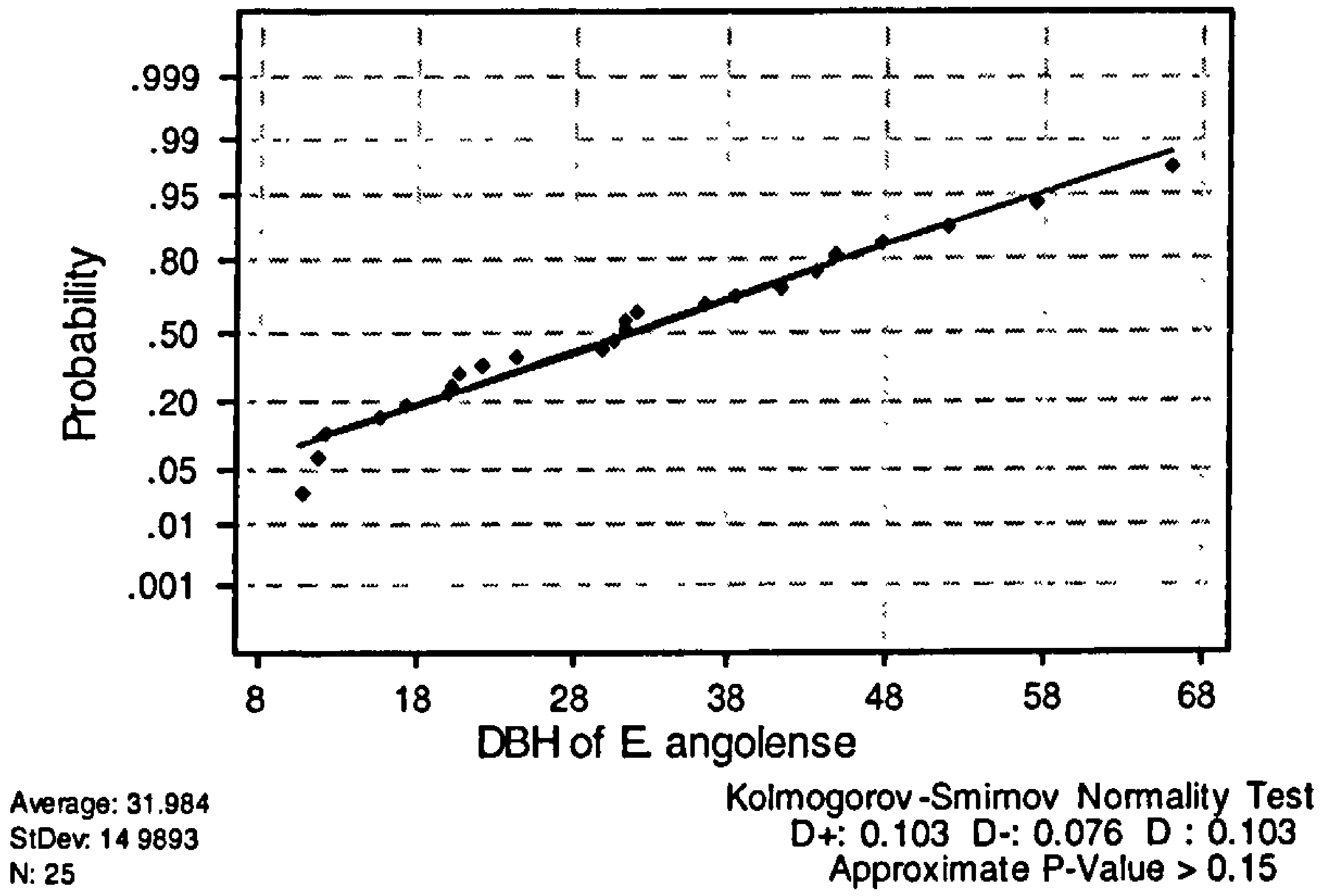
One-way ANOVA: DBH of *A. adianthifolia* trees in different Land use systems

```
Source      DF        SS        MS        F        P
Land use     2      3776      1888    11.03    0.000
Error       51      8733       171
Total       53     12509
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev   -+---------+---------+---------+-----
Cocoa       13     45.40     10.16                       (------*-------)
Fallow      24     26.08     14.59     (----*----)
Forest      17     25.52     12.74   (------*-----)
                                     -+---------+---------+---------+-----
Pooled StDev =     13.09              20        30        40        50

Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.0195

Critical value = 3.41

Intervals for (column level mean) - (row level mean)

               Cocoa       Fallow

       Fallow   8.45
               30.18

       Forest   8.26        -9.44
               31.51        10.57
```

Kruskal-Wallis Test: DBH of A. adianthifolia trees in different Land use systems

```
Land use     N     Median    Ave Rank        Z
1. Cocoa    13      48.90        42.3     3.90
2. Fallow   24      21.60        23.1    -1.85
3. Forest   17      23.50        22.4    -1.62
Overall     54                   27.5

H = 15.27  DF = 2  P = 0.000
H = 15.27  DF = 2  P = 0.000 (adjusted for ties)
```

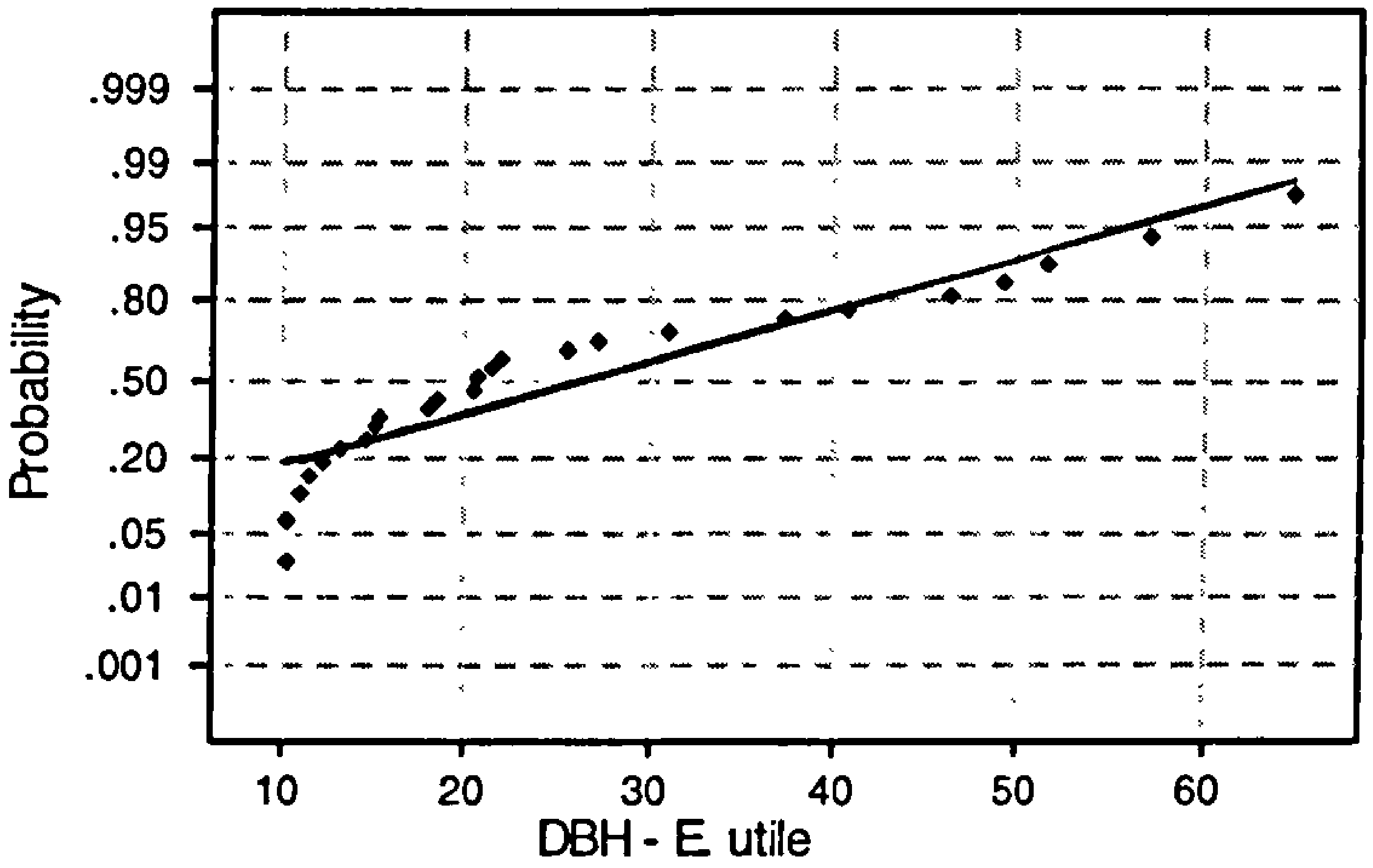
B. *E. angolense*



One-way ANOVA: DBH of *E. angolense* trees in different Landuse systems

```
Source      DF        SS        MS        F        P
Landuse      2      2349      1175     8.49    0.002
Error       22      3043       138
Total       24      5392
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev  -------+---------+---------+---------
1. Cocoa     6     49.12     10.66                    (-------*-------)
2. Fallow    8     25.05     11.53   (------*------)
3. Forest   11     27.68     12.43     (-----*-----)
                                    -------+---------+---------+---------
Pooled StDev =     11.76                  24        36        48

Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.0199

Critical value = 3.55

Intervals for (column level mean) - (row level mean)

                1          2

      2      8.12
            40.01

      3      6.45     -16.35
            36.42      11.09
```

C. *E. utile*



Average: 26.544
StDev: 16.2821
N: 25

Kolmogorov-Smirnov Normality Test
D+: 0.217 D-: 0.156 D : 0.217
Approximate P-Value < 0.01

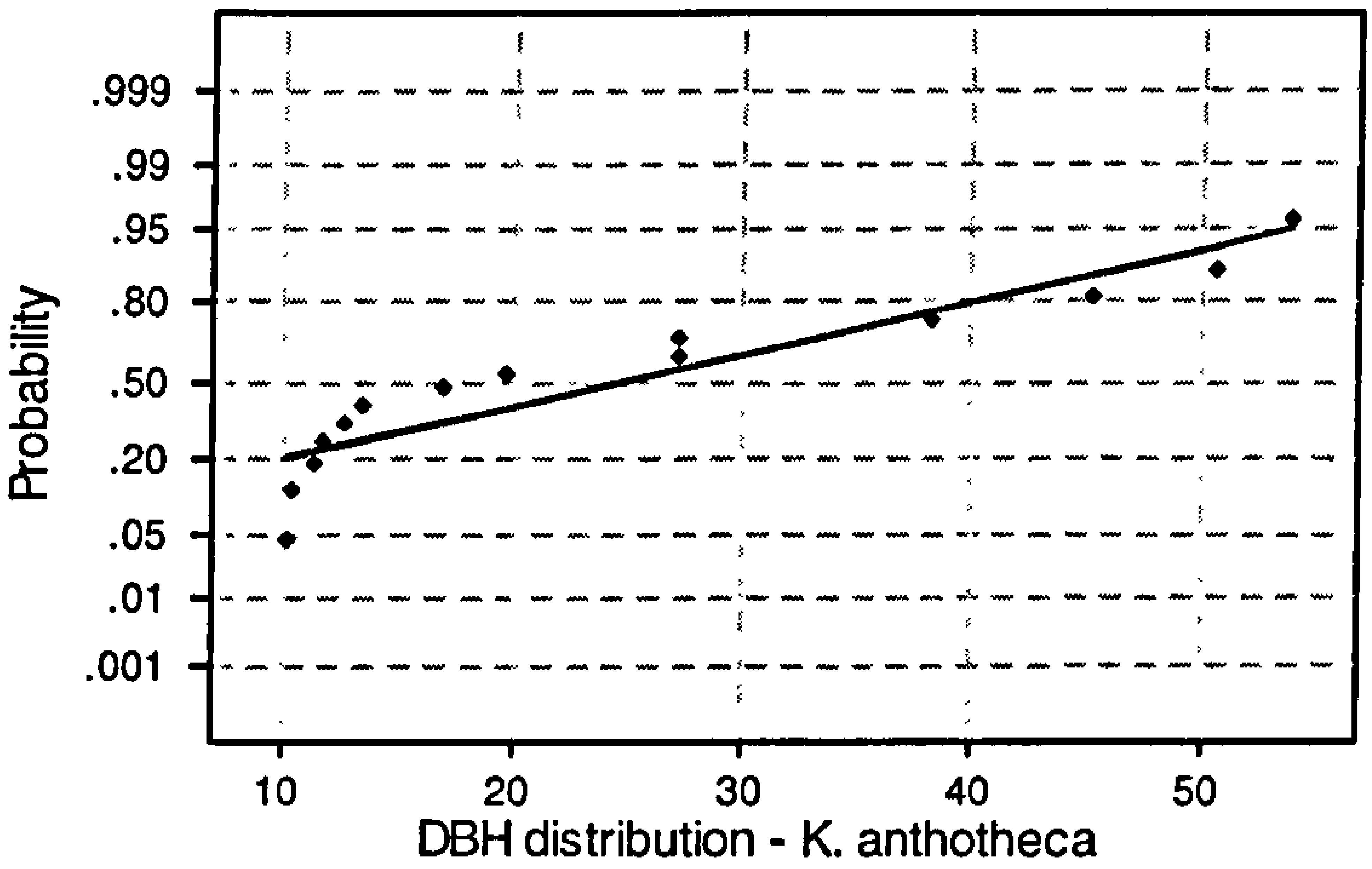
One-way ANOVA: DBH of *E. utile* trees in different Landuse systems

```
Source      DF        SS        MS        F        P
Landuse      2    4169.9    2084.9    20.92    0.000
Error       22    2192.7      99.7
Total       24    6362.6
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev  --+---------+---------+---------+----
1. Cocoa     4    55.750     6.994                        (------*------)
2. Fallow   12    19.017     9.601   (---*---)
3. Forest    9    23.600    11.358     (----*---)
                                    --+---------+---------+---------+----
Pooled StDev =     9.983               15        30        45        60

Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.0199

Critical value = 3.55

Intervals for (column level mean) - (row level mean)

                 1           2

       2       22.26
               51.20

       3       17.09      -15.63
               47.21        6.47
```

Kruskal-Wallis Test: DBH of A. adianthifolia trees in different Land use systems

```
Landuse      N    Median    Ave Rank         Z
1. Cocoa     4     54.50        23.5      3.11
2. Fallow   12     14.80         9.8     -2.07
3. Forest    9     20.60        12.6     -0.23
Overall     25                  13.0

H = 10.40  DF = 2  P = 0.006
```

D. *K. anthotheca*

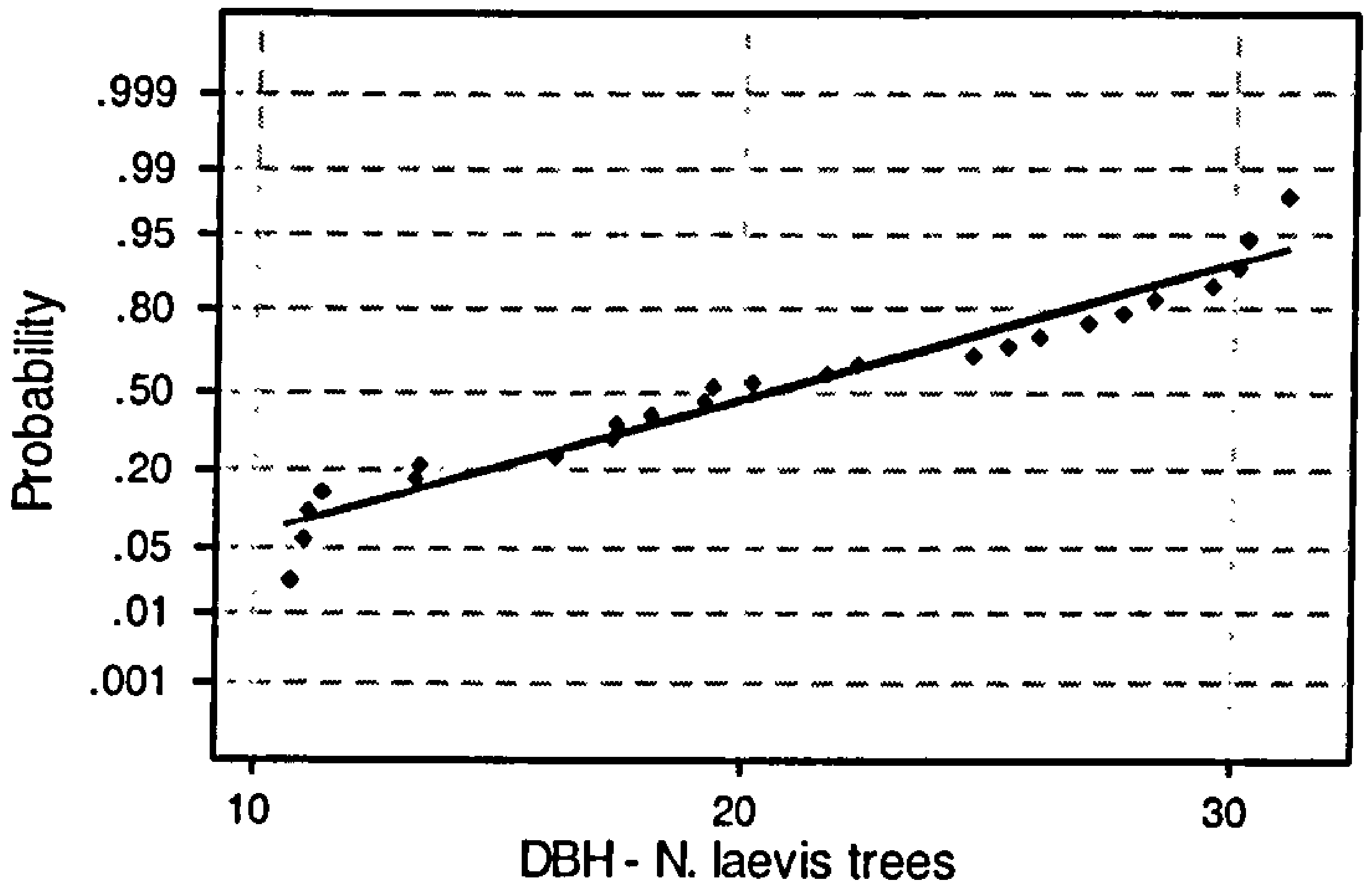


```
Average: 24.9            Kolmogorov-Smirnov Normality Test
StDev: 15.8711             D+: 0.202  D-: 0.176  D : 0.202
N: 14                        Approximate P-Value: 0.121
```

One-way ANOVA: DBH distribution of K. anthotheca trees in different Landuse systems

```
Source      DF        SS        MS        F        P
Landuse      2      1101       550     2.79    0.105
Error       11      2174       198
Total       13      3275
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
Level       N      Mean     StDev   ---------+---------+---------+-------
1. Cocoa    3     36.97     22.30               (-----------*-----------)
2. Fallow   6     15.18      6.82    (-------*--------)
3. Forest   5     29.32     15.38           (---------*--------)
                                    ---------+---------+---------+-------
Pooled StDev =    14.06                         15        30        45

Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.0206

Critical value = 3.82

Intervals for (column level mean) - (row level mean)

                 1           2

       2      -5.07
              48.63

       3     -20.08      -37.13
              35.38        8.86
```

E. ***N. laevis***



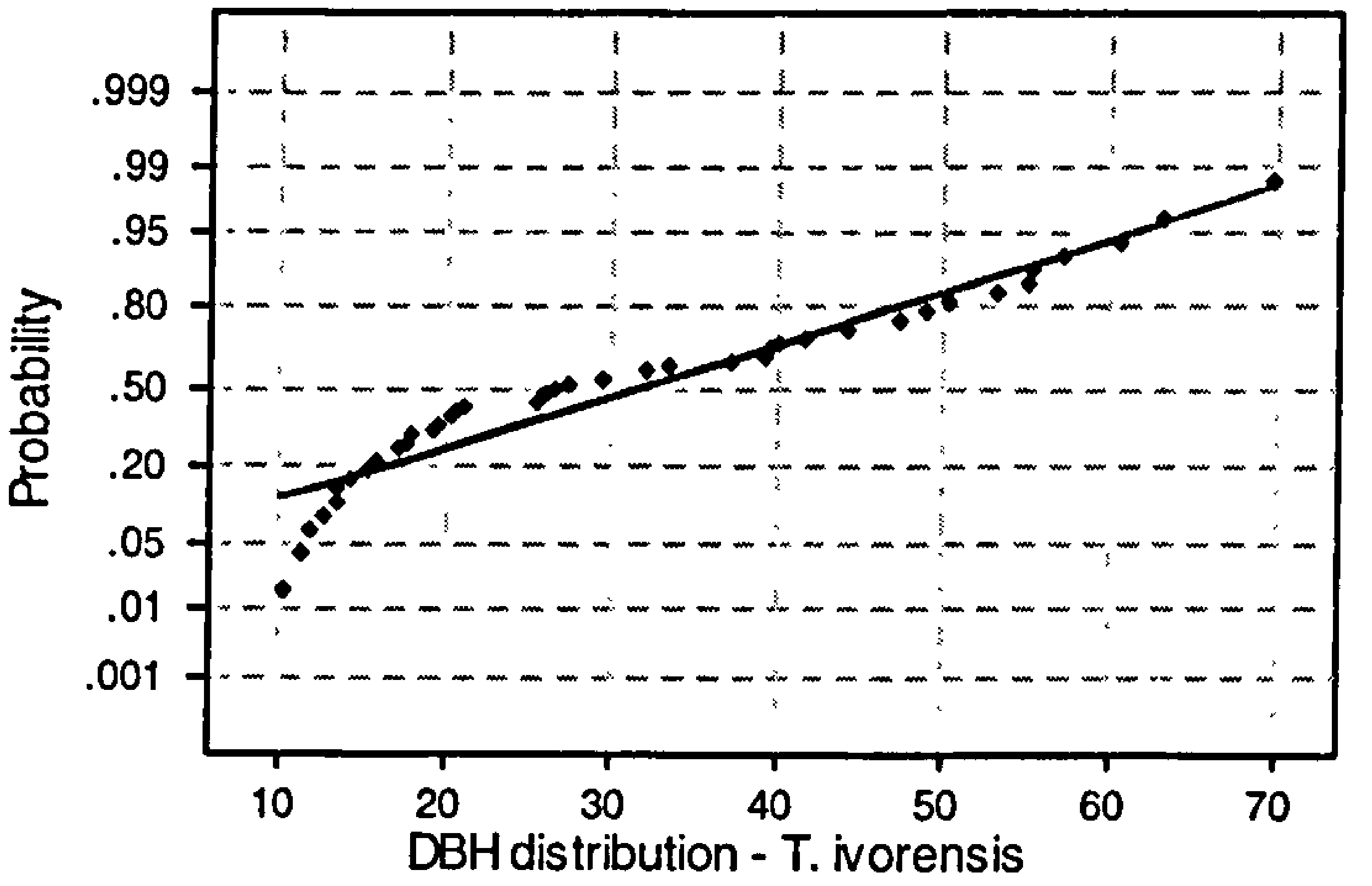
Average: 20.7222
StDev: 6.63228
N: 27

Kolmogorov-Smirnov Normality Test
D+: 0.098 D-: 0.096 D : 0.098
Approximate P-Value > 0.15

One-way ANOVA: DBH distribution of N. laevis trees in different Landuse systems

```
Source     DF        SS        MS        F        P
Landuse     2     221.6     110.8     2.88    0.075
Error      24     922.1      38.4
Total      26    1143.7
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
1. Cocoa    3    26.633     4.717         (--------------*--------------)
2. Fallow  18    18.783     6.585   (-----*-----)
3. Forest   6    23.583     5.300       (---------*----------)
                                   ---------+---------+---------+-------
Pooled StDev =    6.198                  20.0      25.0      30.0

Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.0198

Critical value = 3.53

Intervals for (column level mean) - (row level mean)

                 1           2

       2    -1.798
            17.498

       3    -7.890     -12.093
            13.990       2.493
```

F. *T. ivorensis*



Average: 31.7881
StDev: 17.0753
N: 42

Kolmogorov-Smimov Normality Test
D+: 0.163 D-: 0.102 D : 0.163
Approximate P-Value < 0.01

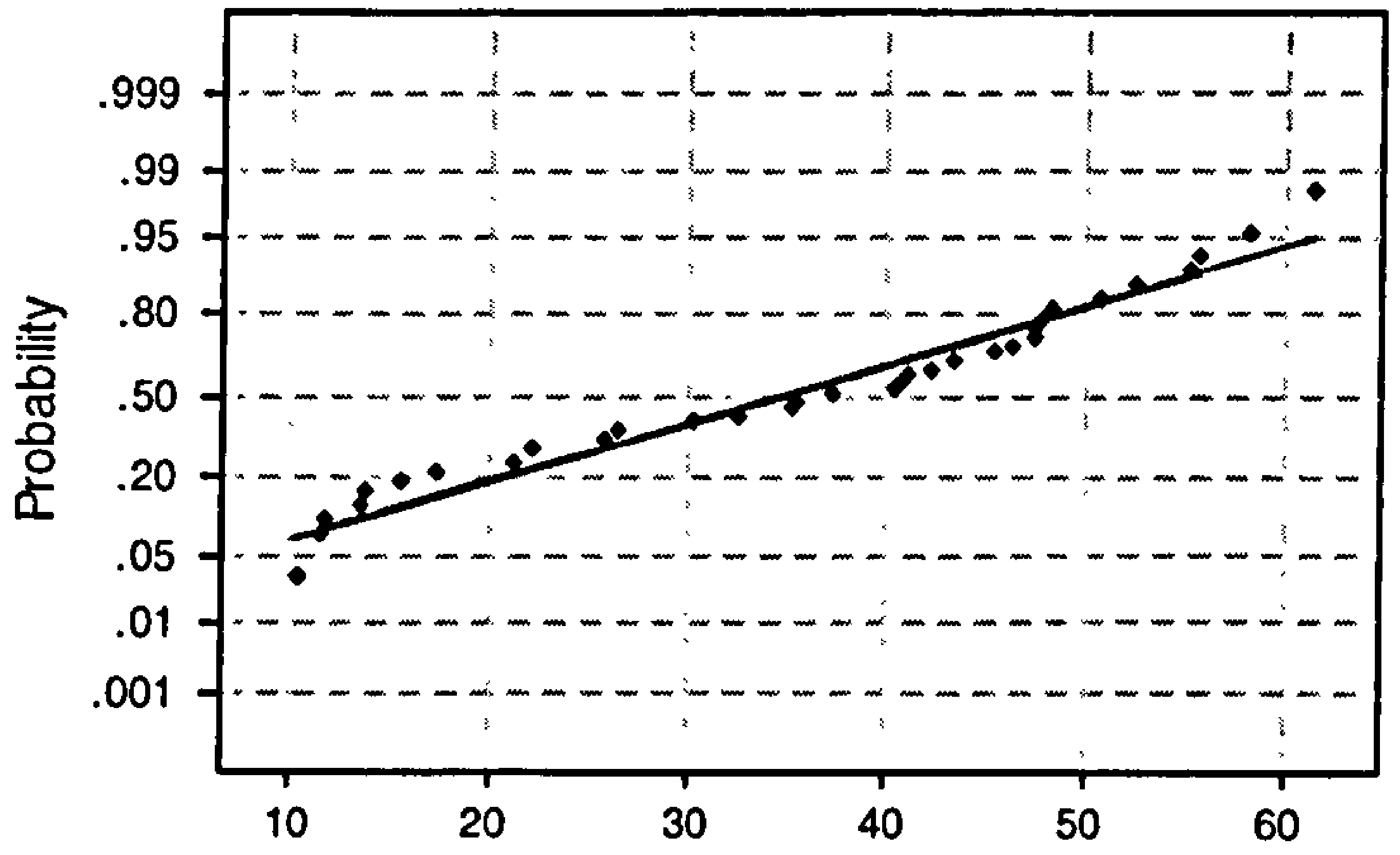
One-way ANOVA: DBH distribution of *T. ivorensis* trees in different Landuse systems

```
Source     DF        SS        MS        F        P
Land typ    2      7432      3716    32.05    0.000
Error      39      4522       116
Total      41     11954
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
Level       N      Mean     StDev   ---------+---------+---------+-------
Cocoa      10     57.41      7.88                        (----*---)
Fallow     19     21.78      9.38   (---*--)
Forest     13     28.55     14.08       (---*---)
                                    ---------+---------+---------+-------
Pooled StDev =    10.77                      30        45        60

Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.0194

Critical value = 3.45

Intervals for (column level mean) - (row level mean)

            Cocoa        Fallow

  Fallow       22.97
               43.49

  Forest       15.41       -16.23
               37.51         2.68
```

Kruskal-Wallis Test: DBH of A. adianthifolia trees in different Land use systems

```
Land typ     N    Median     Ave Rank        Z
Cocoa       10     54.15         36.8     4.50
Fallow      19     19.40         14.8    -3.21
Forest      13     25.90         19.5    -0.69
Overall     42                   21.5

H = 21.43  DF = 2  P = 0.000
H = 21.43  DF = 2  P = 0.000 (adjusted for ties)
```

G. *T. tetraptera*



DBH distribution - T. tetraptera

Average: 34.7229
StDev: 15.7447
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.096 D-: 0.124 D : 0.124
Approximate P-Value > 0.15

One-way ANOVA: DBH distribution of *T. ivorensis* trees in different Landuse systems

```
Source     DF        SS        MS        F        P
Land typ    2       883       442     1.87    0.170
Error      32      7545       236
Total      34      8428
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---+---------+---------+---------+---
Cocoa      10     42.27      5.22                (---------*---------)
Fallow     17     32.98     18.24          (-------*-------)
Forest      8     29.00     16.80   (----------*----------)
                                   ---+---------+---------+---------+---
Pooled StDev =    15.36               20        30        40        50

Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.0194

Critical value = 3.48

Intervals for (column level mean) - (row level mean)

            Cocoa       Fallow

  Fallow      -5.76
              24.35

  Forest      -4.65      -12.22
              31.19       20.18
```

Appendix 4.2. Normal probability plots for adult tree population distribution of shade tree species in different landuse systems in Atwima, Ghana.

A. *Albizia adianthifolia*.

i) Cocoa farm

Average: 0.371429
StDev: 0.843163
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.085 D-: 0.045 D : 0.085
Approximate P-Value > 0.15

ii) Fallow land

Average: 0.685714
StDev: 1.18251
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.152 D-: 0.055 D : 0.152
Approximate P-Value: 0.043

iii) Natural forest.

iv). Analysis of Variance for Population of *A. adianthifolia* in different landuse systems in Atwima, Ghana.

```
Source        DF          SS          MS          F          P
Landuse        2        8.86        4.43       0.47      0.634
Error         18      170.29        9.46
Total         20      179.14
                                     Individual 95% CIs For Mean
                                     Based on Pooled StDev
Level       N      Mean     StDev   ---+---------+---------+---------+---
Cocoa       7     1.857     2.116   (-----------*-----------)
Fallow      7     3.429     4.117           (-----------*-----------)
Forest      7     2.429     2.637      (-----------*-----------)
                                    ---+---------+---------+---------+---
Pooled StDev =    3.076               0.0       2.0       4.0       6.0
```

B. *Entandrophragma angolense*

i) Cocoa farm

Average: 0.171429
StDev: 0 452816
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.090 D-: 0.066 D : 0.090
Approximate P-Value > 0.15

ii) Fallow land

Average: 0.228571
StDev: 0.490241
N: 35

Kolmogorov-Smimov Normality Test
D+: 0.094 D-: 0.071 D : 0.094
Approximate P-Value > 0.15

iii) Natural Forest

Average: 0.314286
StDev: 0.676123
N: 35

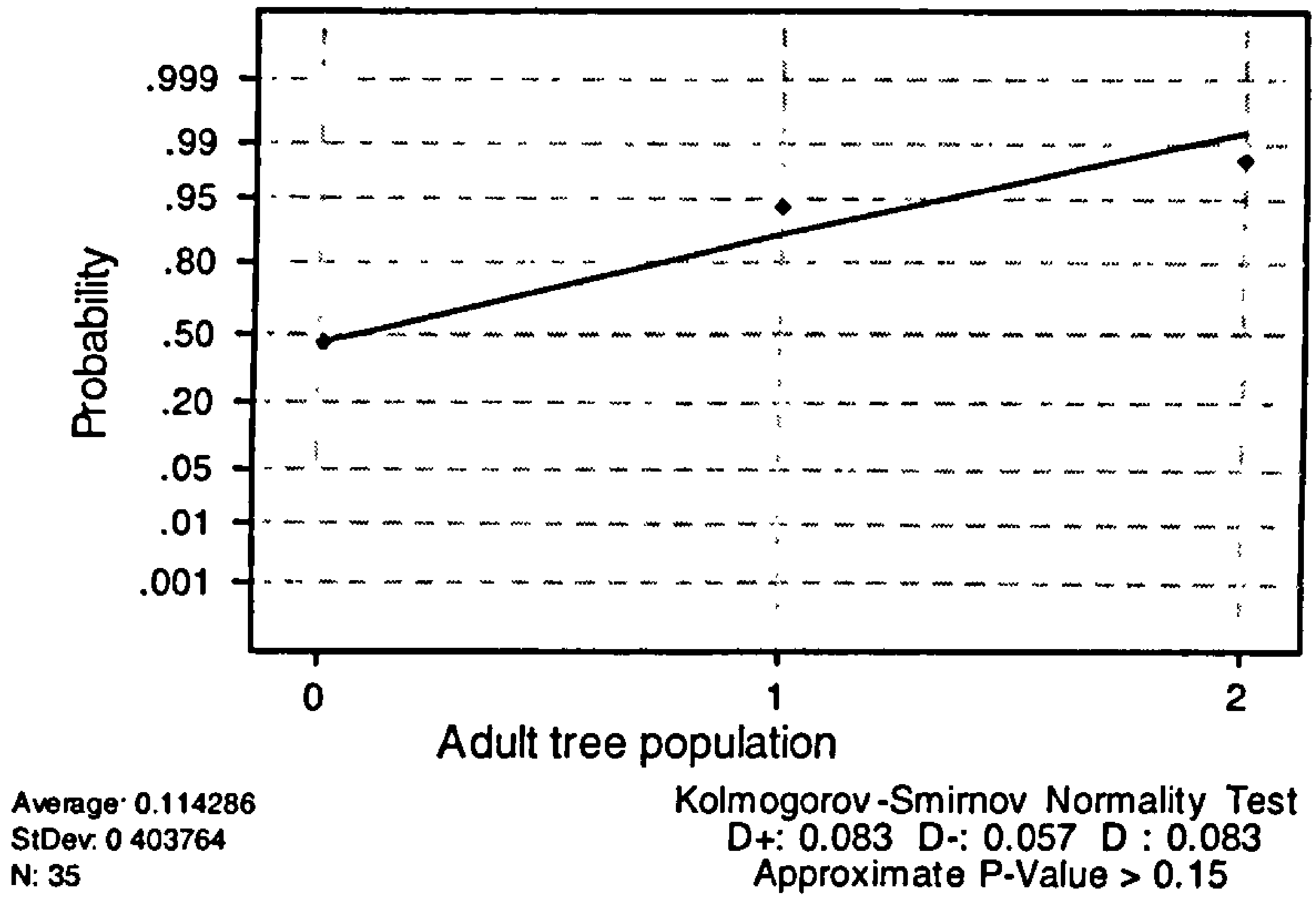
Kolmogorov-Smirnov Normality Test
D+: 0.079 D-: 0.051 D : 0.079
Approximate P-Value > 0.15

iii) Analysis of Variance for adult tree population of *E. angolense* in different landuse systems in Atwima, Ghana.

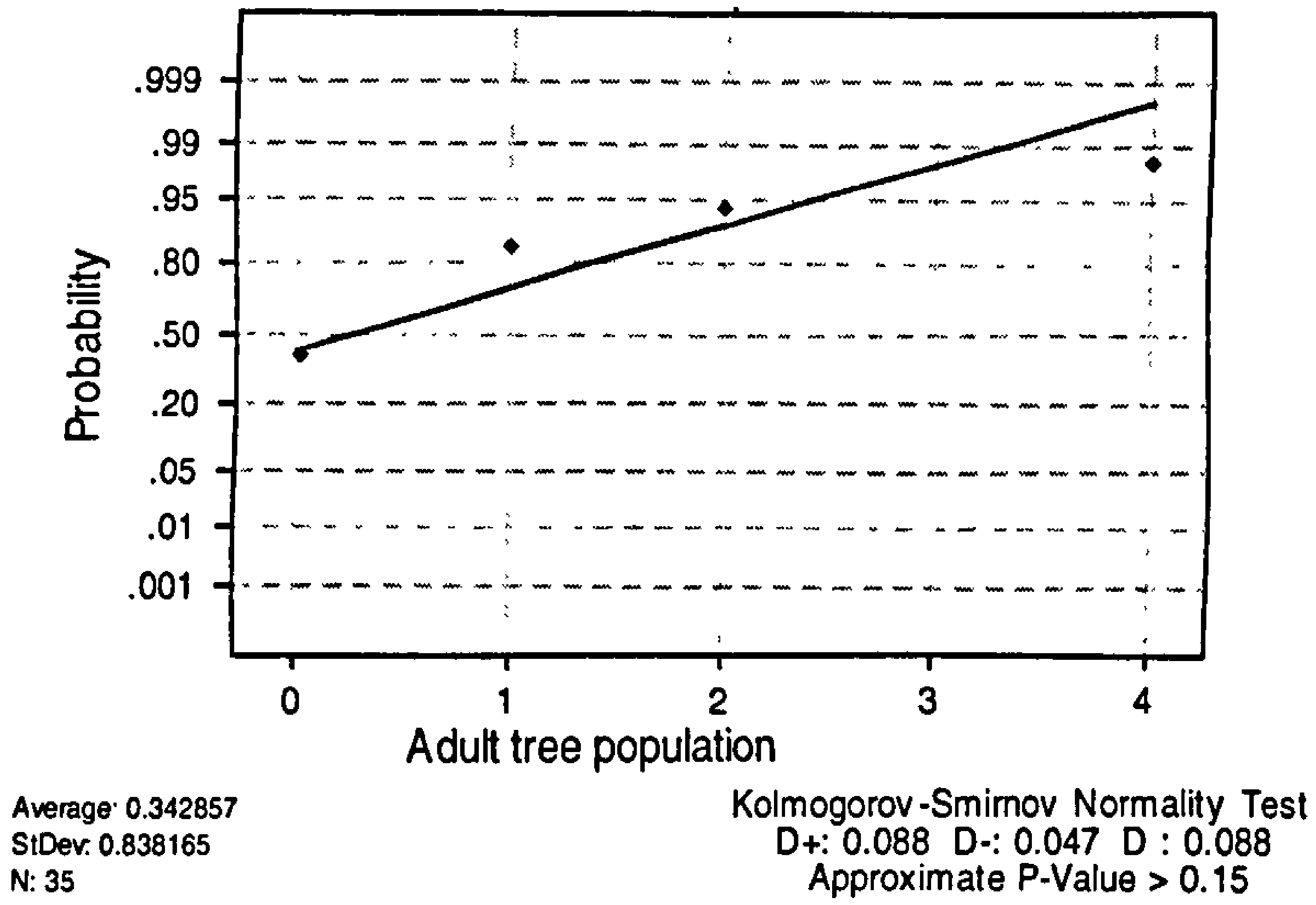
```
Source       DF          SS          MS           F           P
Landuse       2        1.81        0.90        0.55       0.584
Error        18       29.43        1.63
Total        20       31.24
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
1           7     0.857     1.069  (------------*-----------)
2           7     1.143     1.215      (-----------*------------)
3           7     1.571     1.512           (------------*-----------)
                                   --+---------+---------+---------+----
Pooled StDev =    1.279            0.00      0.80      1.60      2.40
```

C. *Entandrophragma utile*

i) Cocoa farm



ii) Fallow land



iii) Natural forest.

Average: 0.228571
StDev: 0.645606
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.081 D-: 0.054 D : 0.081
Approximate P-Value > 0.15

iv) Analysis of Variance for adult tree population of *E. utile* in different landuse systems in Atwima, Ghana.

```
Source        DF         SS          MS          F          P
Landuse        2      0.914       0.457       1.07      0.347
Error        102     43.600       0.427
Total        104     44.514
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
Level        N       Mean     StDev   ------+---------+---------+---------+
1           35     0.1143    0.4038    (----------*----------)
2           35     0.3429    0.8382              (----------*----------)
3           35     0.2286    0.6456         (----------*----------)
                                      ------+---------+---------+---------+
Pooled StDev =     0.6538                  0.00      0.20      0.40      0.60
```

D. *Khaya anthotheca*

i) Cocoa farms

Average: 0.0857143
StDev 0.284029
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.090 D-: 0.056 D : 0.090
Approximate P-Value > 0.15

ii) Fallow land

Average: 0.171429
StDev: 0.513678
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.088 D-: 0.047 D : 0.088
Approximate P-Value > 0.15

iii) Natural forest

Average: 0.142857
StDev: 0.429970
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.087 D-: 0.063 D : 0.087
Approximate P-Value > 0.15

iv) Analysis of Variance for adult tree population of *K. anthotheca* in different landuse systems in Atwima, Ghana.

```
Source      DF        SS        MS        F        P
Landuse      2     0.171     0.086     0.44    0.648
Error      137    26.971     0.197
Total      139    27.143
                                 Individual 95% CIs For Mean
                                 Based on Pooled StDev
Level      N      Mean     StDev  -------+---------+---------+---------
1         35    0.0857    0.2840   (--------------*-------------)
2         70    0.1714    0.5099              (---------*----------)
3         35    0.1429    0.4300        (--------------*--------------)
                                  -------+---------+---------+---------
Pooled StDev =  0.4437                  0.00      0.10      0.20
```

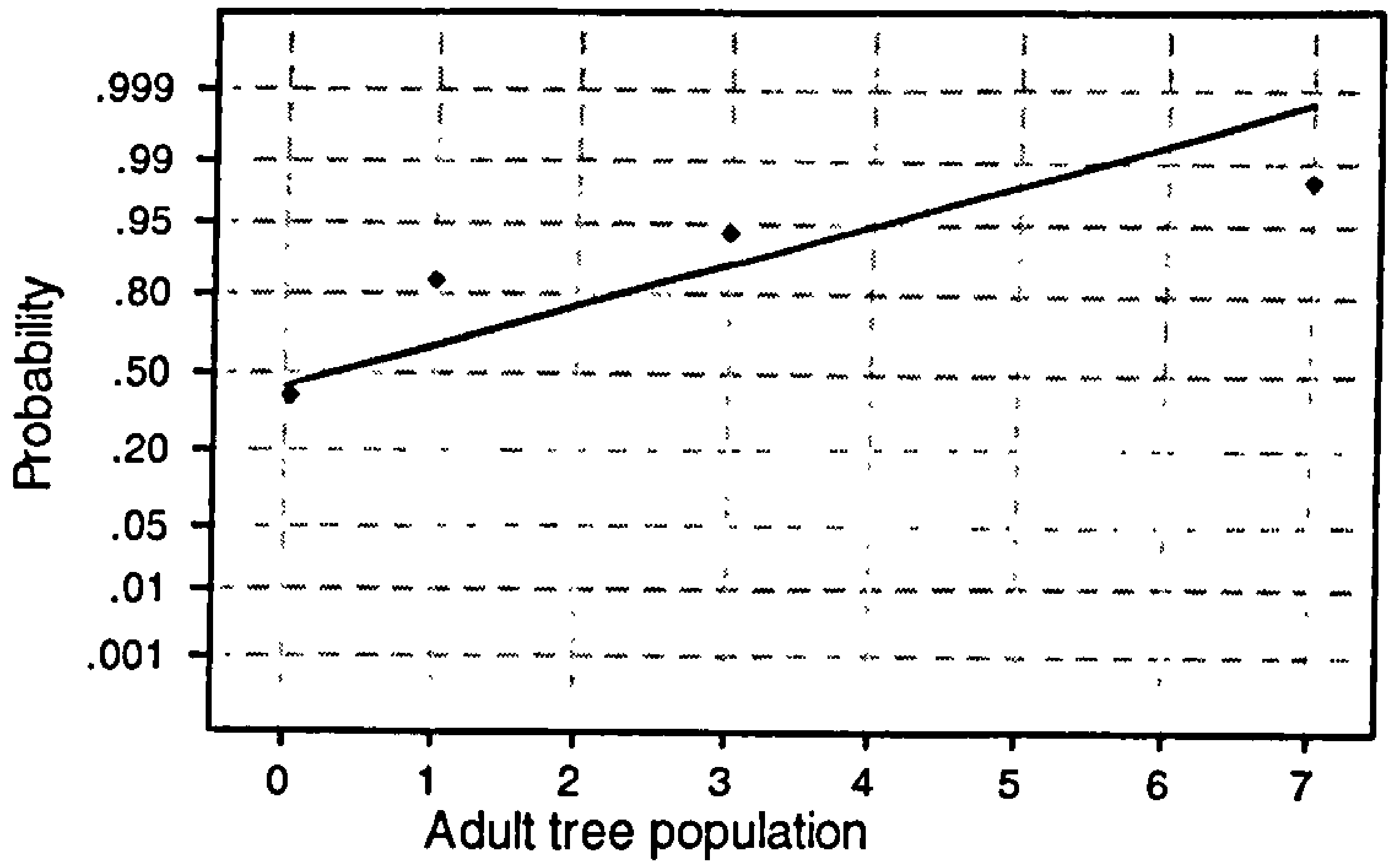
E. *Newbouldia laevis*

i) Cocoa farms

Average: 0.0857143
StDev: 0.373491
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.076 D-: 0.050 D : 0.076
Approximate P-Value > 0.15

ii) Fallow land



Average: 0.514286
StDev: 1.35845
N. 35

Kolmogorov-Smirnov Normality Test
D+: 0.217 D-: 0.038 D : 0.217
Approximate P-Value < 0.01

iii) Natural forest

Average· 0.171429
StDev: 0.568057
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.076 D-: 0.013 D : 0.076
Approximate P-Value > 0.15

iv) Analysis of Variance for adult tree population of *N. laevis* in different landuse systems in Atwima, Ghana.

```
Source      DF        SS         MS        F        P
Landuse      2     3.600      1.800     2.34    0.101
Error      102    78.457      0.769
Total      104    82.057
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
1          35    0.0857    0.3735  (---------*---------)
2          35    0.5143    1.3584               (---------*---------)
3          35    0.1714    0.5681    (---------*---------)
                                   -------+---------+---------+---------
Pooled StDev =   0.8770                  0.00      0.30      0.60
```

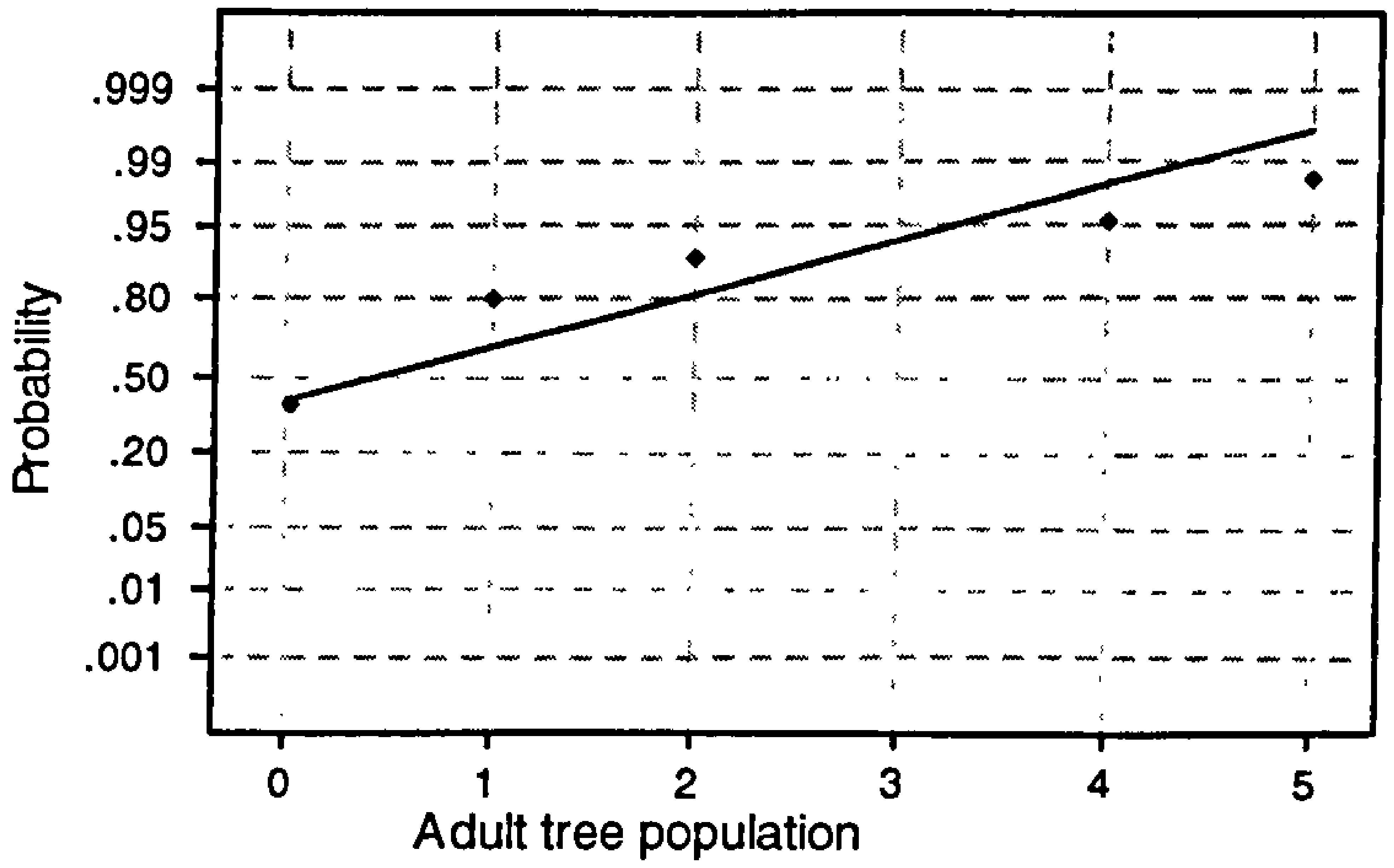
F. *Terminalia ivorensis*

i) Cocoa farms

Average: 0.285714
StDev: 0.667367
N: 35

Kolmogorov-Smimov Normality Test
D+: 0.080 D-: 0.052 D : 0.080
Approximate P-Value > 0.15

ii) Fallow land



Average: 0.542857
StDev: 1.17180
N: 35

Kolmogorov-Smimov Normality Test
D+: 0.163 D-: 0.056 D : 0.163
Approximate P-Value: 0.028

iii) Natural forest

```
Average: 0.371429
StDev: 0.807528
N: 35
```

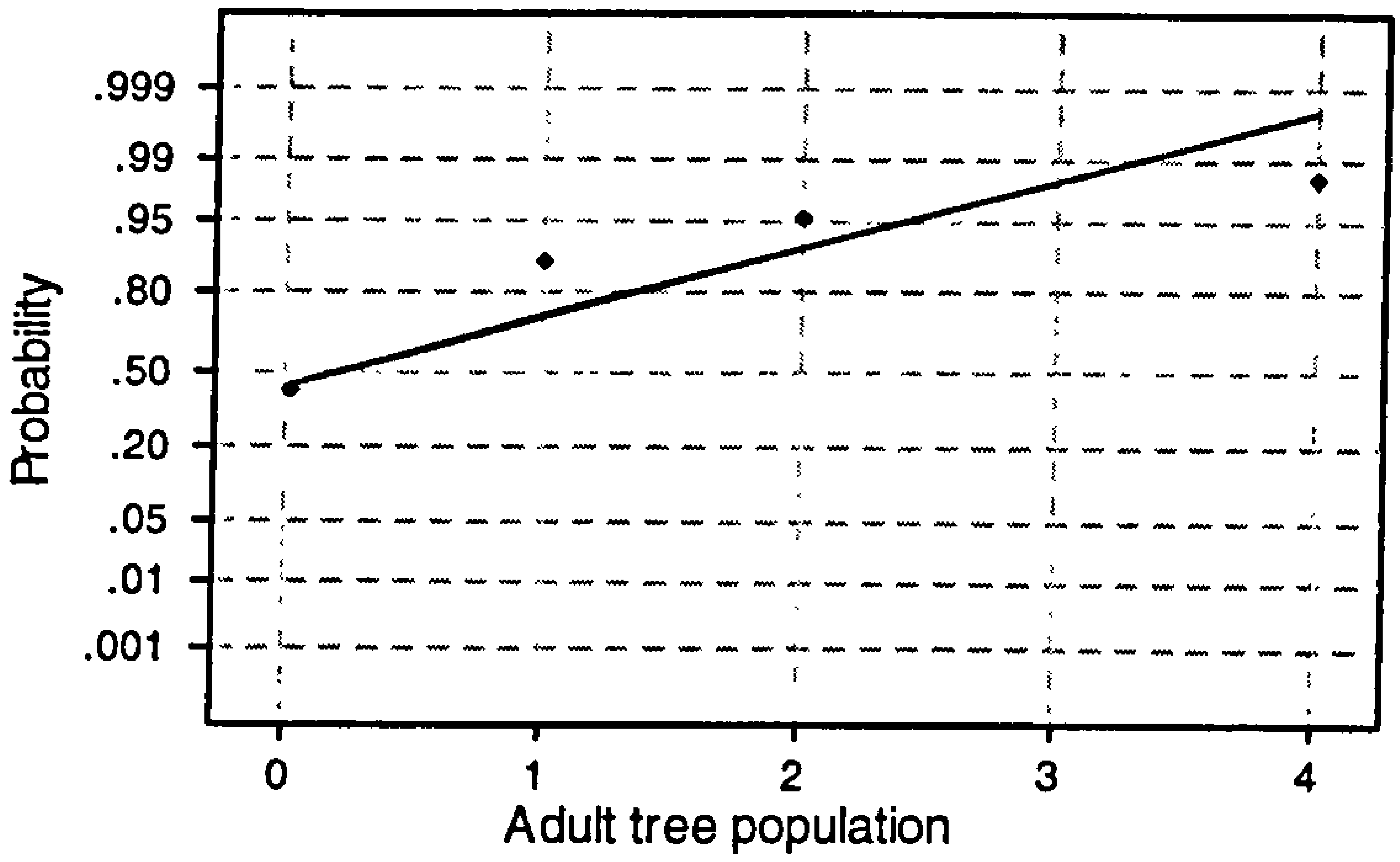
```
Kolmogorov-Smirnov Normality Test
D+: 0.077  D-: 0.064  D : 0.077
Approximate P-Value > 0.15
```

iv) Analysis of Variance for adult tree population of *T. ivorensis* in different landuse systems in Atwima, Ghana.

```
Source      DF        SS         MS        F        P
Landuse      2     1.200      0.600     0.73    0.485
Error      102    84.000      0.824
Total      104    85.200
                                 Individual 95% CIs For Mean
                                 Based on Pooled StDev
Level      N      Mean    StDev  -+---------+---------+---------+-----
1         35    0.2857   0.6674  (-----------*------------)
2         35    0.5429   1.1718            (-----------*-----------)
3         35    0.3714   0.8075       (-----------*-----------)
                                 -+---------+---------+---------+-----
Pooled StDev =  0.9075          0.00      0.25      0.50      0.75
```

G. *Tetrapleura tetraptera*

i) Cocoa farms



Average: 0.285714
StDev: 0.788574
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.083 D-: 0.042 D : 0.083
Approximate P-Value > 0.15

ii) Fallow land

Average: 0.485714
StDev: 0.919444
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.102 D-: 0.065 D : 0.102
Approximate P-Value > 0.15

iii) Natural forest

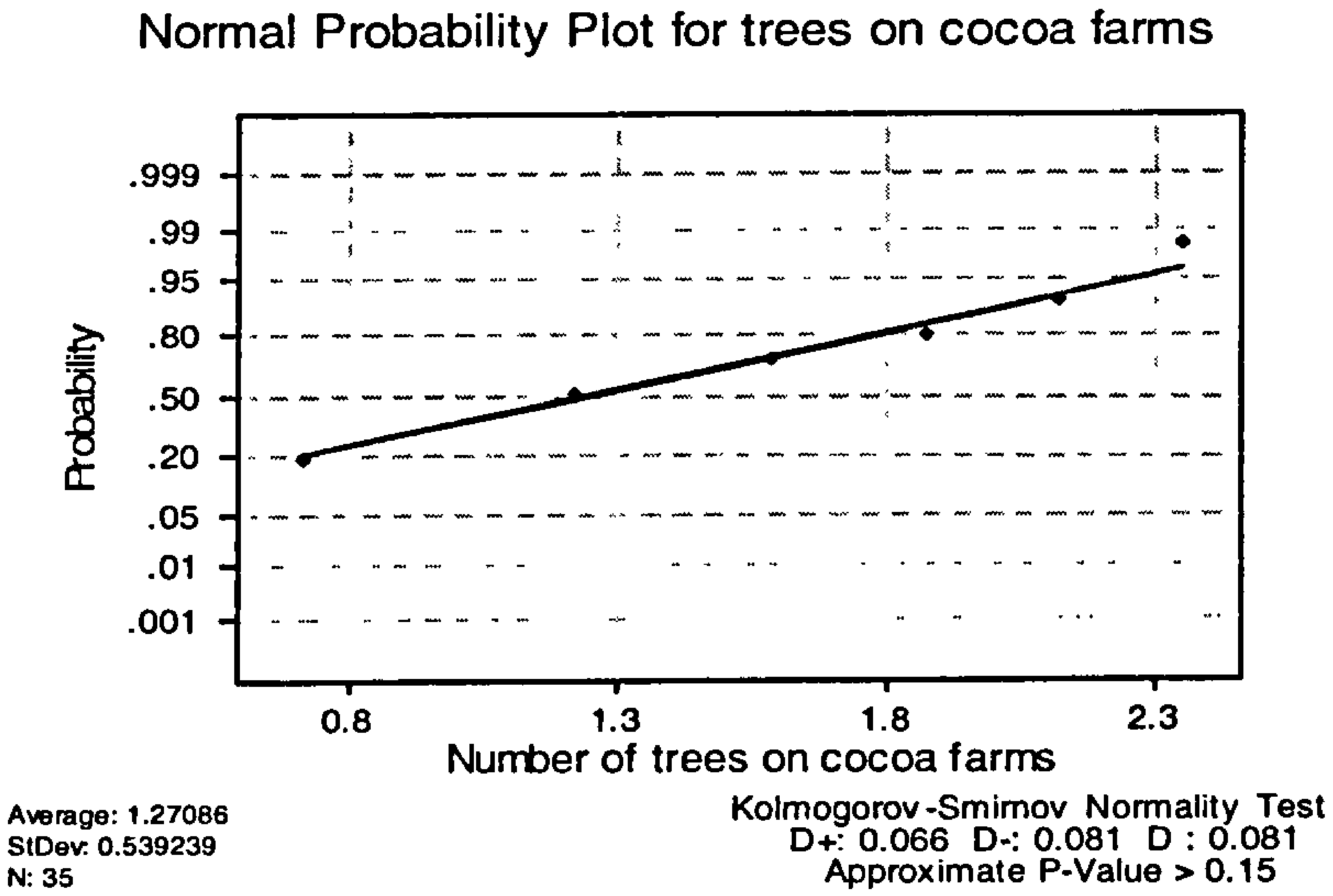
Average: 0.228571
StDev: 0.490241
N. 35

Kolmogorov-Smirnov Normality Test
D+: 0.094 D-: 0.071 D : 0.094
Approximate P-Value > 0.15

iv) Analysis of Variance for adult tree population of *T. tetraptera* in different landuse systems in Atwima, Ghana.

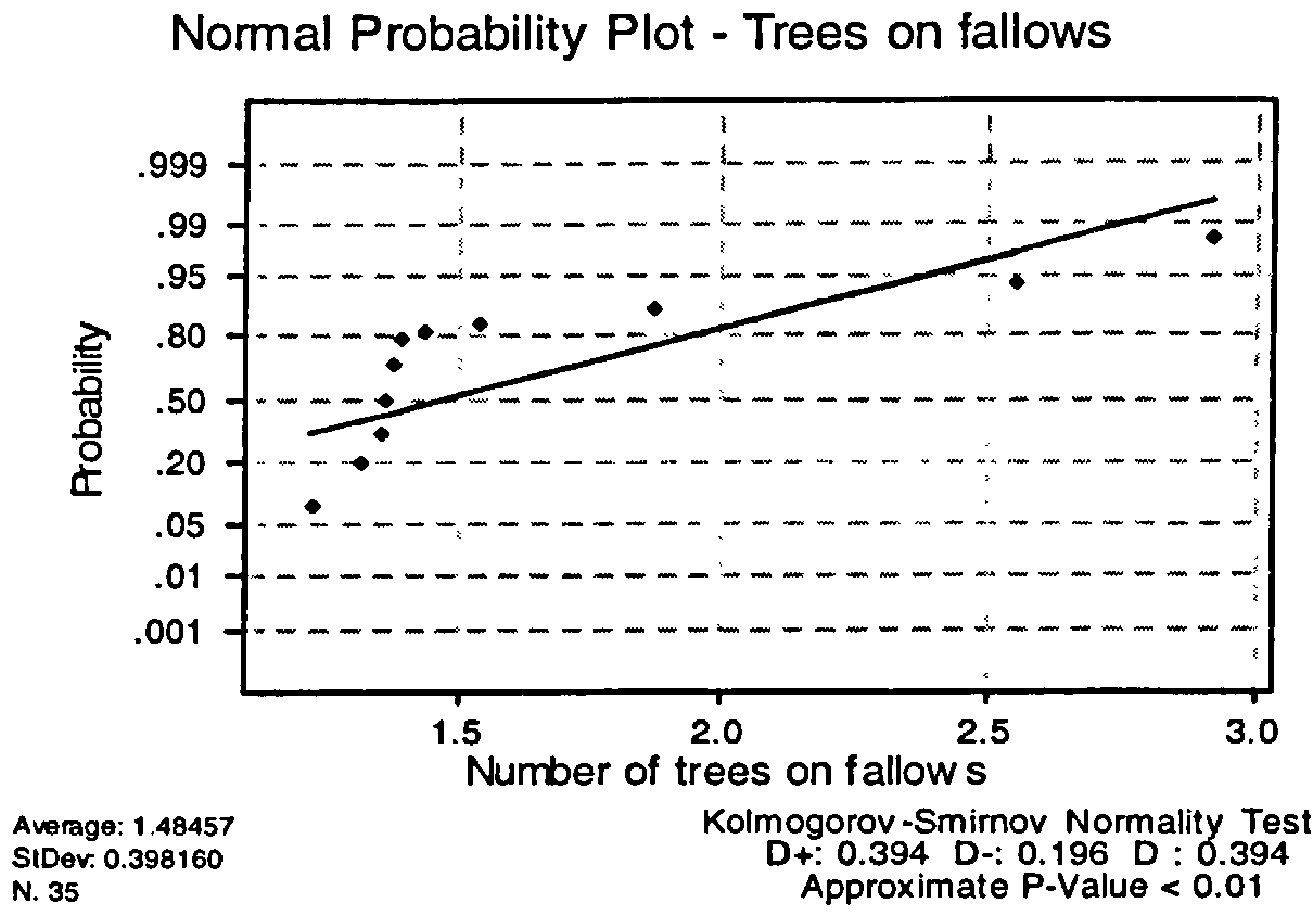
```
Source      DF        SS        MS        F        P
Landuse      2     1.276     0.638     1.12    0.330
Error      102    58.057     0.569
Total      104    59.333
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -+---------+---------+---------+-----
1          35    0.2857    0.7886    (---------*----------)
2          35    0.4857    0.9194            (---------*----------)
3          35    0.2286    0.4902  (---------*---------)
                                   -+---------+---------+---------+-----
Pooled StDev =   0.7544           0.00      0.25      0.50      0.75
```

Appendix 4.3: Statistical analysis of density of shade tree species in the different landuse systems in Atwima.



One-way ANOVA: Number of individuals versus Tree species on Cocoa farms

```
Analysis of Variance for Number o
Source     DF        SS        MS        F        P
Tree spe    6     3.021     0.503     2.05    0.092
Error      28     6.866     0.245
Total      34     9.886
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----------+---------+---------+------
1           5    1.7320    0.3442                 (--------*--------)
2           5    1.1400    0.7115     (--------*--------)
3           5    0.9920    0.6306  (--------*--------)
4           5    0.9860    0.3988  (--------*--------)
5           5    0.9860    0.3988  (--------*--------)
6           5    1.5300    0.4336            (--------*--------)
7           5    1.5300    0.4336            (--------*--------)
                                   ----------+---------+---------+------
Pooled StDev =    0.4952                   1.00      1.50      2.00
```

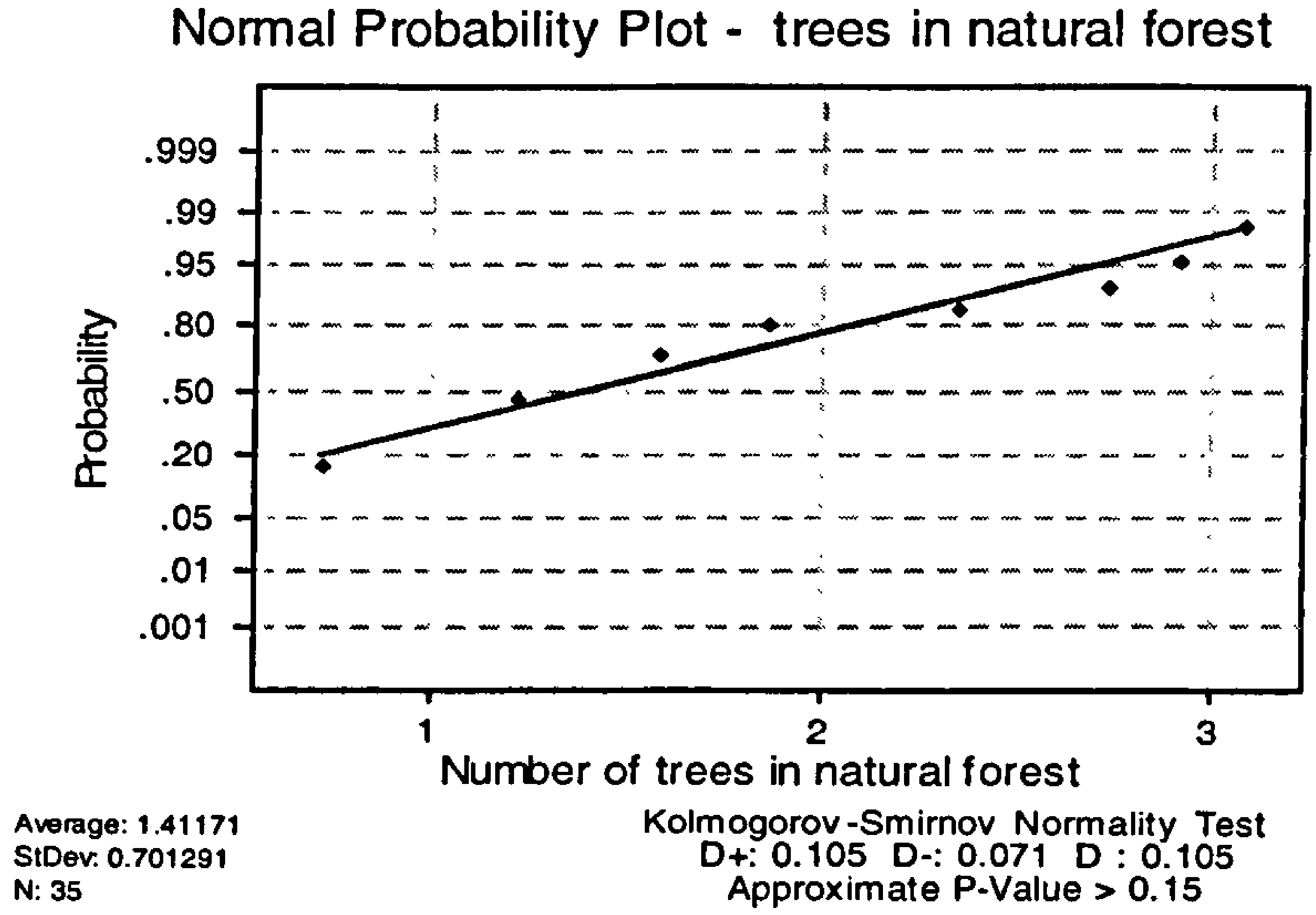


One-way ANOVA: Number of individuals versus Tree species on Fallows

```
Analysis of Variance for Number o
Source      DF        SS        MS        F        P
Tree spe     6    3.1735    0.5289     6.68    0.058
Error       28    2.2165    0.0792
Total       34    5.3901
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev   ---+---------+---------+---------+---
1            5    2.2220    0.6764                        (------*-----)
2            5    1.3500    0.2907   (------*-----)
3            5    1.3560    0.1029   (------*-----)
4            5    1.3660    0.0358    (-----*------)
5            5    1.3660    0.0134    (-----*------)
6            5    1.3620    0.0045    (-----*-----)
7            5    1.3700    0.0000    (-----*------)
                                     ---+---------+---------+---------+---
Pooled StDev =    0.2814                1.20      1.60      2.00      2.40
```

Kruskal-Wallis Test: Number of individuals versus Tree species on fallows

```
Kruskal-Wallis Test on Number o

Tree spe      N    Median    Ave Rank        Z
1             5     2.550        27.3     2.19
2             5     1.220         8.7    -2.19
3             5     1.310        12.0    -1.41
4             5     1.350        15.0    -0.71
5             5     1.360        19.6     0.38
6             5     1.360        18.9     0.21
7             5     1.370        24.5     1.53
Overall      35                  18.0

H = 12.55  DF = 6  P = 0.051
H = 12.84  DF = 6  P = 0.050 (adjusted for ties)
```

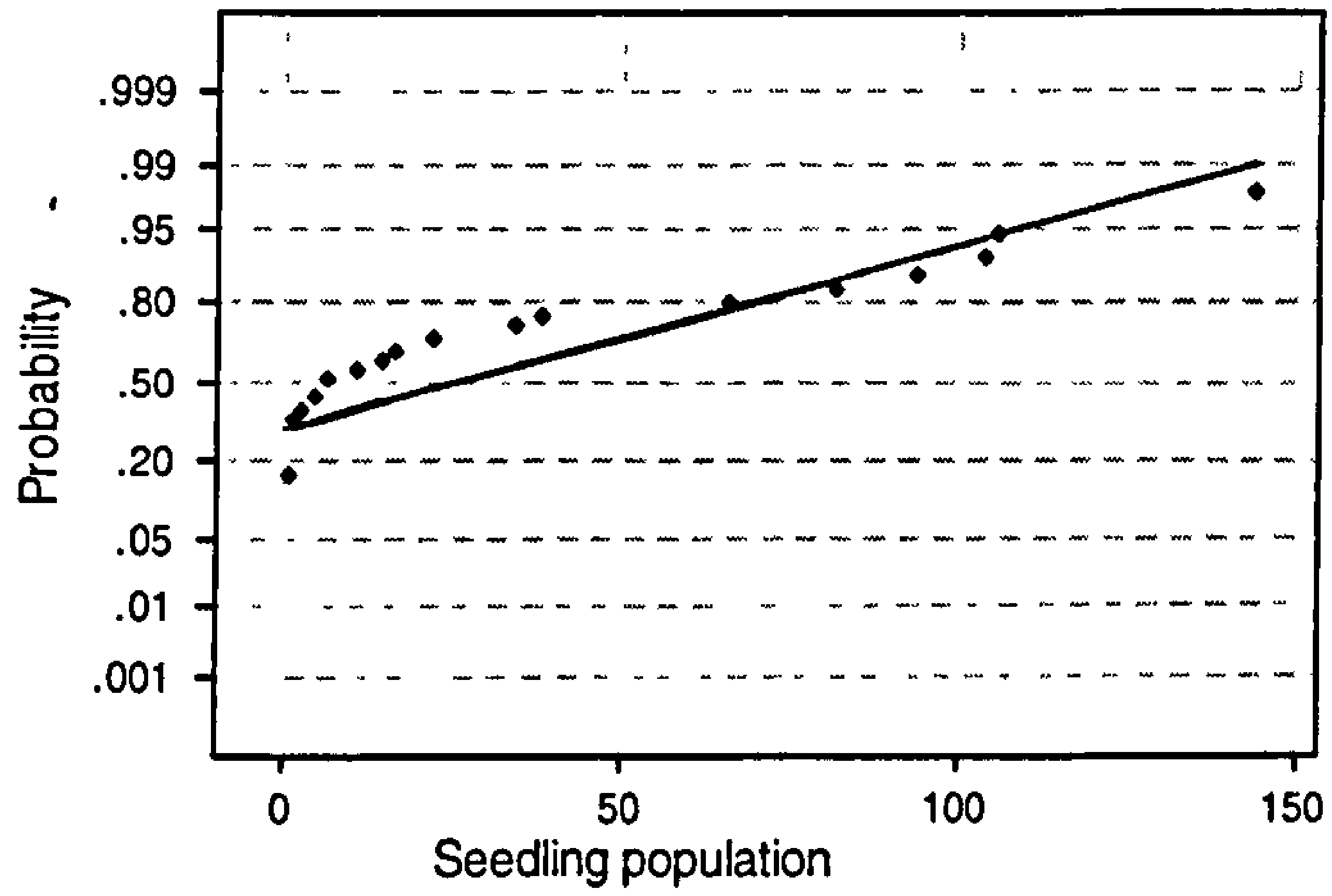


One-way ANOVA: Number of individuals versus Tree species in natural forest

```
Analysis of Variance for Number o
Source     DF        SS        MS        F        P
Tree spe    6     2.472     0.412     0.81    0.571
Error      28    14.250     0.509
Total      34    16.721
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
Level       N      Mean     StDev   ----+---------+---------+---------+--
1           5    1.8660    0.7167                (----------*----------)
2           5    1.4280    0.9115          (----------*----------)
3           5    1.3200    0.8338        (----------*----------)
4           5    1.0380    0.7334   (----------*----------)
5           5    1.1400    0.7115     (----------*----------)
6           5    1.6680    0.6257             (----------*----------)
7           5    1.4220    0.2950          (----------*----------)
                                    ----+---------+---------+---------+--
Pooled StDev =    0.7134              0.60      1.20      1.80      2.40
```

Appendix 4.4: Normal probability plot for seedling population density in different landuse systems in Atwima, Ghana.

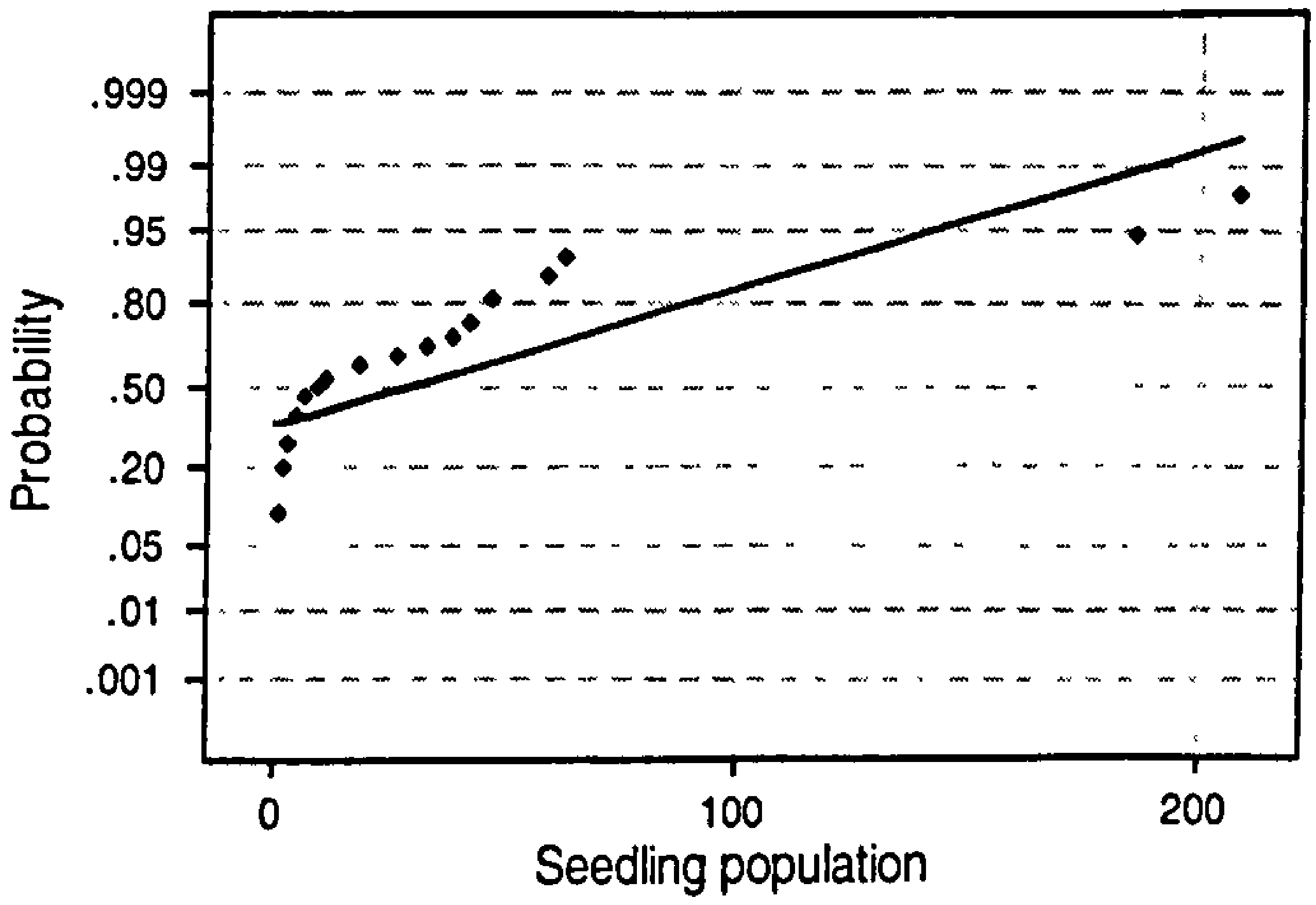
A. Normal probability plot for seedling population density on cocoa farms



Average: 27.6786
StDev: 41.0429
N: 28

Kolmogorov-Smirnov Normality Test
D+: 0.255 D-: 0.107 D : 0.255
Approximate P-Value < 0.01

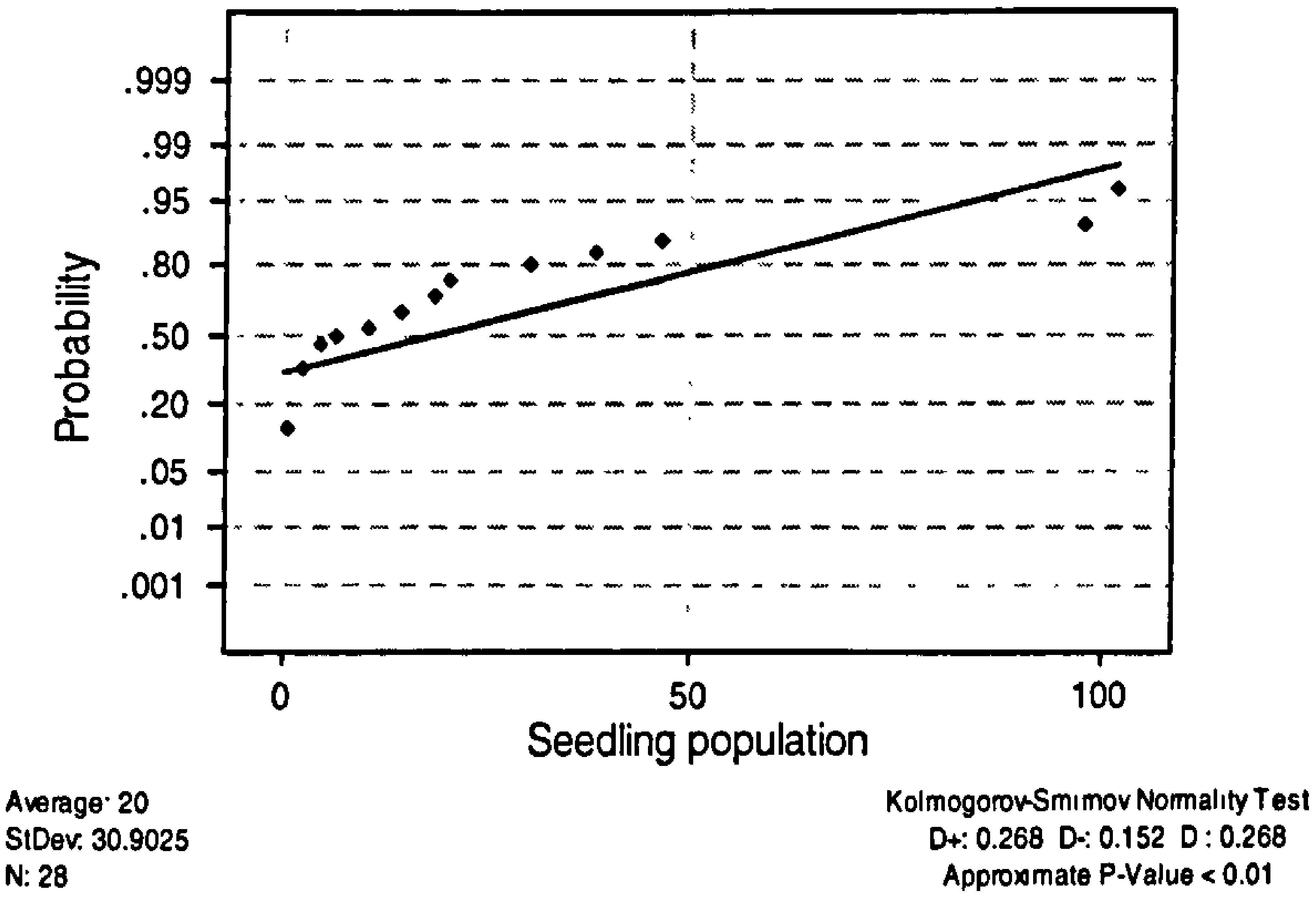
B. Normal probability plot for seedling population distribution in fallows



Average: 30.6071
StDev: 51.0725
N: 28

Kolmogorov-Smirnov Normality Test
D+: 0.221 D-: 0.203 D : 0.221
Approximate P-Value < 0.01

C. Normal probability plot for seedling distribution in natural forest



Kruskal-Wallis Test: Seedling population versus Tree species

```
Kruskal-Wallis Test on Seedling Population verses Tree Species

Tree spe     N     Median    Ave Rank        Z
11           3    62.5000        17.7     2.01
12           3     4.5000         7.7    -1.01
13           3     5.5000         9.3    -0.50
14           3     1.5000         4.0    -2.11
15           3     0.7100         8.0    -0.90
16           3    50.0000        17.0     1.81
17           3    19.0000        13.3     0.70
Overall     21                   11.0

H = 12.29  DF = 6  P = 0.056
H = 12.30  DF = 6  P = 0.056 (adjusted for ties)
```

1 = *Albizia adianthifolia*; 2 = *E. angolense*; 3 = *E. utile*;
4 = *K. anthotheca*; 5 = *N. laevis*; 6 = *T. ivorensis*;
7 = *T. tetraptera*.

Kruskal-Wallis Test: Seedling population versus Landuse

```
Kruskal-Wallis Test on Seedling Population verses Landuse system

Landuse      N     Median    Ave Rank        Z
1            7      5.500        10.6    -0.19
2            7     21.000        11.9     0.45
3            7      8.500        10.5    -0.26
Overall     21                   11.0

H = 0.20  DF = 2  P = 0.904
H = 0.20  DF = 2  P = 0.904 (adjusted for ties)
```

General Linear Model: Seedling Population versus Landuse, Tree species

```
Factor          Type      Levels     Values
Landuse         fixed       3         1 2 3
Tree species    random      7        11 12 13 14 15 16 17


Analysis of Variance for Seedling Population, using Adjusted SS for Tests

Source          DF      Seq SS     Adj SS      Adj MS       F        P
Landuse          2         355        355         177    0.16    0.858
Tree species     6       10509      10509        1752    1.54    0.247
Error           12       13669      13669        1139
Total           20       24533
```

D. Normal probability plot for sapling distribution on cocoa farms

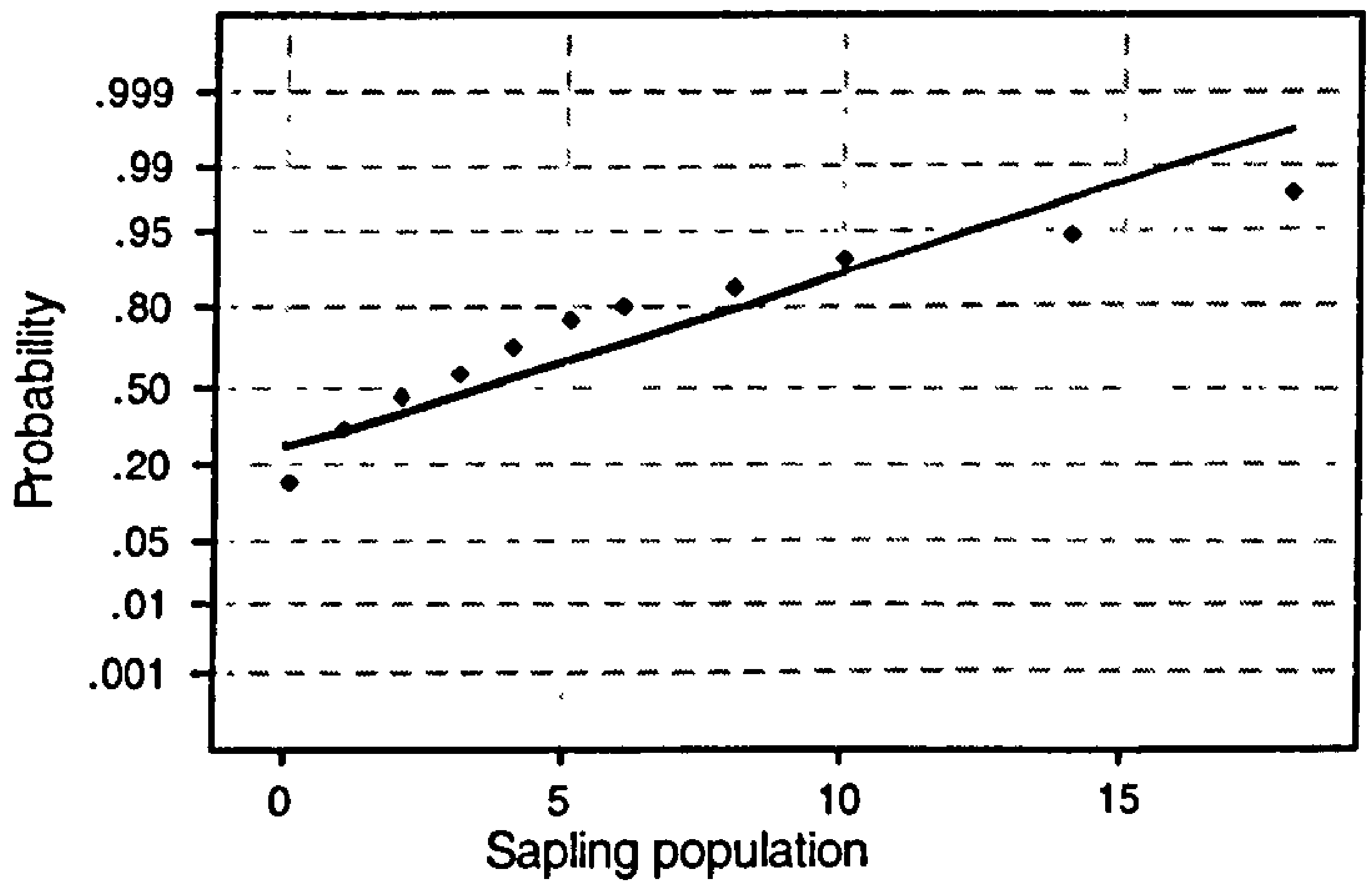
```
Average: 1.78571                 Kolmogorov-Smirnov Normality Test
StDev: 2.40920                      D+: 0.181  D-: 0.085  D : 0.181
N: 28                                     Approximate P-Value: 0.027
```

E. Normal probability plot for sapling distribution on fallows

Average: 8.21429
StDev: 9.42556
N: 28

Kolmogorov-Smirnov Normality Test
D+: 0.169 D-: 0.138 D : 0.169
Approximate P-Value: 0.044

F. Normal probability plot for sapling distribution in the natural forest.



Average: 3.71429
StDev: 4.44603
N: 28

Kolmogorov-Smirnov Normality Test
D+: 0.172 D-: 0.077 D : 0.172
Approximate P-Value: 0.040

One-way ANOVA: Sapling Population versus Tree species

```
Analysis of Variance for Populati
Source          DF        SS          MS          F         P
Tree species     6      6.220       1.037       1.05     0.434
Error           14     13.784       0.985
Total           20     20.003
```

One-way ANOVA: Sapling Population versus Landuse

```
Analysis of Variance
Source       DF        SS         MS         F        P
Factor        1     0.000      0.000      0.00    0.984
Error        40    34.003      0.850
Total        41    34.003
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level          N      Mean      StDev  -------+---------+---------+---------
Population    21    2.0057     1.0001    (---------------*---------------)
Landuse       21    2.0000     0.8367    (---------------*---------------)
                                       -------+---------+---------+---------
Pooled StDev =    0.9220                    1.75      2.00      2.25
```

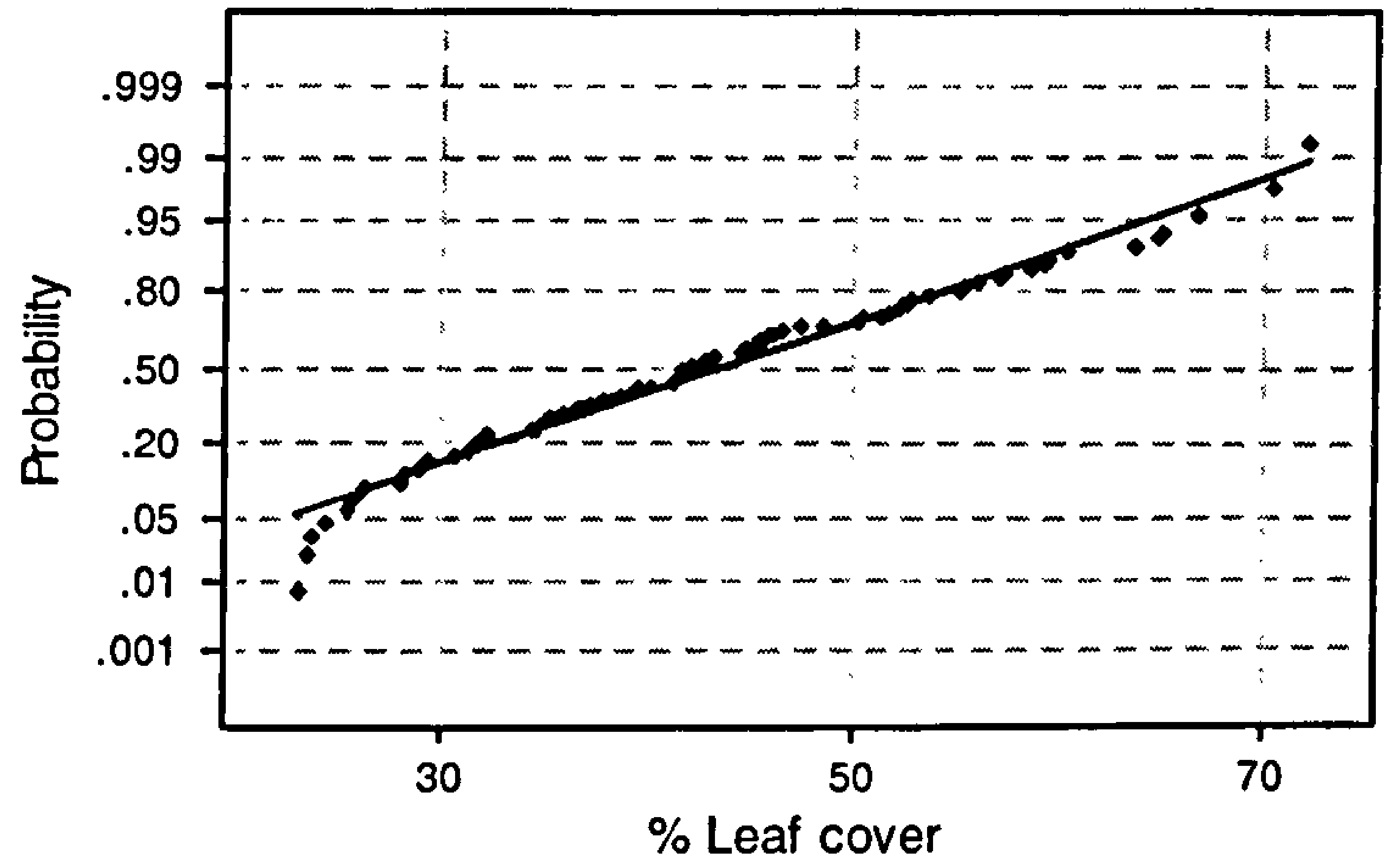
General Linear Model: Population versus Landuse, Tree species

```
Factor      Type Levels Values
Landuse    fixed      3 1 2 3
Tree spe random       7 11 12 13 14 15 16 17

Analysis of Variance for Sapling Population, using Adjusted SS for Tests

Source         DF     Seq SS     Adj SS     Adj MS       F       P
Landuse         2     4.8642     4.8642     2.4321    3.27   0.073
Tree species    6     6.2196     6.2196     1.0366    1.39   0.293
Error          12     8.9193     8.9193     0.7433
Total          20    20.0031
```

1 = *Albizia adianthifolia*; 2 = *E. angolense*; 3 = *E. utile*;
4 = *K. anthotheca*; 5 = *N. laevis*; 6 = *T. ivorensis*;
7 = *T. tetraptera*.

Appendix 5.1: Normal probability plots for phenological patterns of selected cocoa shade tree species in the Atwima district of Ghana.

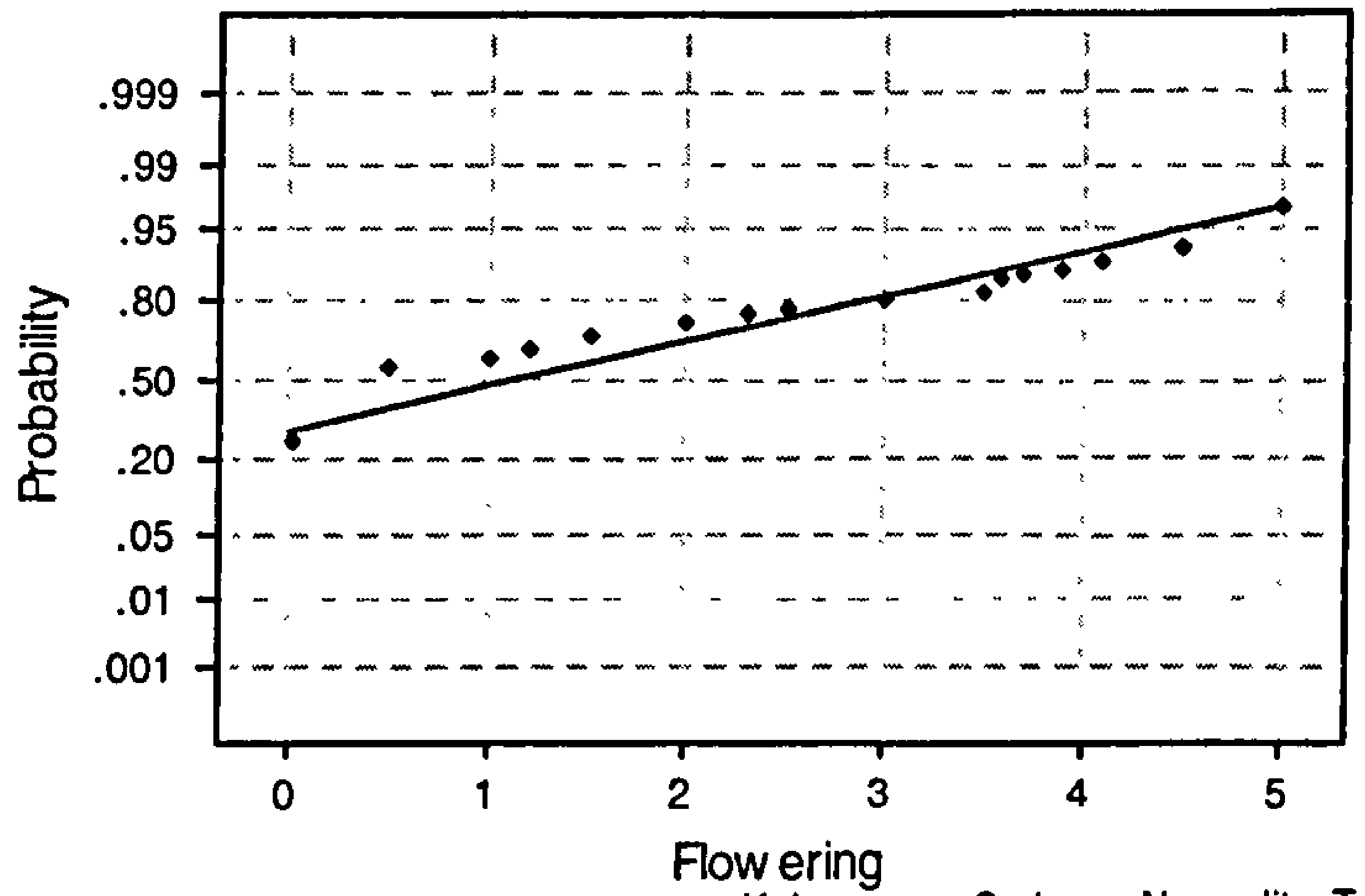
A. Normal probability plot for leafing phenology of cocoa shade tree species.



Average: 43.4048
StDev: 12.4831
N: 84

Kolmogorov-Smirnov Normality Test
D+: 0.076 D-: 0.049 D : 0.076
Approximate P-Value > 0.15

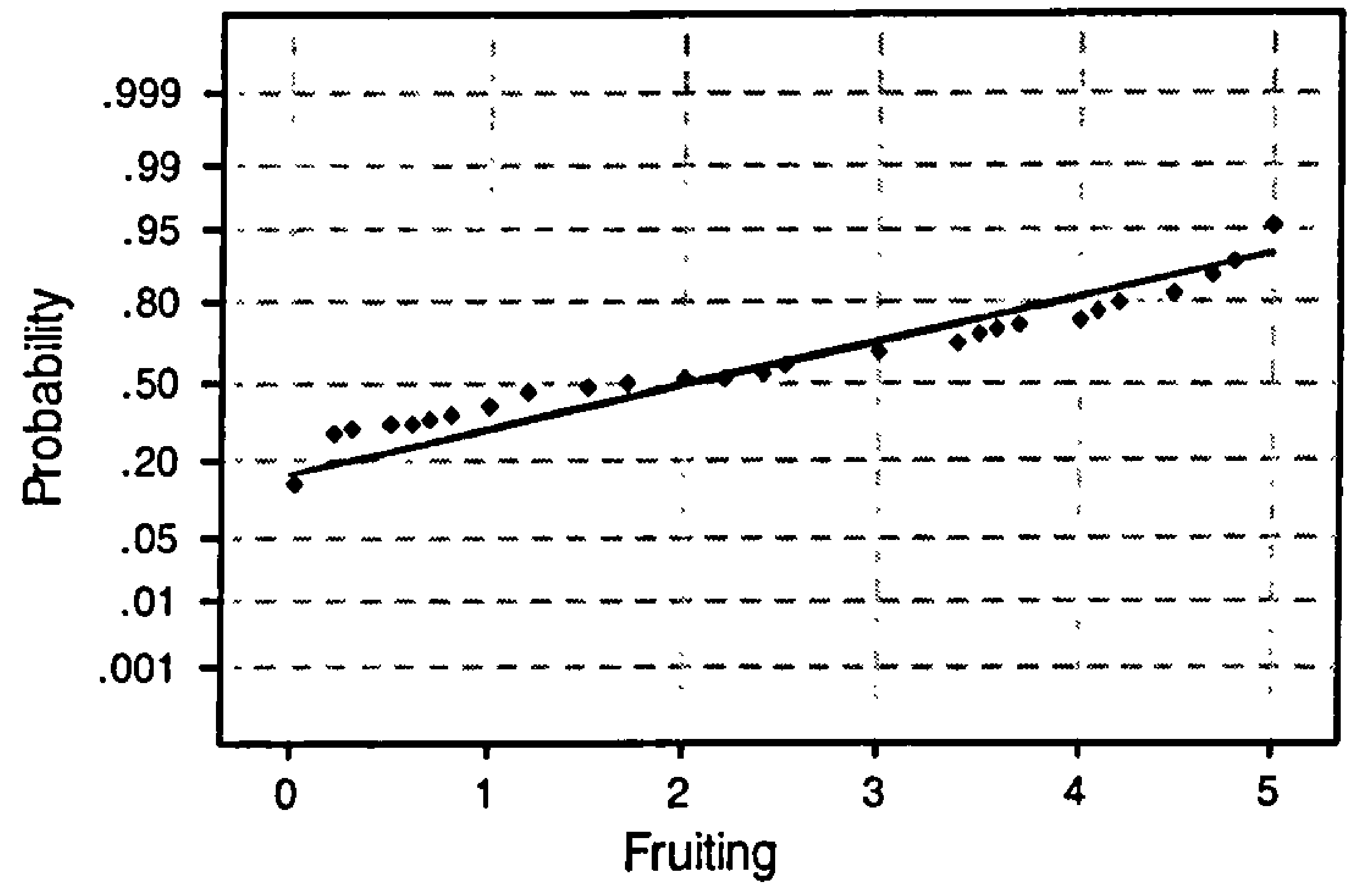
B. Normal probability plot for flowering phenology of cocoa shade tree species.



Average: 1.24405
StDev: 1.66497
N: 84

Kolmogorov-Smirnov Normality Test
D+: 0.220 D-: 0.085 D : 0.220
Approximate P-Value < 0.01

C. Normal probability plot for fruiting phenology of cocoa shade tree species.

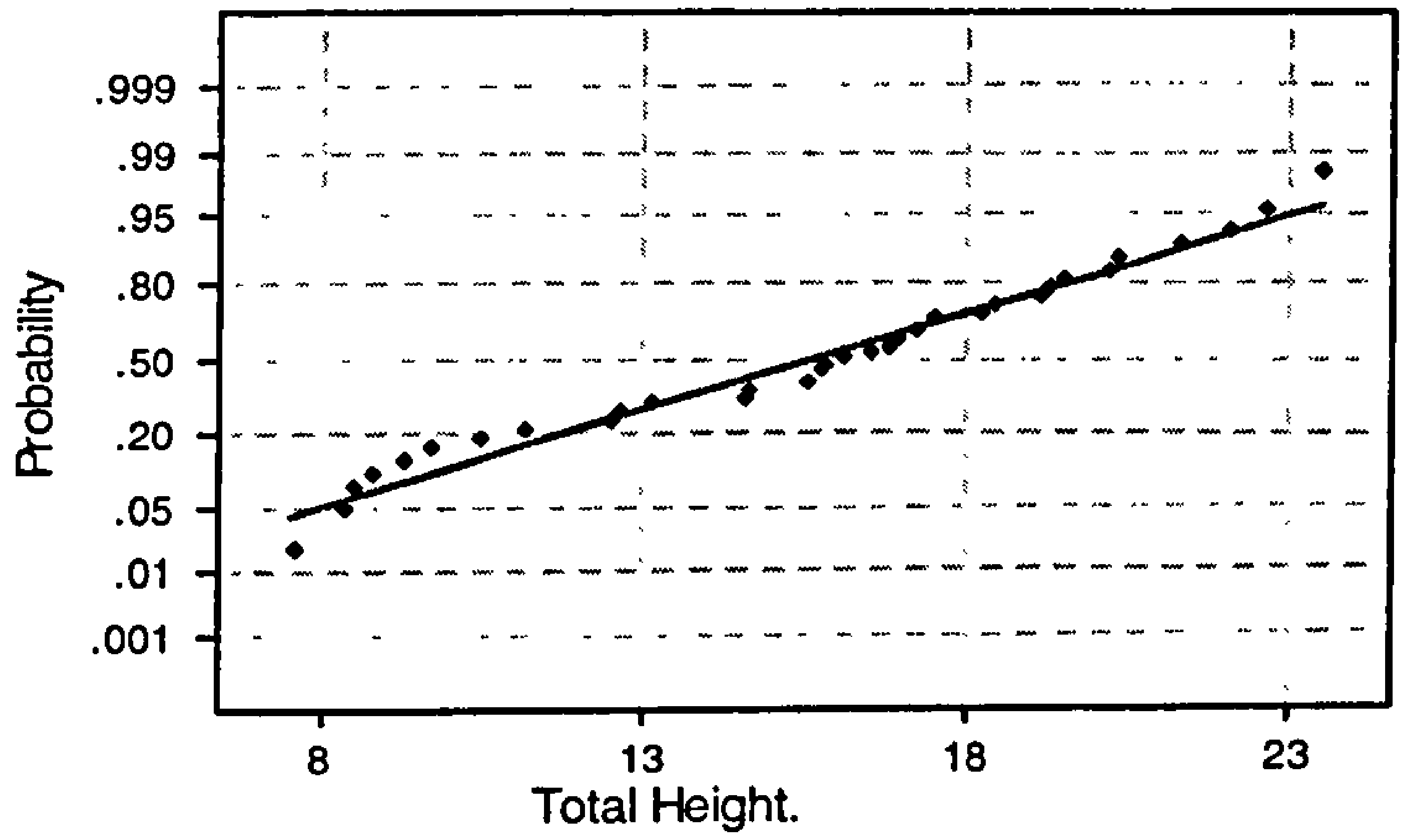


Average: 2.11905
StDev: 1.87060
N: 84

Kolmogorov-Smirnov Normality Test
D+: 0.141 D-: 0.099 D : 0.141
Approximate P-Value < 0.01

Appendix 5.2: Normal probability plots for crown characteristics of selected cocoa shade tree species growing on fallows in Bontomuruso Atwima district.

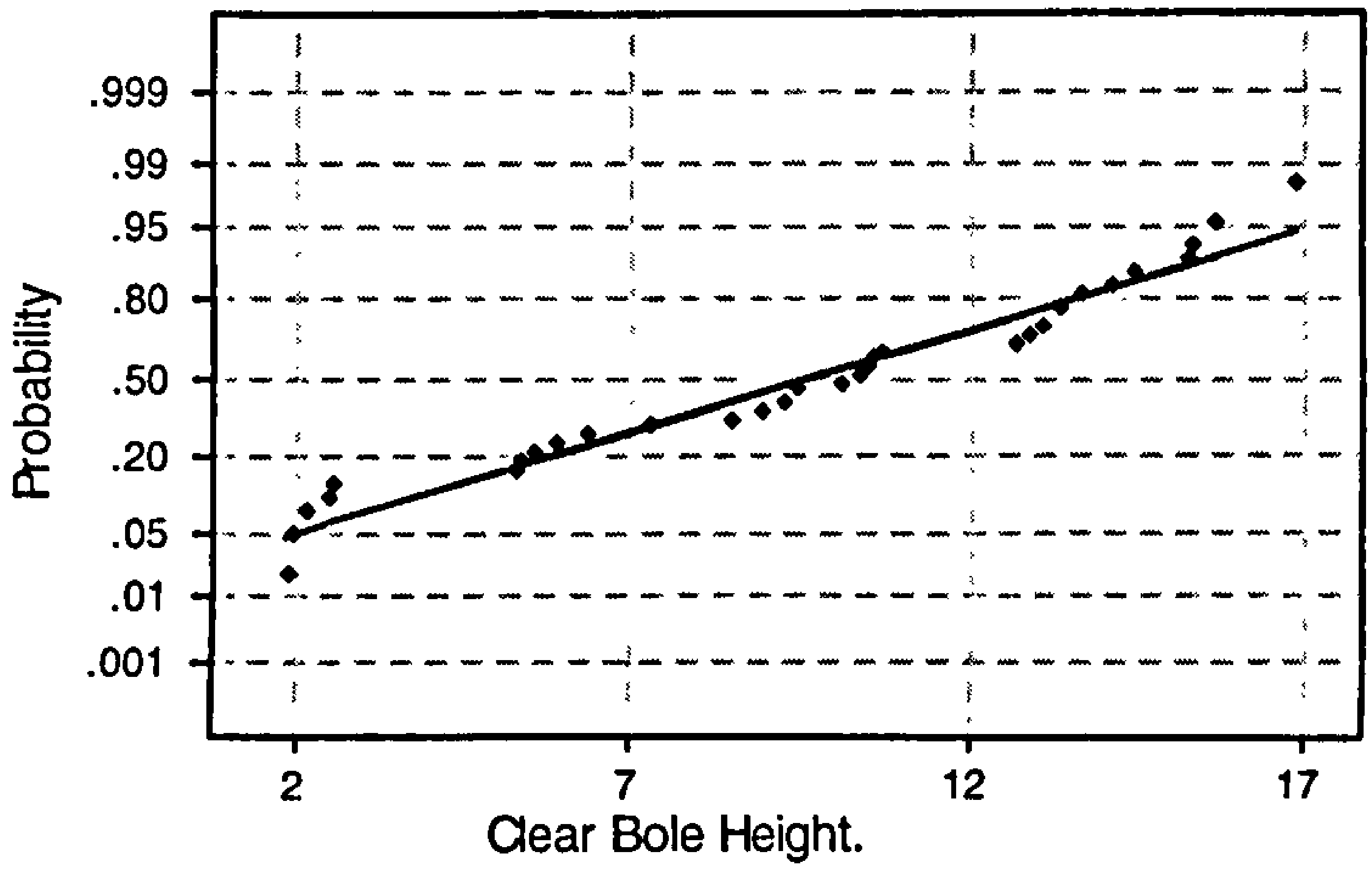
A. Normal Probabilty Plot for total Height of Shade trees



Average: 15 5943
StDev: 4.43654
N. 35

Kolmogorov-Smirnov Normality Test
D+: 0.083 D-: 0.106 D : 0.106
Approximate P-Value > 0.15

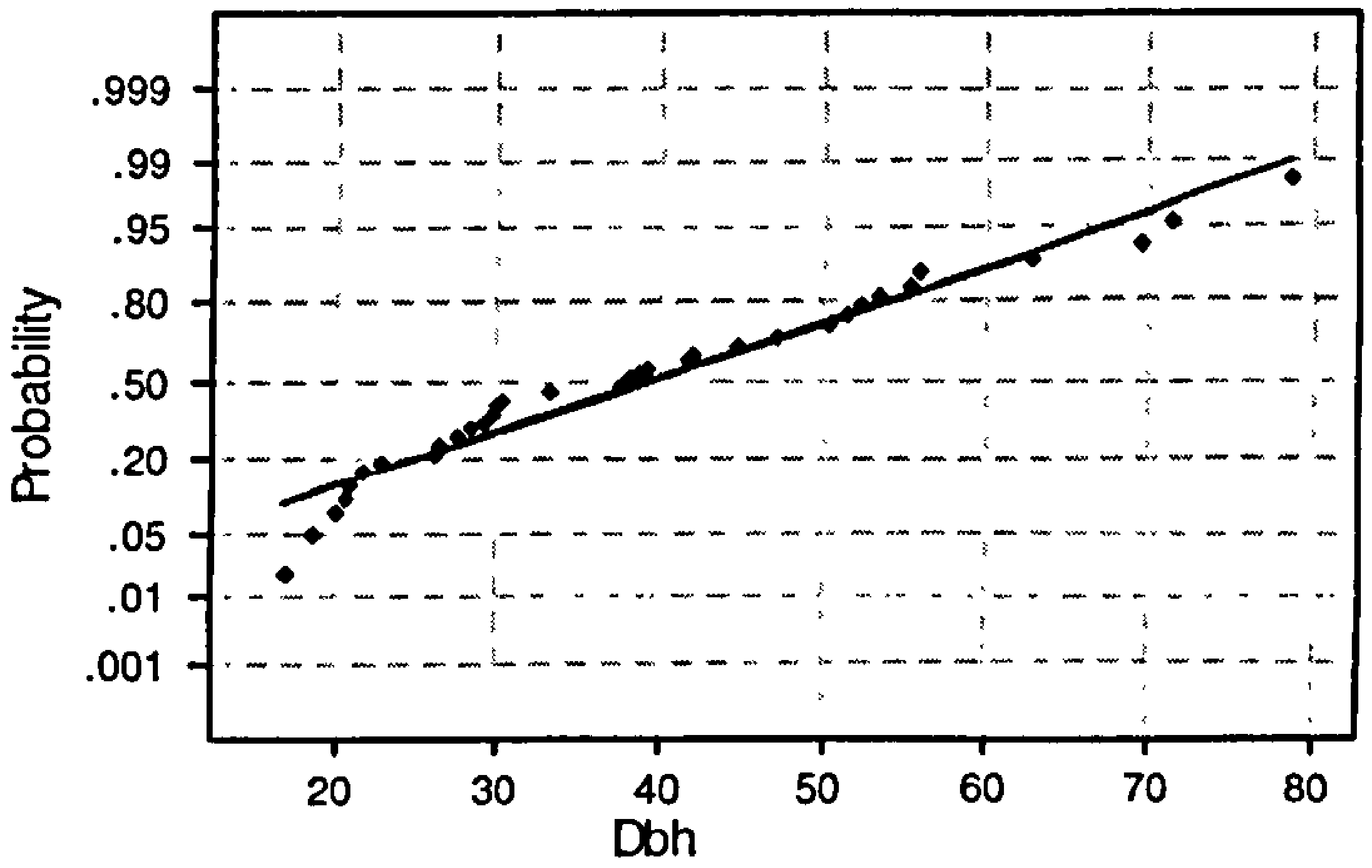
B. Normal Probabilty Plot for clear bole height of Shade trees



Average: 9.66
StDev: 4 41782
N. 35

Kolmogorov-Smirnov Normality Test
D+: 0.090 D-: 0.126 D : 0.126
Approximate P-Value > 0.15

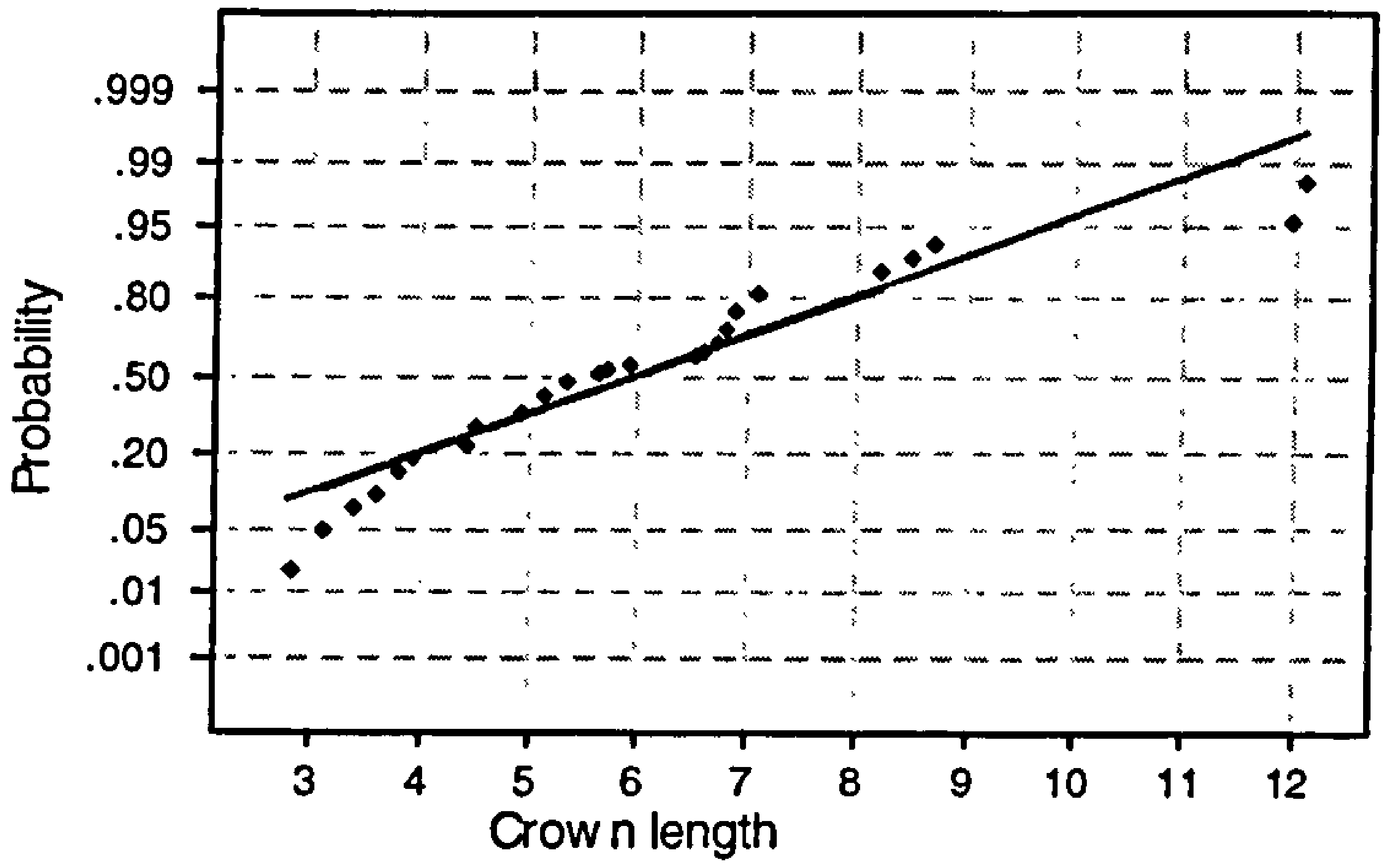
C. Normal Probabilty Plot for DBH of Shade trees



Average: 39.3303
StDev: 16.2572
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.143 D-: 0.084 D : 0.143
Approximate P-Value: 0.068

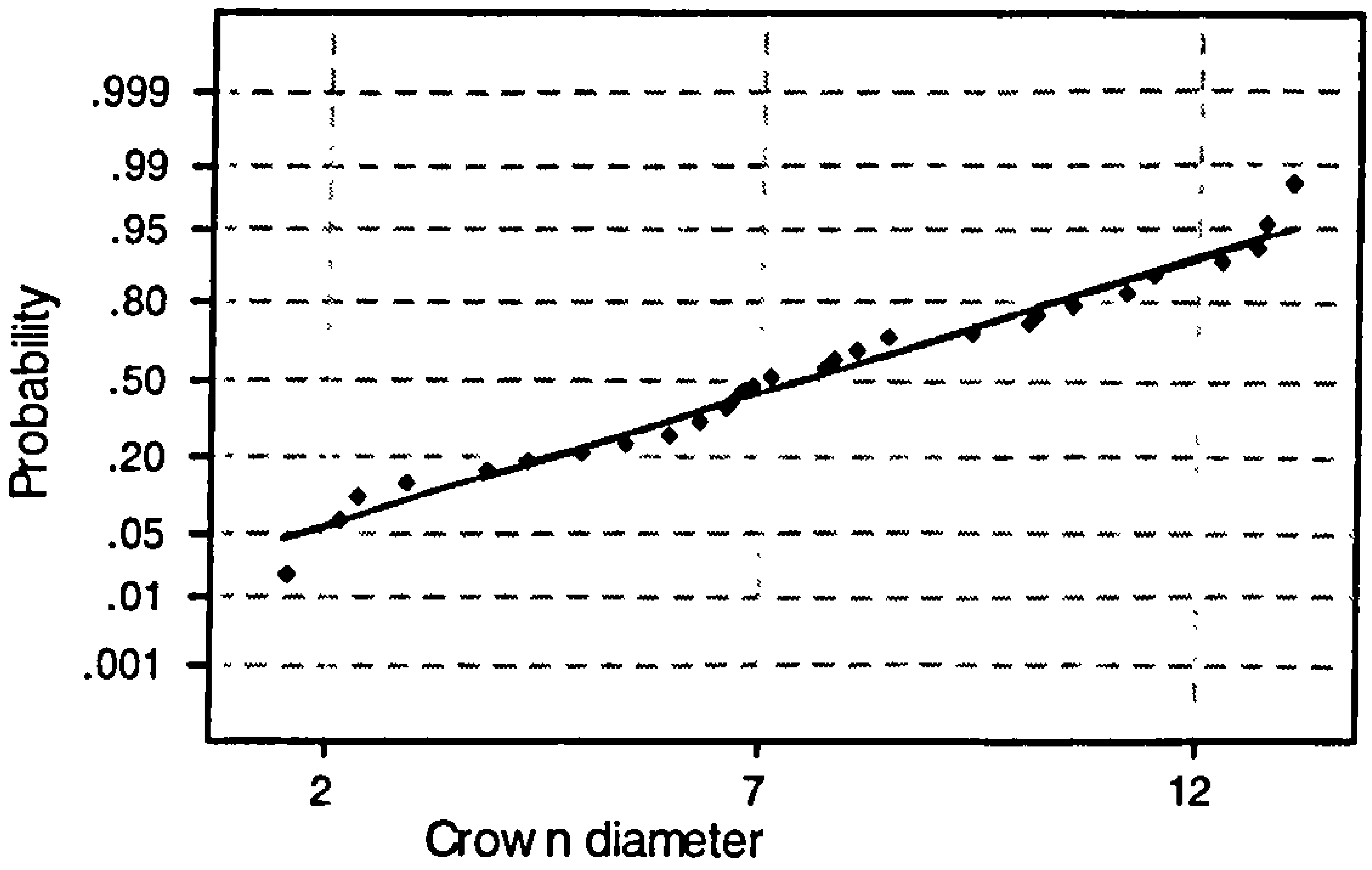
D. Normal Probabilty Plot for Crown Length (Cl) of Shade trees



Average: 5.93429
StDev: 2.16509
N. 35

Kolmogorov-Smirnov Normality Test
D+: 0.124 D-: 0.074 D : 0.124
Approximate P-Value > 0.15

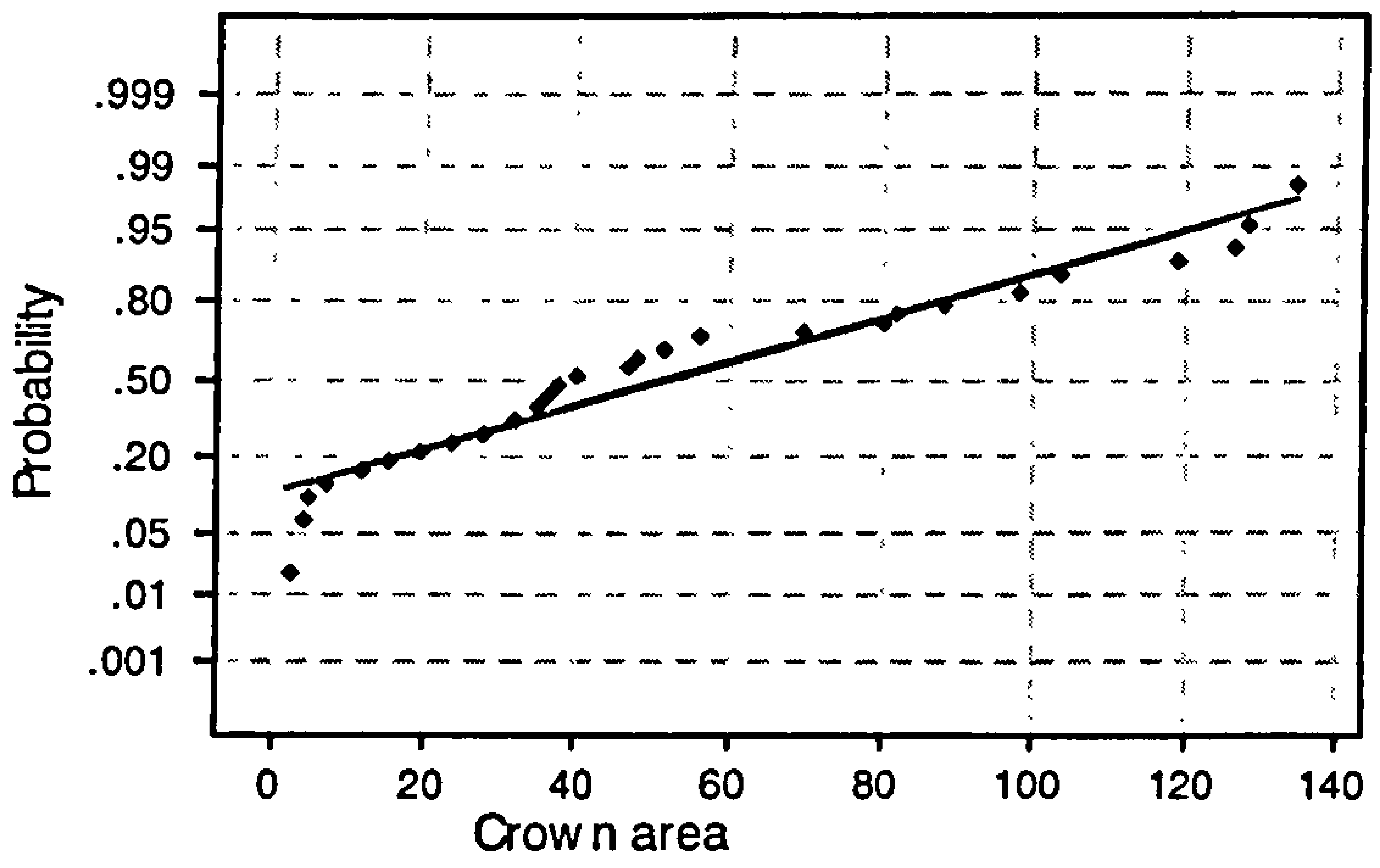
E. Normal Probabilty Plot for Crown Diameter (Cd) of Shade trees



Average: 7.45371
StDev: 3.28998
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.071 D-: 0.075 D : 0.075
Approximate P-Value > 0.15

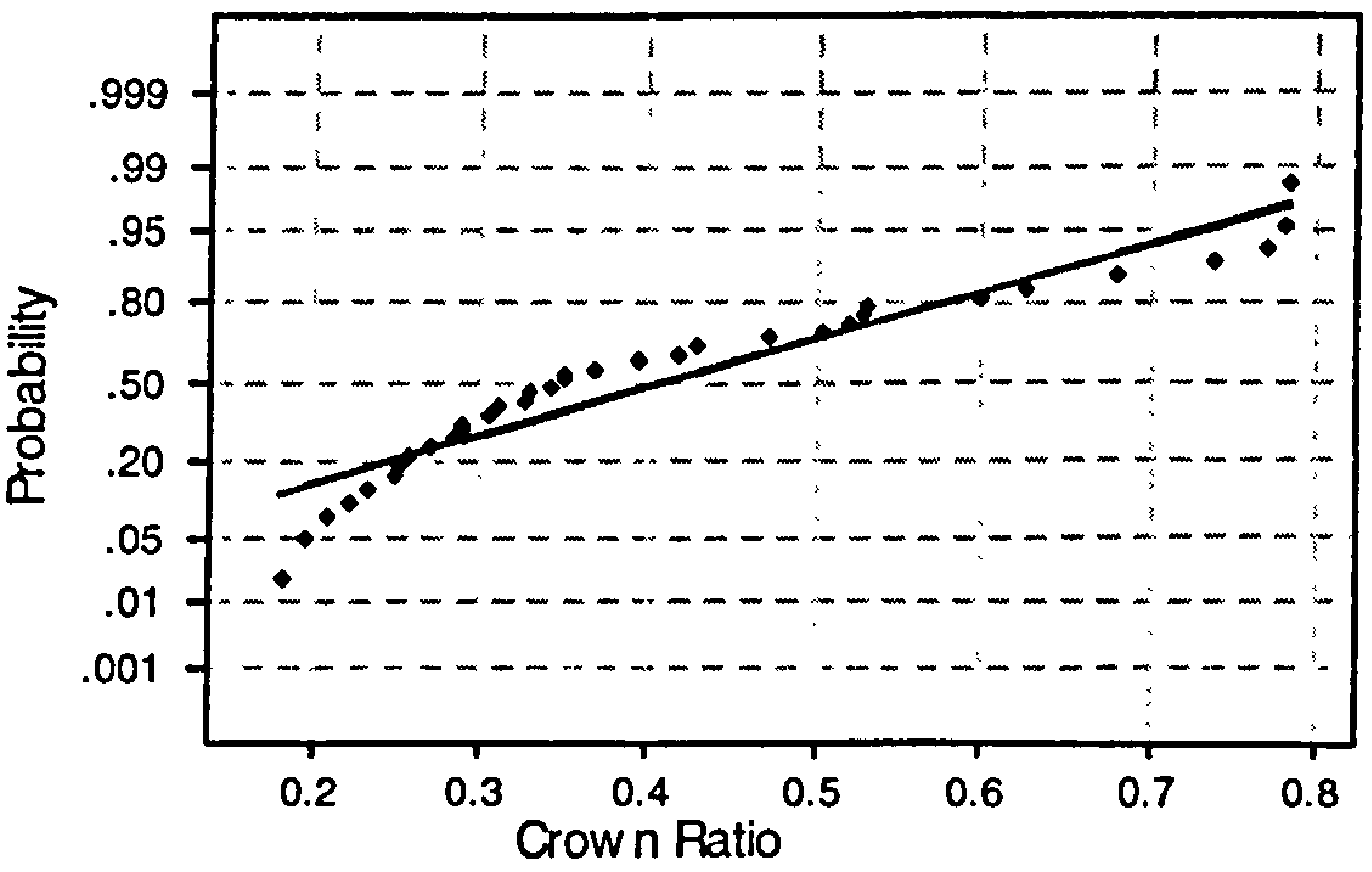
F. Normal Probabilty Plot for Crown Area (Ca) of Shade trees



Average: 51.9000
StDev: 39.4430
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.151 D-: 0.102 D : 0.151
Approximate P-Value: 0.045

G. Normal Probabilty Plot for Crown Ratio (CR) of Shade trees



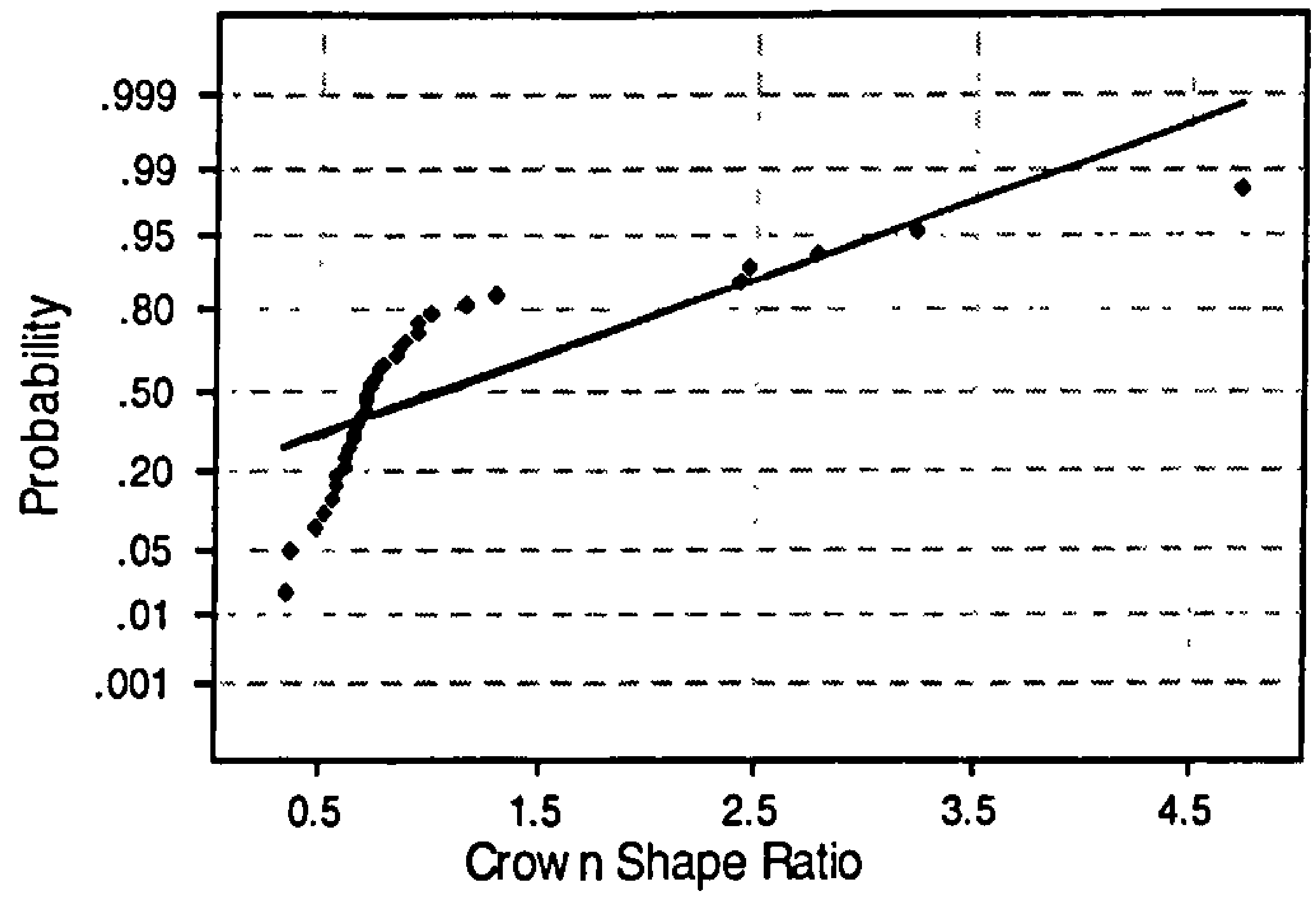
Average: 0.410548
StDev: 0.181902
N: 35

Kolmogorov-Smirnov Normality Test
D+: 0.175 D-: 0.103 D : 0.175
Approximate P-Value < 0.01

Kruskal-Wallis Test: Crown Ratio of shade tree species

```
Kruskal-Wallis Test on CR

Tree spe     N    Median    Ave Rank        Z
1            5    0.5286        26.8     2.07
2            5    0.2822        12.4    -1.32
3            5    0.1171         7.0    -2.59
4            5    0.3248        18.6     0.14
5            5    0.7717        33.0     3.54
6            5    0.2880        16.8    -0.28
7            5    0.2236        11.4    -1.56
Overall     35                  18.0

H = 23.82  DF = 6  P = 0.001
```

H. Normal Probabilty Plot for Crown Shape Ratio (CSR) of Shade trees



Average: 1.06238
StDev: 0.935555
N: 35

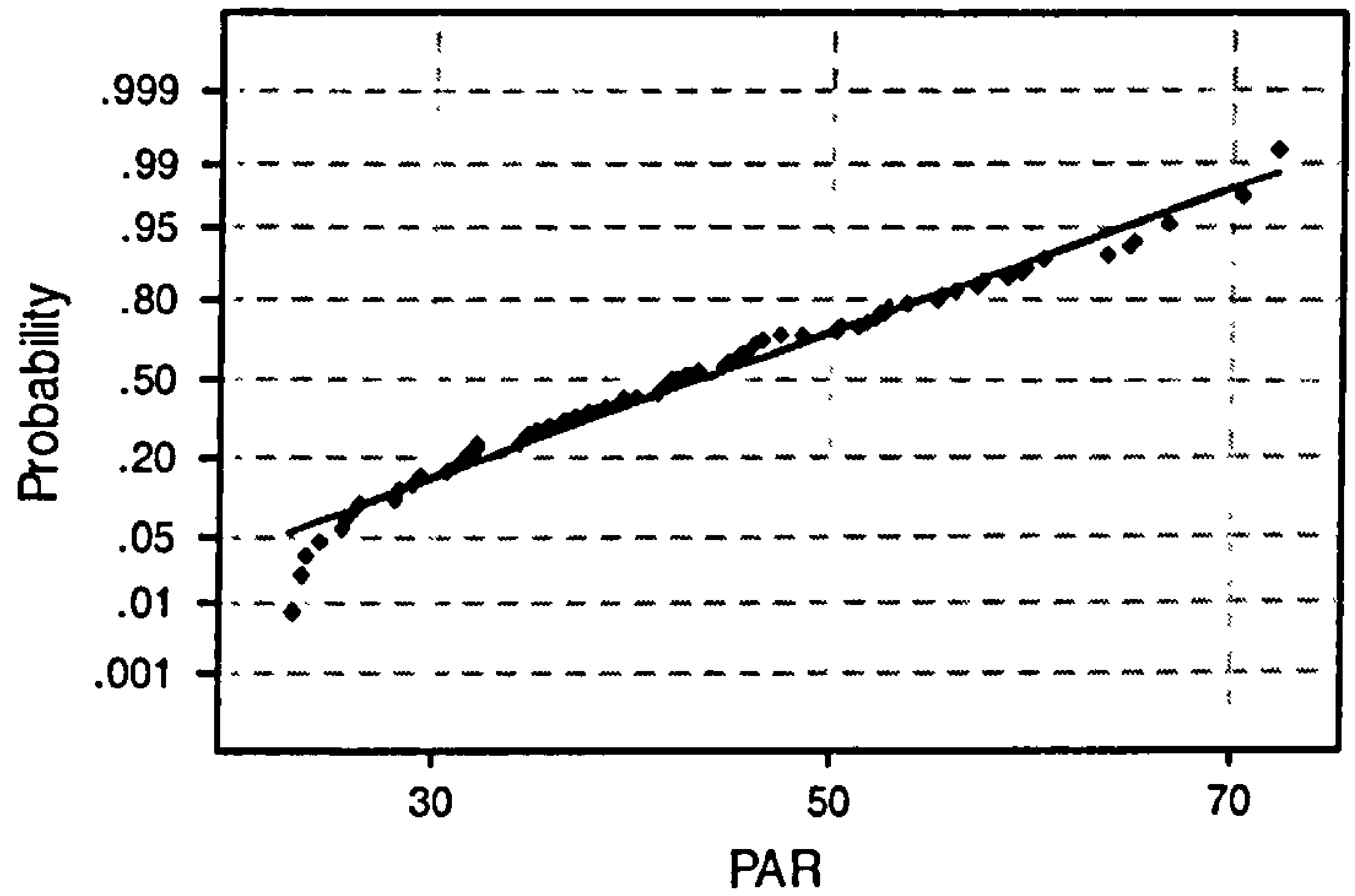
Kolmogorov-Smirnov Normality Test
D+: 0.327 D-: 0.217 D : 0.327
Approximate P-Value < 0.01

Kruskal-Wallis Test: Crown Shape Ratio of shade tree species

```
Kruskal-Wallis Test on CSR

Tree spe      N     Median     Ave Rank          Z
1             5     0.9449         24.2       1.46
2             5     0.8636         24.6       1.56
3             5     0.2976          4.8      -3.11
4             5     0.6538         17.4      -0.14
5             5     2.7660         33.0       3.54
6             5     0.4732         12.8      -1.23
7             5     0.3564          9.2      -2.07
Overall      35                    18.0

H = 27.91  DF = 6  P = 0.000
```

Appendix 5.3: Normal probability plots for light transmission through the canopies of selected cocoa shade tree species growing on fallows in Bontomuruso Atwima district.

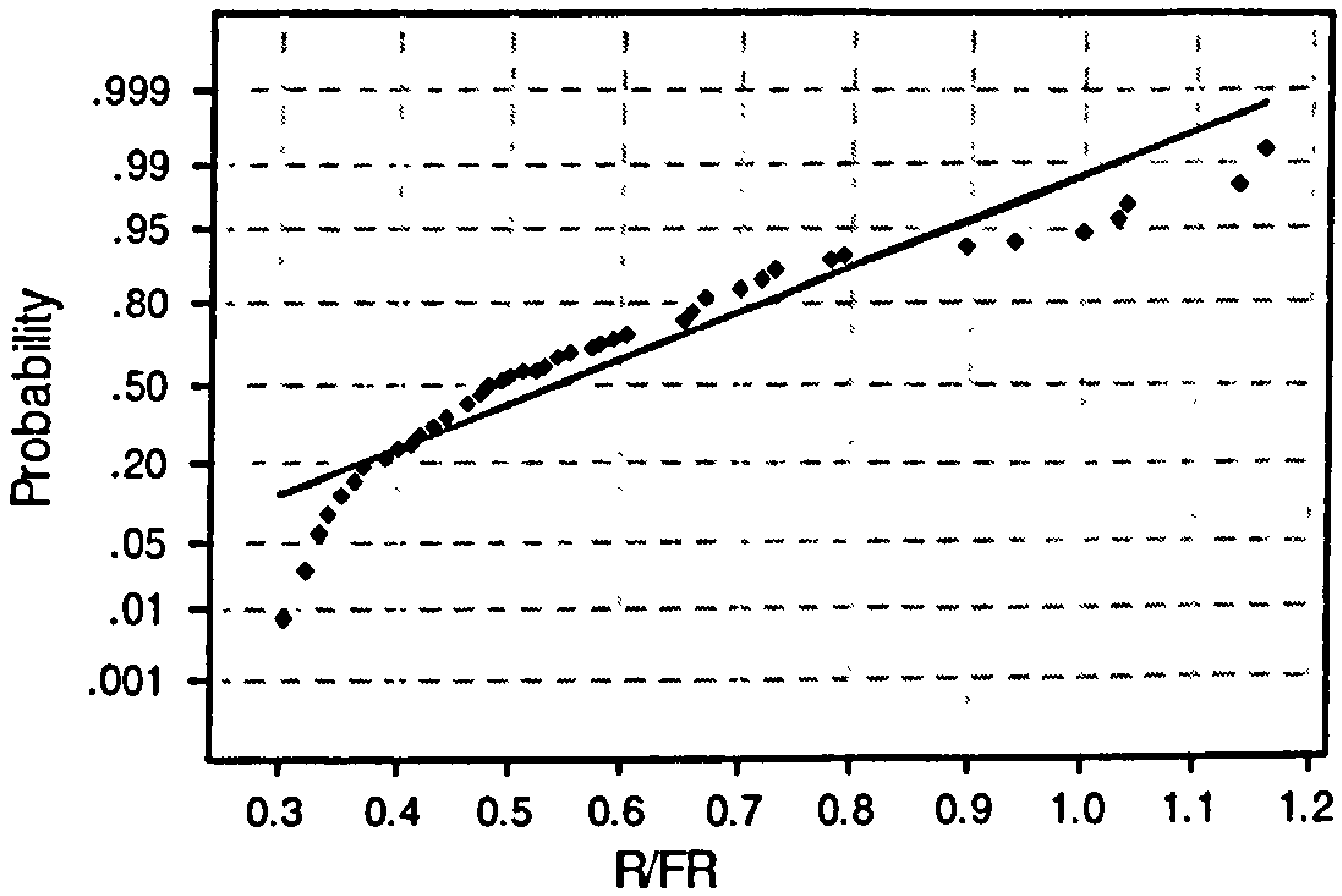
A. Normal Probability Plot for Monthly PAR



Average: 43.4048
StDev: 12.5248
N: 84

Kolmogorov-Smirnov Normality Test
D+: 0.076 D-: 0.050 D : 0.076
Approximate P-Value > 0.15

B. Normal Probability Plot for Red/Far Red Light

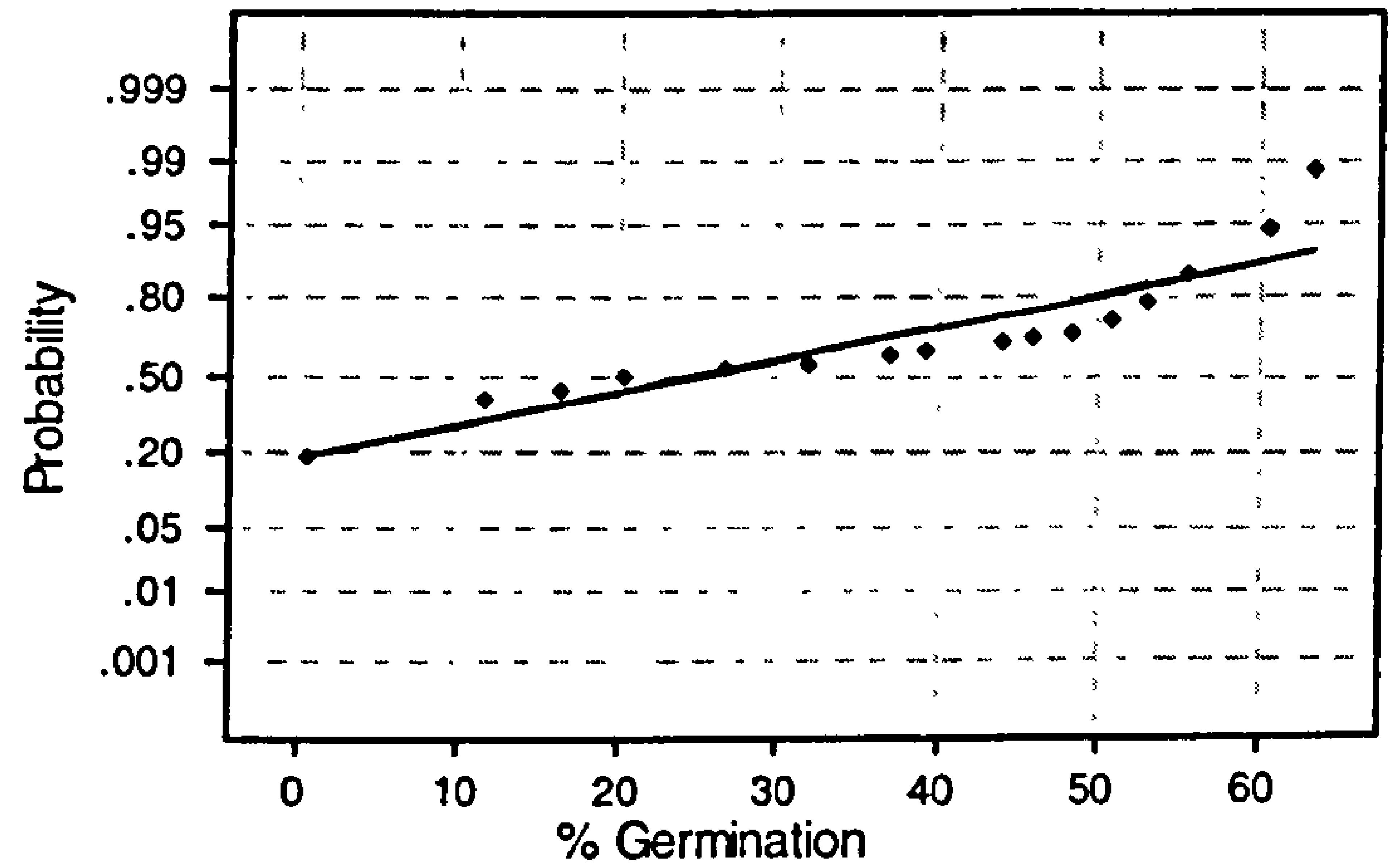


Average: 0.542857
StDev: 0.193475
N: 84

Kolmogorov-Smirnov Normality Test
D+: 0.126 D-: 0.107 D : 0.126
Approximate P-Value < 0.066

Appendix 6.1: Normal probability plots for germination and vegetative propagation trials of *T. tetraptera*.

A. Normal Probability Plot for Germination Percentage



Average: 26.3592
StDev: 24 2092
N: 48

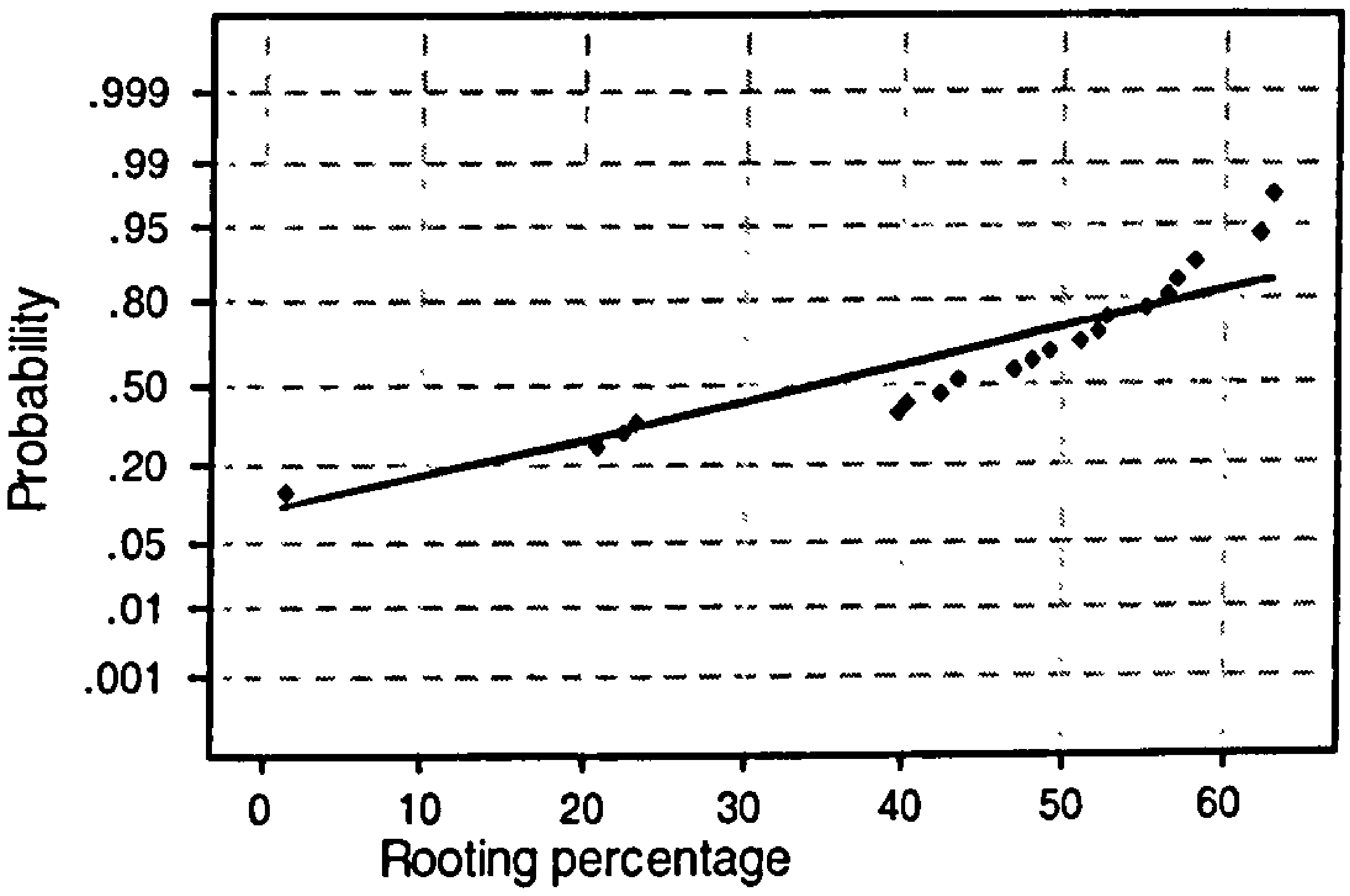
Kolmogorov-Smirnov Normality Test
D+: 0.137 D-: 0.152 D : 0.152
Approximate P-Value < 0.01

Kruskal-Wallis Test: % Germination versus Treatments

```
Kruskal-Wallis Test on % Germination

Treatmen    N     Median    Ave Rank        Z
10 Min      4    51.9500        37.3     1.90
12 Hrs C    4     0.3300        13.1    -1.70
15 Min      4    51.9500        39.4     2.22
20 Min      4    60.7000        45.0     3.06
24Hrs Co    4     0.3300         9.5    -2.24
5min        4    55.6000        40.4     2.37
6 Hrs Co    4     0.3300        12.0    -1.87
Citric a    4    40.4000        30.0     0.82
Control     4     0.3300        12.5    -1.79
Hot wate    4     0.3300        12.0    -1.87
Light po    4    29.2000        26.8     0.34
Sand Pap    4     8.3650        16.1    -1.25
Overall    48                   24.5

H = 40.25  DF = 11  P = 0.000
H = 42.59  DF = 11  P = 0.000 (adjusted for ties)
```

Appendix 6.2: Normal probability plots for effects of IBA treatment and leaf trimming on rooting of cuttings of *T. tetraptera*.

A. Normal Probability Plot for effect of IBA concentration on rooting percentage



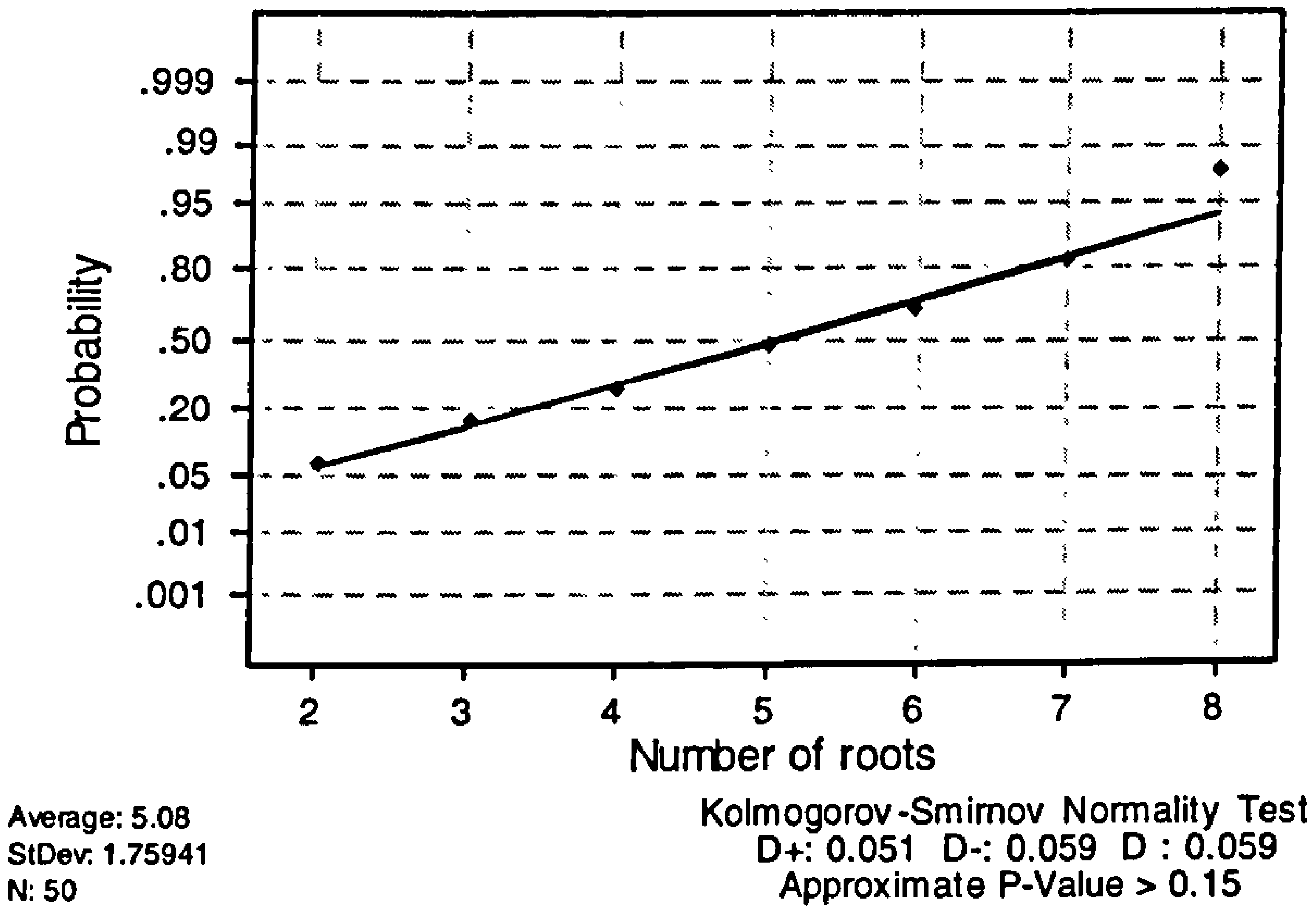
Average: 38.9428
StDev: 11.1259
N: 250

Kolmogorov-Smirnov Normality Test
D+: 0.152 D-: 0.238 D : 0.238
Approximate P-Value < 0.01

Kruskal-Wallis Test: Rooting percentage versus IBA concentration

```
Kruskal-Wallis Test on Rooting

IBA conc     N    Median    Ave Rank        Z
1           10     20.70        11.9    -3.30
2           10     52.24        30.9     1.31
3           10     52.83        32.9     1.79
4           10     51.06        28.9     0.82
5           10     47.01        22.9    -0.63
Overall     50                  25.5

H = 13.52  DF = 4  P = 0.009
H = 13.72  DF = 4  P = 0.008 (adjusted for ties)
```

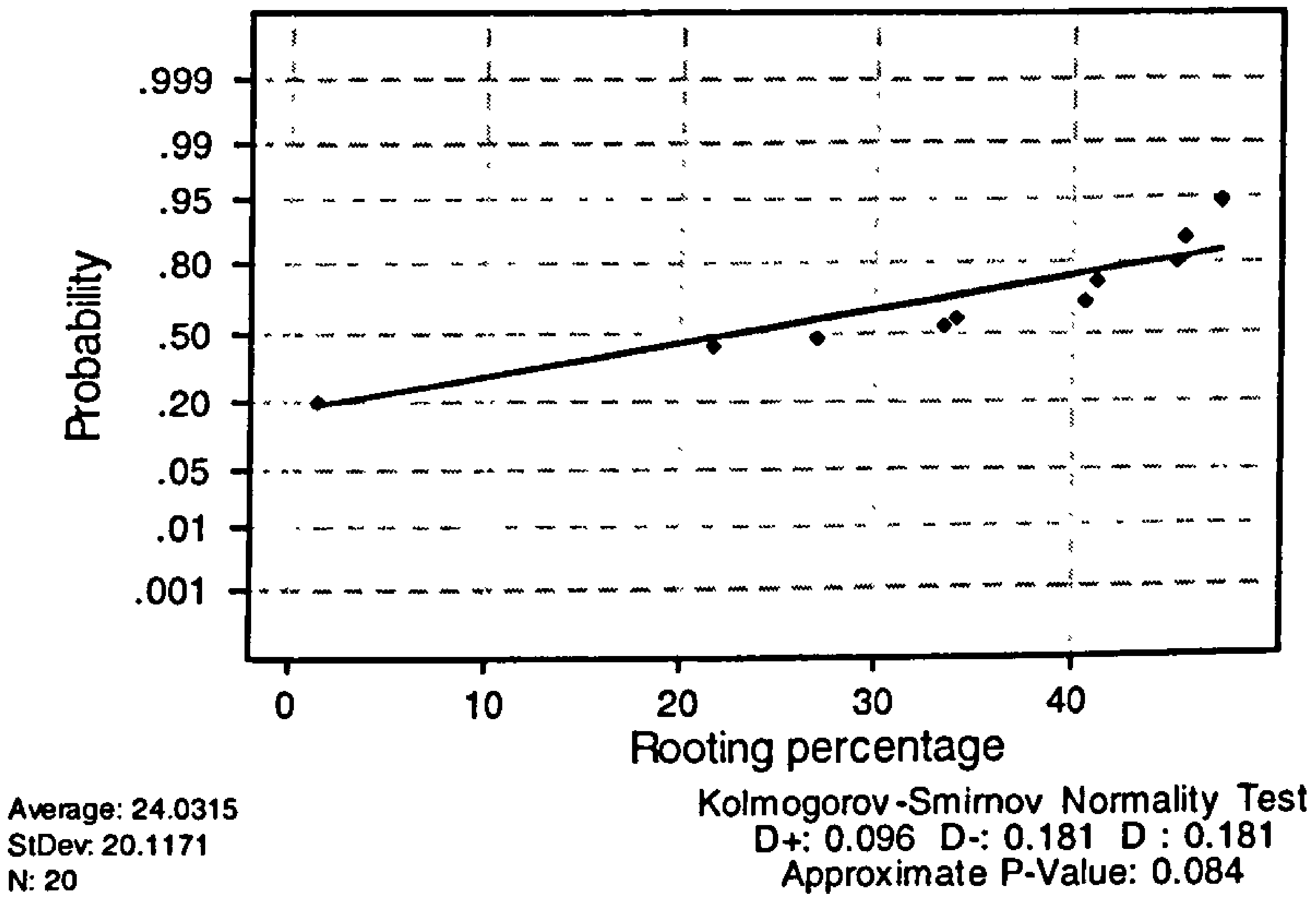
B. Normal Probability Plot for effect of IBA concentration on mean number of roots per rooted cutting



Average: 5.08
StDev: 1.75941
N: 50

Kolmogorov-Smirnov Normality Test
D+: 0.051 D-: 0.059 D : 0.059
Approximate P-Value > 0.15

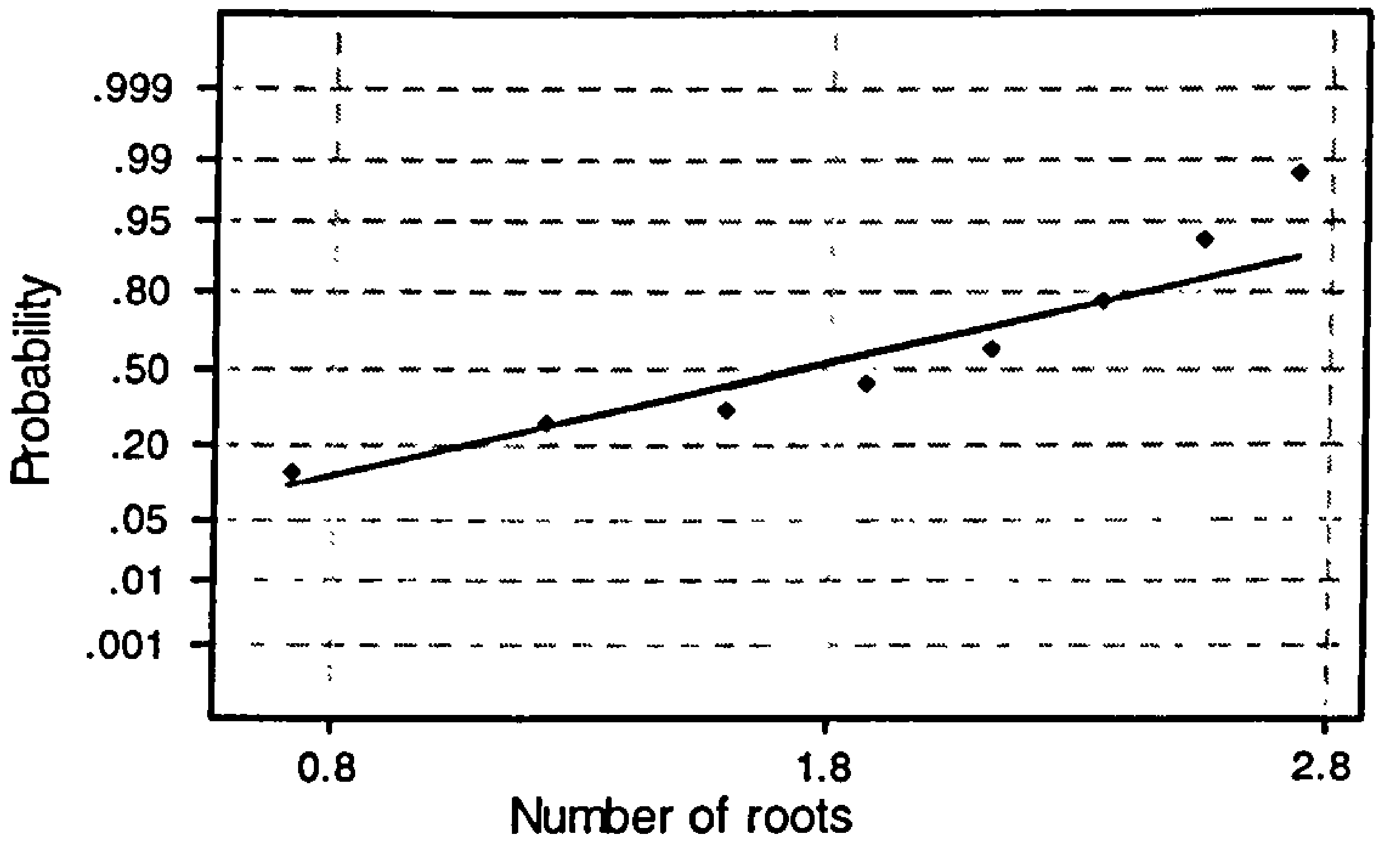
C. Normal Probability Plot for effect of Leaf Area on rooting percentage.



Average: 24.0315
StDev: 20.1171
N: 20

Kolmogorov-Smirnov Normality Test
D+: 0.096 D-: 0.181 D : 0.181
Approximate P-Value: 0.084

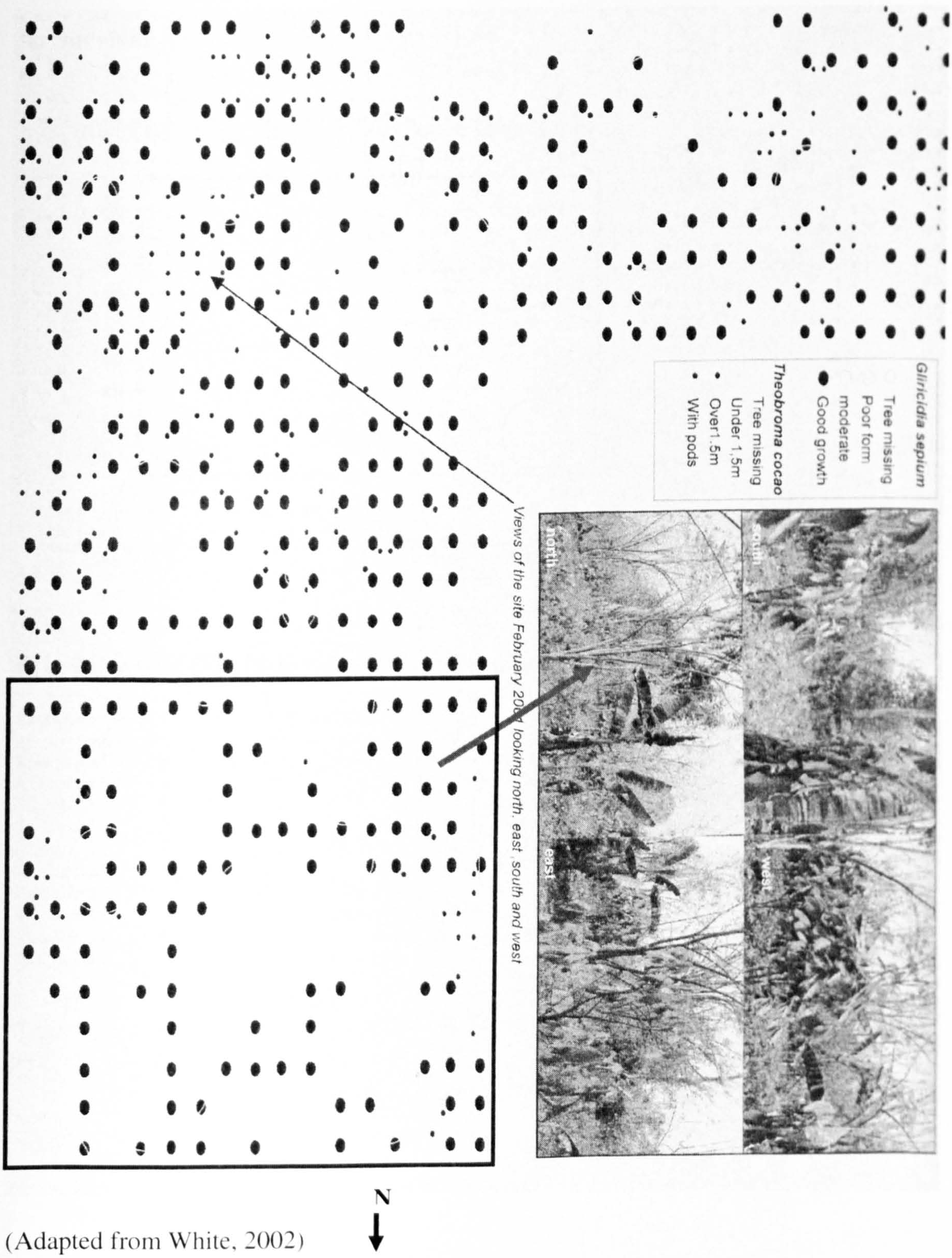
D. Normal Probability Plot for effect of leaf area on number of roots.



Average: 1.76425
StDev 0.691612
N: 40

Kolmogorov-Smirnov Normality Test
D+: 0.079 D-: 0.136 D : 0.136
Approximate P-Value: 0.063

Appendix 7.1: GCGRA/Cadbury site map in Bontomuruso showing the location of the experimental plot.

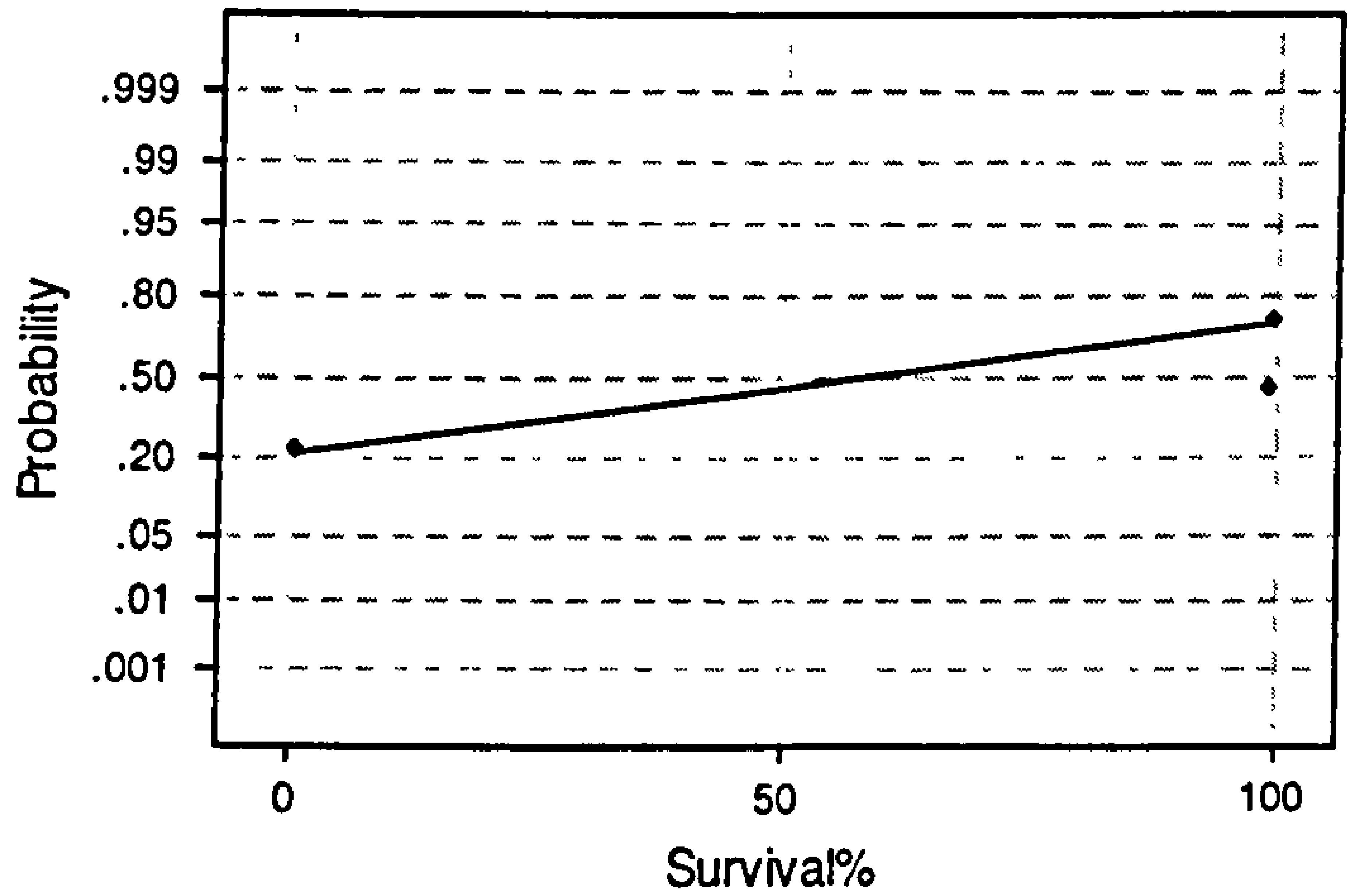


(Adapted from White, 2002)

Appendix 7.2: Normal probability plots for growth characteristics of cocoa shade tree species planted in different locations in Ghana.

A. Survival

i. Normal Probability Plot of % Survival in Gogoikrom



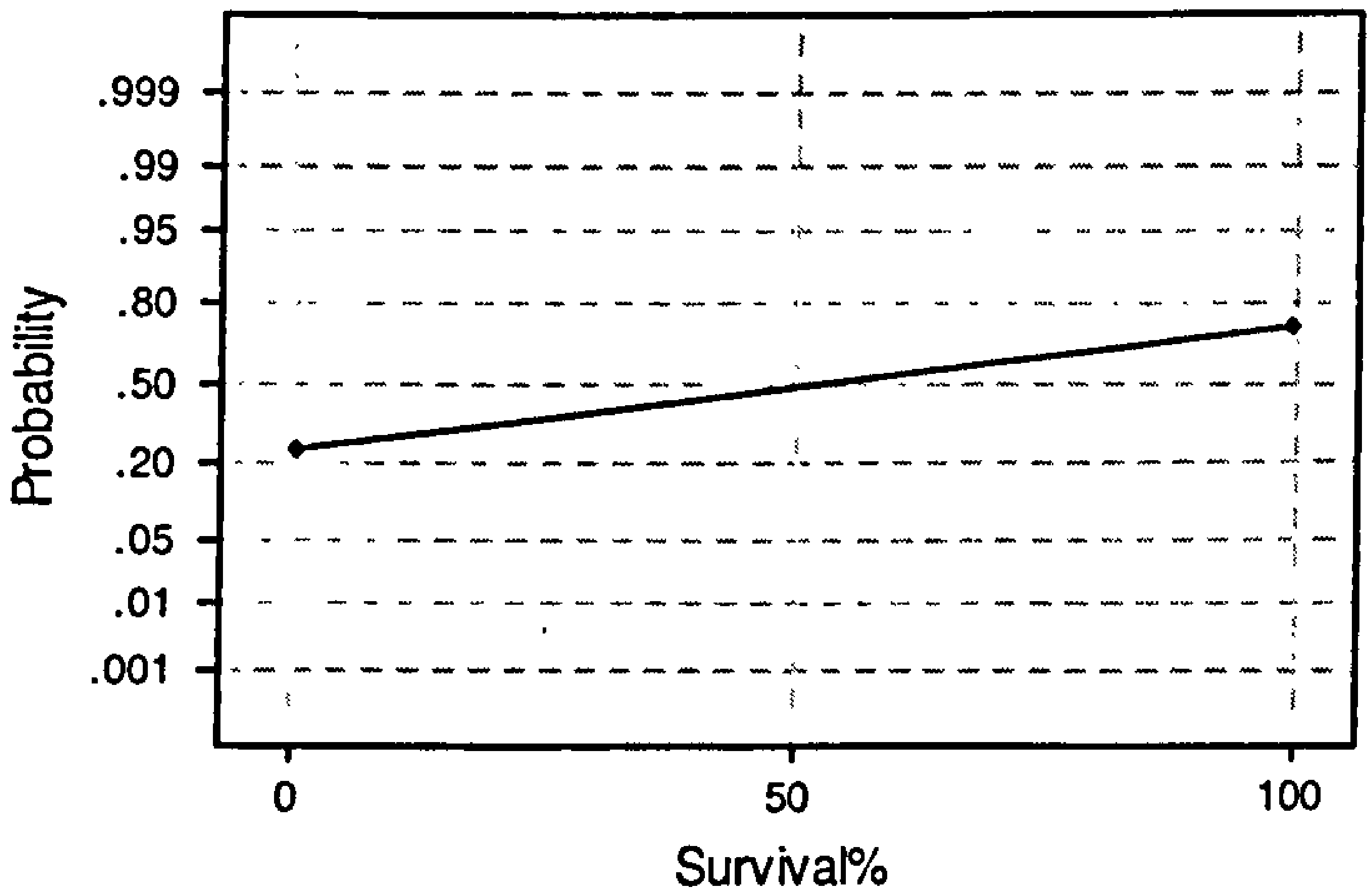
Average: 56.2156
StDev: 49.6685
N: 72

Kolmogorov-Smirnov Normality Test
D+: 0.095 D-: 0.371 D : 0.371
Approximate P-Value < 0.01

Kruskal-Wallis Test: Survival% versus Tree Species in Gogoikrom

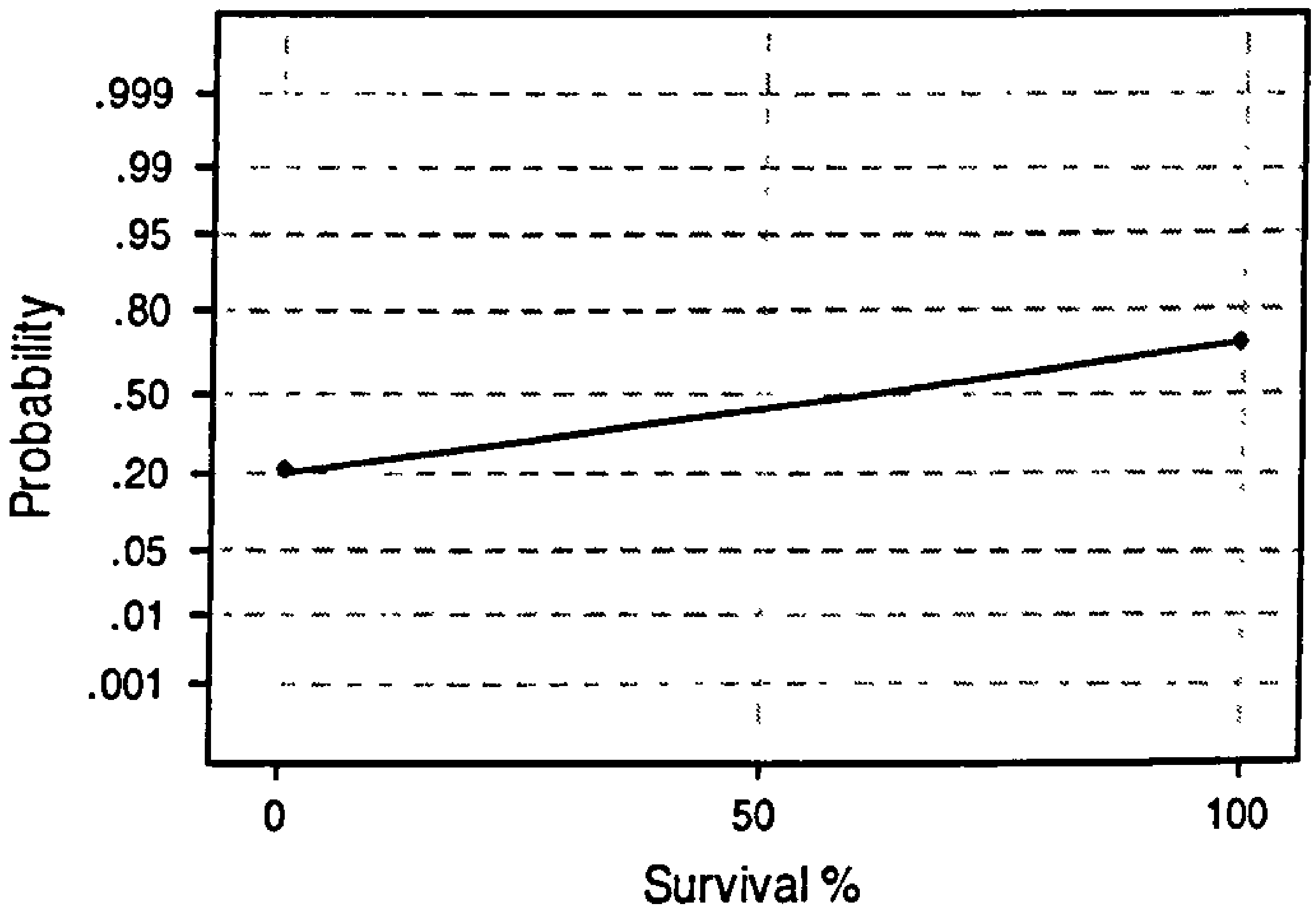
```
Kruskal-Wallis Test on Survival

Species     N    Median    Ave Rank       Z
Albizia     9    0.2500        16.5   -3.06
Cocoa       9   99.7500        53.0    2.53
Edinam      9   99.7500        40.8    0.66
Khaya       9   99.7500        48.9    1.91
Kokrodua    9    0.2500        18.3   -2.78
Prekese     9   99.7500        53.0    2.53
Sesemasa    9   99.7500        44.9    1.29
Utile       9    0.2500        16.5   -3.06
Overall    72                  36.5

H = 39.42  DF = 7  P = 0.000
H = 52.32  DF = 7  P = 0.000 (adjusted for ties)
```

ii. Normal Probability Plot of % Survival in Bontomuruso



```
Average: 53.3167                         Kolmogorov-Smirnov Normality Test
StDev: 50.4879                           D+: 0.103  D-: 0.104  D : 0.104
N: 30                                    Approximate P-Value > 0.15
```

iii. Normal Probability Plot of % Survival in South Formangso

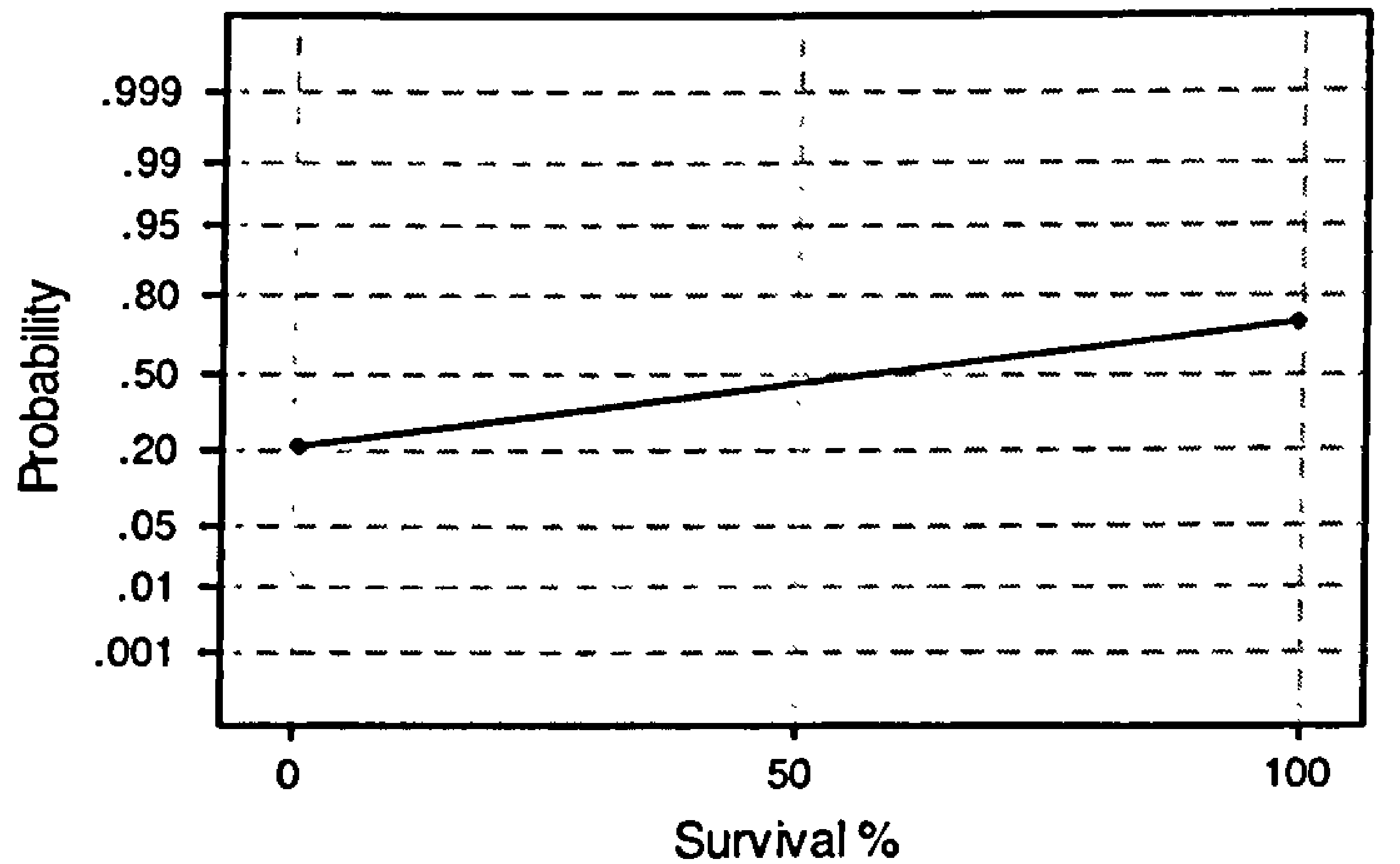


```
Average: 59.2130                         Kolmogorov-Smirnov Normality Test
StDev: 49.1174                           D+: 0.093  D-: 0.096  D : 0.096
N: 108                                   Approximate P-Value: 0.020
```

Kruskal-Wallis Test: Survival % versus Tree species

```
Kruskal-Wallis Test on Survival

C8           N    Median    Ave Rank        Z
Cocoa       18   99.7500        76.5     3.26
Edinam      18   99.7500        52.5    -0.30
Emire       18   99.7500        70.5     2.37
Prekese     18   99.7500        61.5     1.04
Sesemasa    18    0.2500        22.5    -4.75
Utile       18    0.2500        43.5    -1.63
Overall    108                  54.5

H = 35.56  DF = 5  P = 0.000
H = 49.09  DF = 5  P = 0.000 (adjusted for ties)
```

iv. Normal Probability Plot of % Survival on all three sites



Average: 57.5379
StDev: 49.3253
N: 165

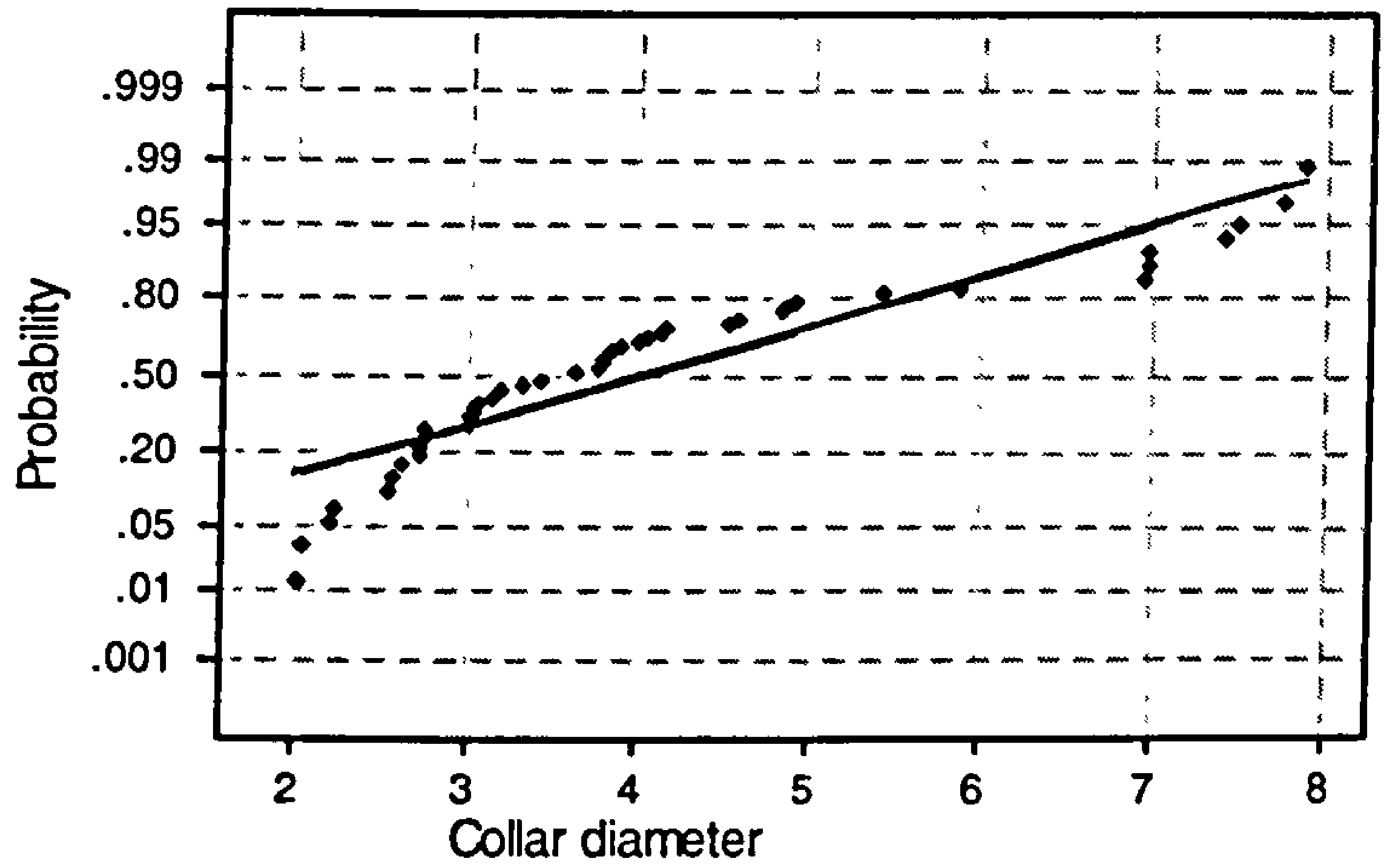
Kolmogorov-Smirnov Normality Test
D+: 0.092 D-: 0.095 D : 0.095
Approximate P-Value < 0.01

Kruskal-Wallis Test: Survival % versus tree spcies

```
Kruskal-Wallis Test on Survival

C17          N    Median    Ave Rank         Z
Ea. B        5    0.2500        68.5     -0.69
Ea. O-F     10   99.7500        93.3      0.70
Ea. SF      18   99.7500        81.3     -0.16
Eu. B        5    0.2500        52.0     -1.47
Eu. O-F     10    0.2500        35.5     -3.24
Eu. SF      18    0.2500        67.6     -1.45
Nl. B        5    0.2500        68.5     -0.69
Nl. O-F     10   99.7500       101.5      1.26
Nl. SF      18    0.2500        35.5     -4.47
Tc. B        5   99.7500       101.5      0.88
Tc. O-F     10   99.7500       118.0      2.39
Tc. SF      18   99.7500       118.0      3.29
Tt. B        5   99.7500        85.0      0.10
Tt. O-F     10   99.7500       118.0      2.39
Tt. SF      18   99.7500        95.1      1.14
Overall    165                  83.0

H = 56.86  DF = 14  P = 0.000
H = 77.60  DF = 14  P = 0.000 (adjusted for ties)
```

B. Collar diameter

i. Normal Probability Plot of collar diameter in Gogoikrom



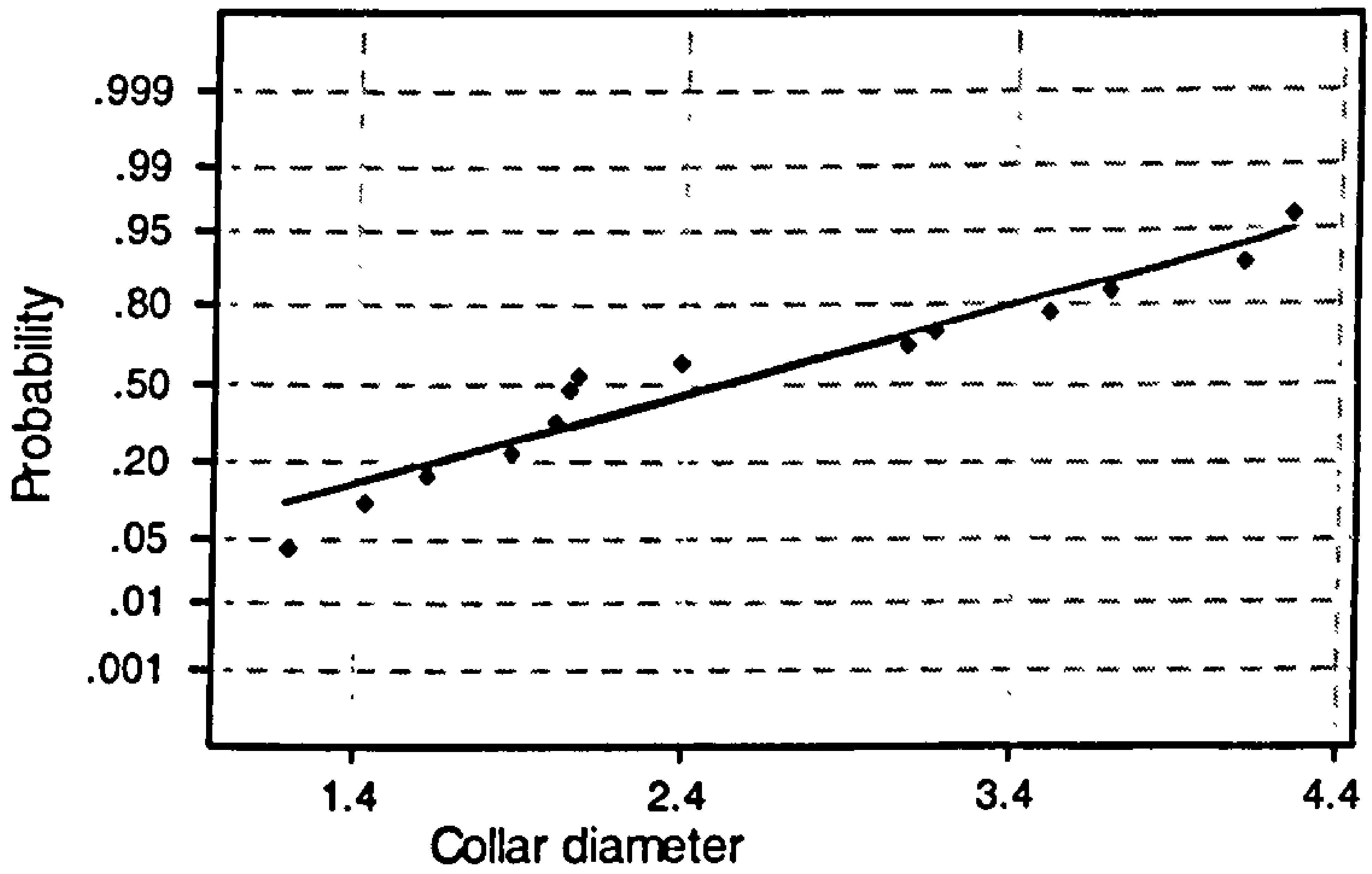
Average: 4.02608
StDev: 1.66252
N: 51

Kolmogorov-Smirnov Normality Test
D+: 0.179 D-: 0.117 D : 0.179
Approximate P-Value < 0.01

Kruskal-Wallis Test: Collar diameter versus Tree species in Gogoikrom

```
Kruskal-Wallis Test on Collar diameter

Tree species           N     Median     Ave Rank         Z
T. tetraptera          9      4.010         28.3      0.55
E. angolense           6      3.775         28.2      0.52
T. cacao               9      2.715         11.7     -3.40
N. laevis              7      3.075         17.7     -1.98
K. anthotheca          8      6.980         46.5      4.86
P. elata               1      2.190          3.0     -1.56
Overall               40                    26.0

H = 34.34  DF = 5  P = 0.000
H = 34.35  DF = 5  P = 0.000 (adjusted for ties)
```

ii. Normal Probability Plot of Collar diameter in Bontomuruso



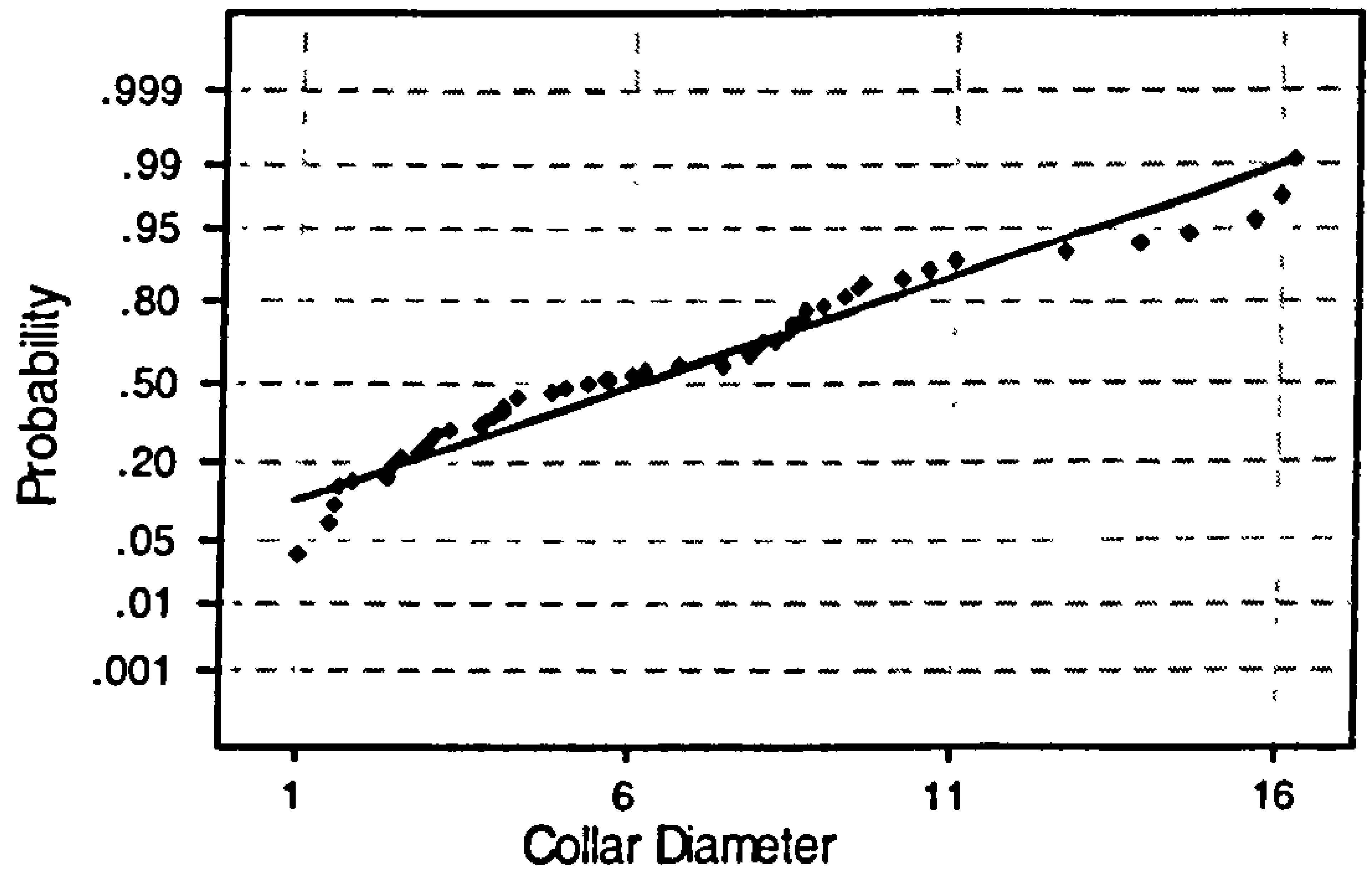
Average: 2.52625
StDev: 0.967553
N: 16

Kolmogorov-Smirnov Normality Test
D+: 0.244 D-: 0.095 D : 0.244
Approximate P-Value: 0.014

Kruskal-Wallis Test on Collar diameter of cocoa and shade trees in Bontomuruso

```
Tree species      N     Median    Ave Rank          Z
T. ivorensis      4      3.905        14.5       2.91
T. tetraptera     3      2.390         9.0       0.20
E. angolense      2      1.715         4.0      -1.43
E. utile          1      2.010         6.0      -0.54
T. cacao          4      1.970         6.5      -0.97
N. laevis         2      1.830         5.5      -0.95
Overall          16                    8.5

H =  9.95  DF = 5  P = 0.077
H = 10.01  DF = 5  P = 0.075 (adjusted for ties)
```

iii. Normal Probability Plot of collar diameter in South Formangso

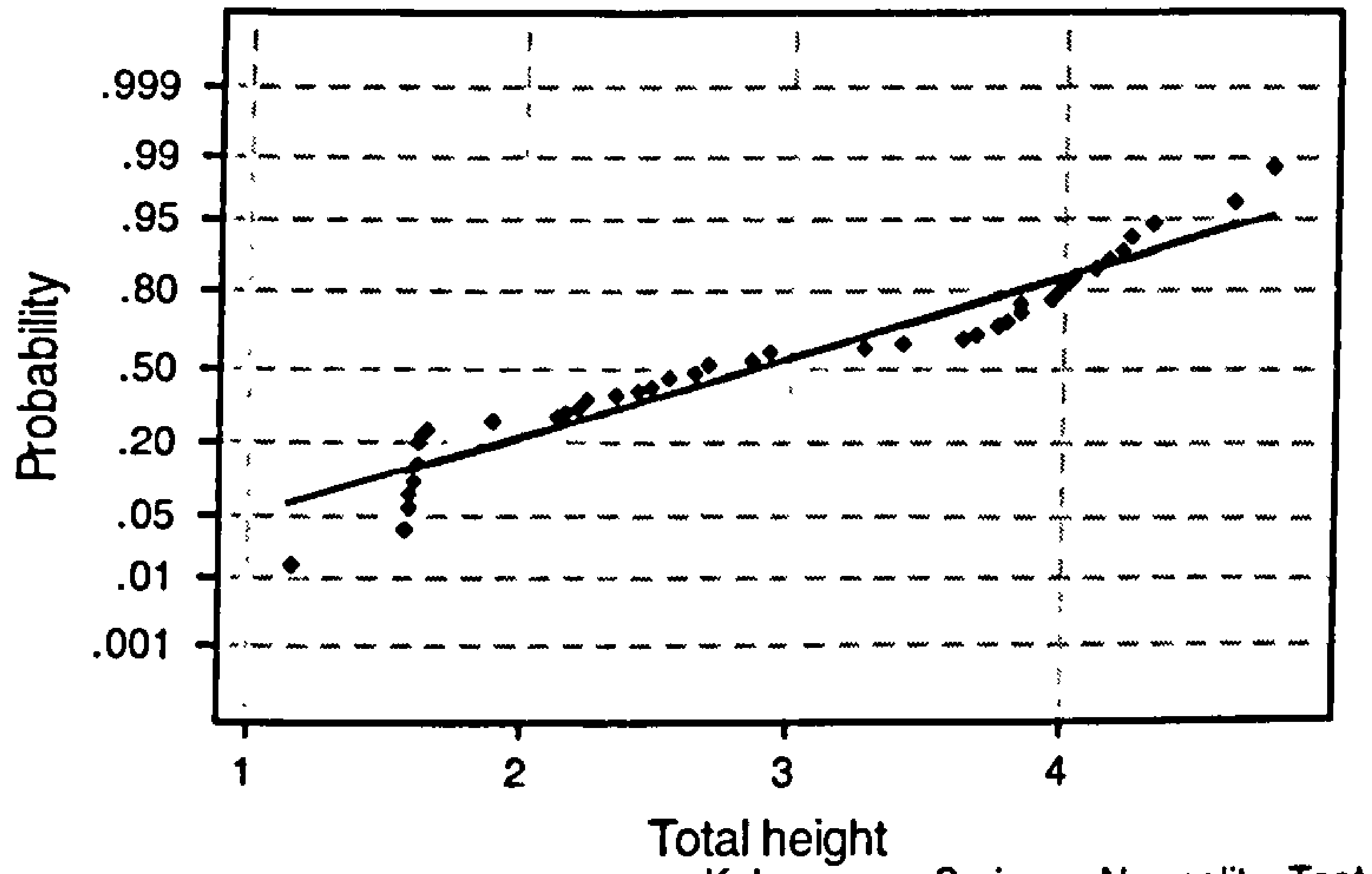


Average: 6.22277
StDev: 4.02905
N: 65

Kolmogorov-Smirnov Normality Test
D+: 0.117 D-: 0.071 D : 0.117
Approximate P-Value: 0.036

C. Total height growth

i. Normal Probability Plot of Tree height in Gogoikrom



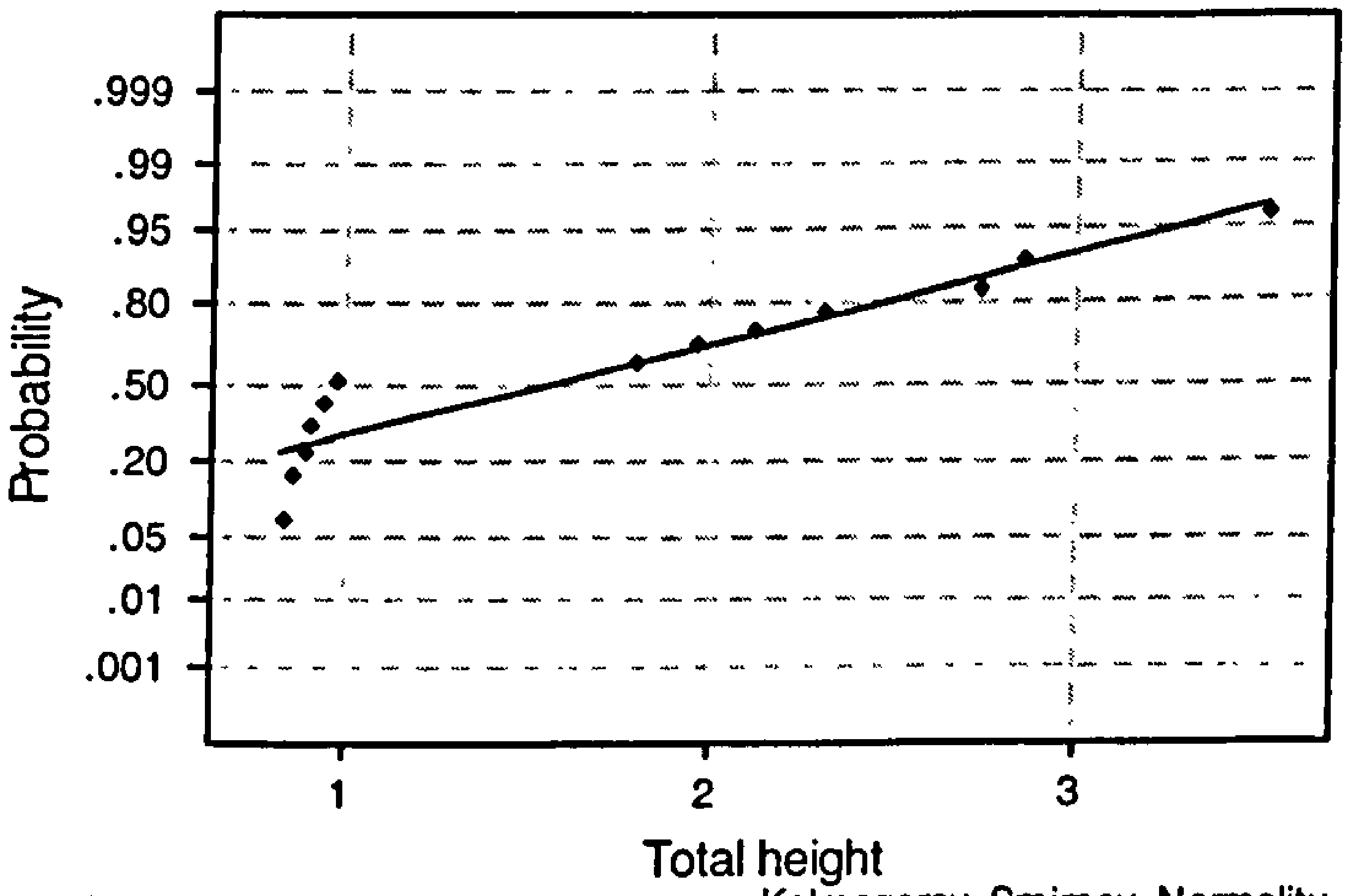
Average: 2.88021
StDev: 1.05522
N: 47

Kolmogorov-Smirnov Normality Test
D+: 0.133 D-: 0.147 D : 0.147
Approximate P-Value: 0.013

Kruskal-Wallis Test: Total height versus Tree Species in Gogoikrom

```
Kruskal-Wallis Test on Total he

Species                  N    Median    Ave Rank         Z
T.tetraptera             9     3.815        34.0      2.60
E. angolense             6     2.670        23.5     -0.10
T. cacao                 9     1.610         7.5     -4.29
N. laevis                7     2.225        16.1     -2.05
K. anthotheca            8     4.185        41.0      4.42
P. elata                 1     1.150         1.0     -1.70
Overall                 40                  24.0

H = 41.31  DF = 5  P = 0.000
H = 41.33  DF = 5  P = 0.000 (adjusted for ties)
```

ii. Normal Probability Plot of total height in Bontomuruso



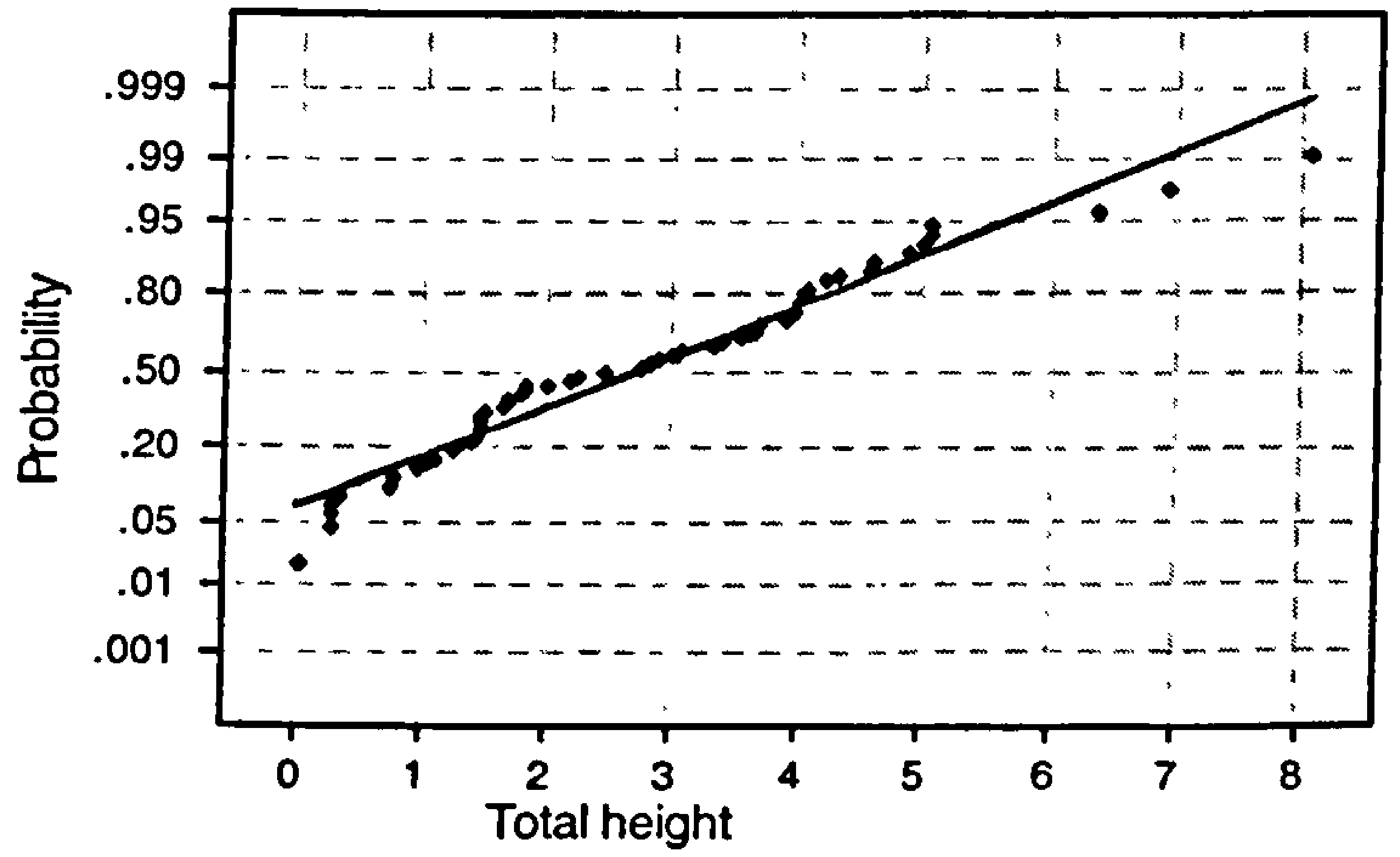
Average: 1.57938
StDev: 0 895280
N: 16

Kolmogorov-Smirnov Normality Test
D+: 0.287 D-: 0.167 D : 0.287
Approximate P-Value < 0.01

Kruskal-Wallis Test: Total height versus tree species in Bontomuruso

```
Kruskal-Wallis Test on Total he

C8          N    Median    Ave Rank        Z
Cocoa       4    0.9250         6.0    -1.21
Edinam      2    0.9100         6.3    -0.71
Emire       4    2.7900        14.3     2.79
Prekese     3    1.9600        11.3     1.14
Sesemasa    2    0.8500         2.8    -1.83
Utile       1    0.8500         3.0    -1.19
Overall    16                   8.5

H = 12.70  DF = 5  P = 0.026
H = 12.75  DF = 5  P = 0.026 (adjusted for ties)
```

iii. Normal Probability Plot of total height of tree species in South Formangso



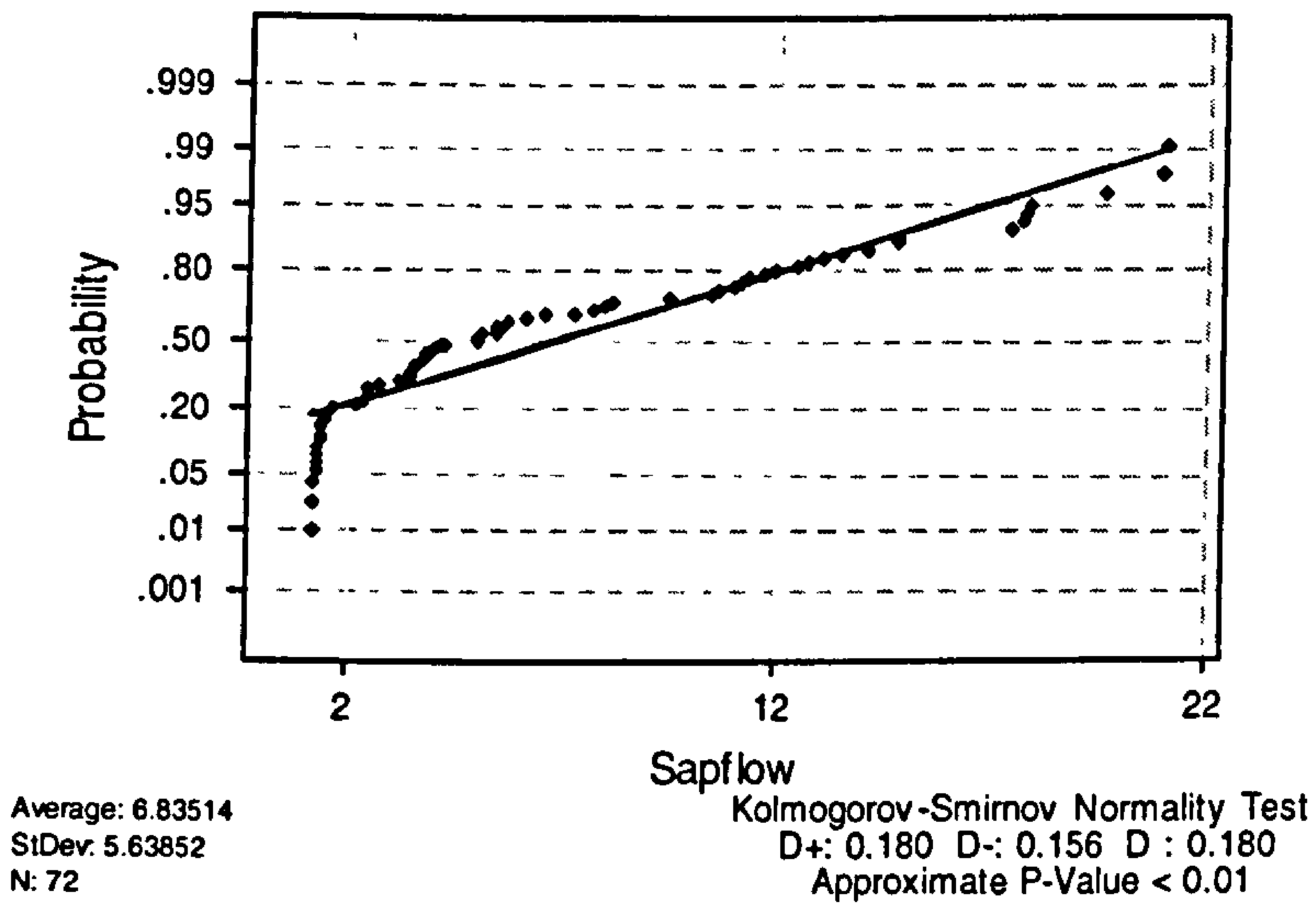
Average: 2.70262
StDev: 1.73268
N: 65

Kolmogorov-Smirnov Normality Test
D+: 0.132 D-: 0.052 D : 0.132
Approximate P-Value < 0.01

Kruskal-Wallis Test: Tot. Ht. versus tree species in South Formangso

```
Kruskal-Wallis Test on Tot. Ht.

Species     N    Median    Ave Rank        Z
Cocoa      18    1.4200        16.7    -3.49
Edinam     10    3.6200        42.3     1.98
Emire      16    4.8600        58.2     5.36
Prekese    14    2.8000        35.8     0.61
Utile       7    0.7300        12.0    -4.47
Overall    65                  33.0

H = 52.15  DF = 4  P = 0.000
H = 52.16  DF = 4  P = 0.000 (adjusted for ties)
```

Appendix 7.3: Normal probability plot sapflow from 3-years old cocoa shade tree species planted in South Formangso, Ghana.

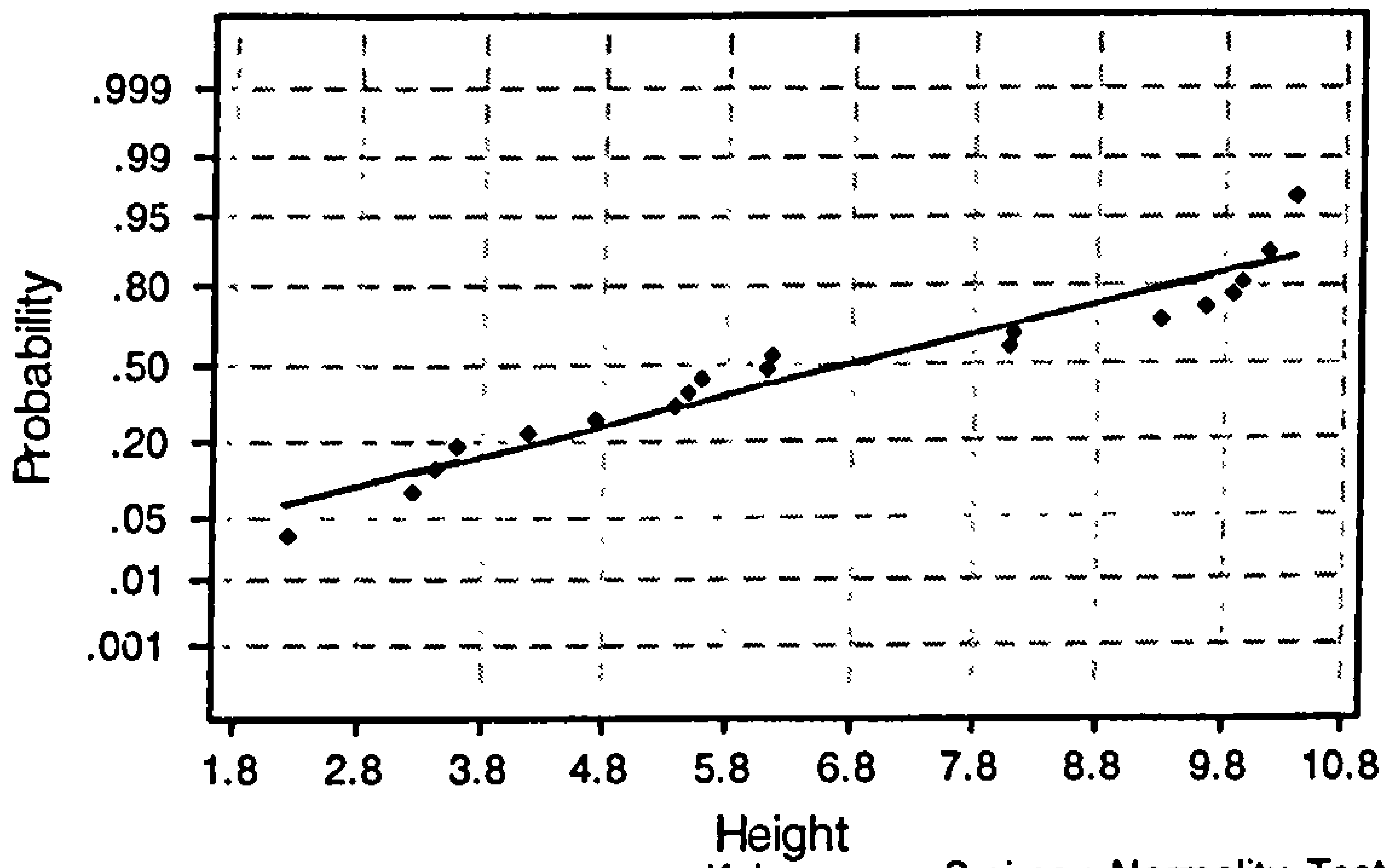


Kruskal-Wallis Test: Sapflow versus Tree species

```
Kruskal-Wallis Test on Sapflow

Tree spe     N    Median    Ave Rank        Z
1           24     7.080        46.8     2.94
2           24     2.520        27.6    -2.56
3           24     3.765        35.2    -0.38
Overall     72                  36.5

H = 10.21  DF = 2  P = 0.006
H = 10.21  DF = 2  P = 0.006 (adjusted for ties)
```

Appendix 8.1: Normal probability plots and statistical analysis of growth and dry matter production of cocoa and *G. sepium* agroforestry system in Bontomuruso.

A. Total height of cocoa and *G. sepium* shade trees



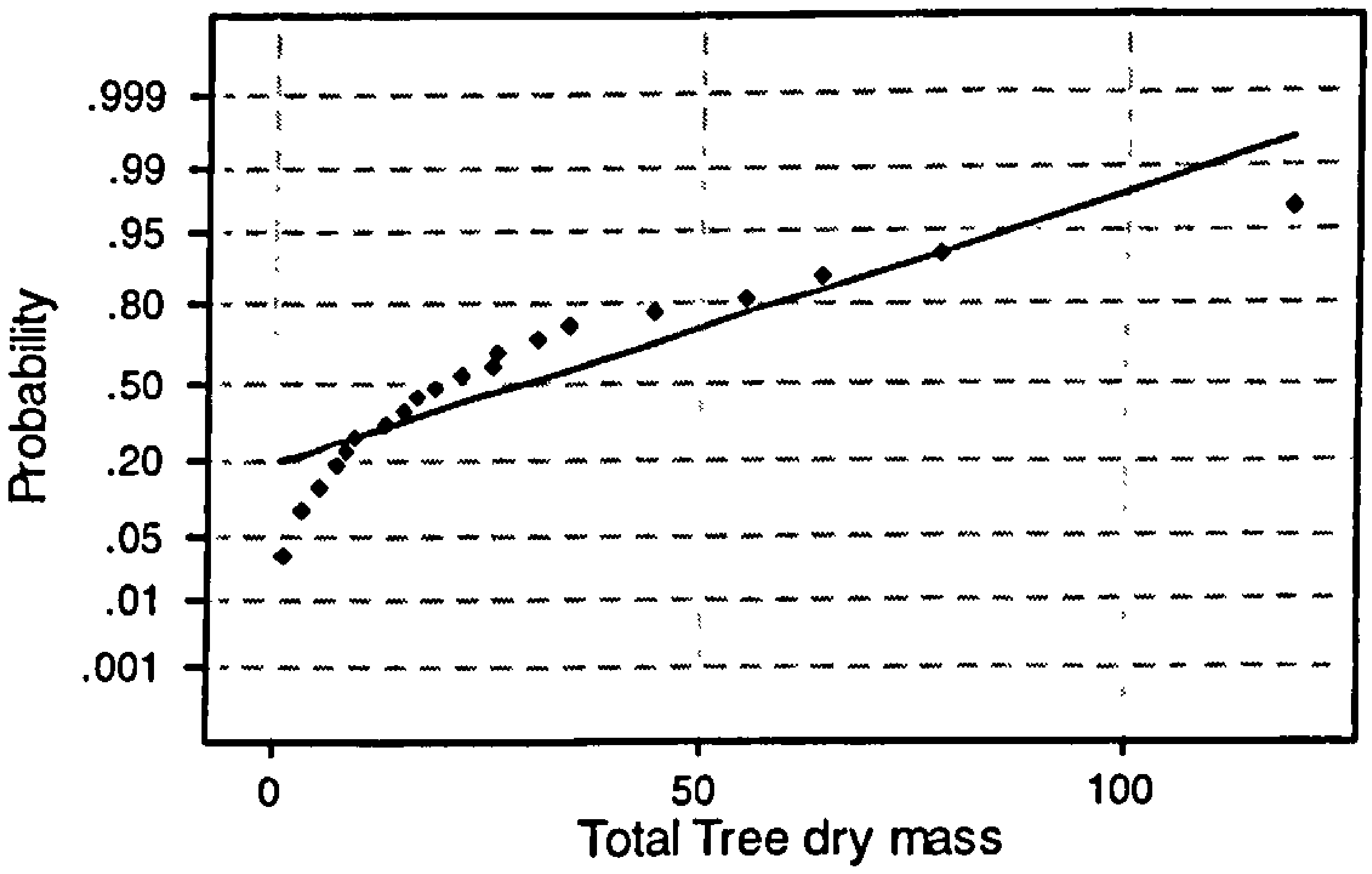
Average: 6.797
StDev: 2.78459
N. 20

Kolmogorov-Smirnov Normality Test
D+: 0.142 D-: 0.168 D : 0.168
Approximate P-Value: 0.140

Two-Sample T-Test and CI: Gliricidia Ht (m), Cocoa Ht (m)

```
            N      Mean     StDev   SE Mean
G. sepium  10      9.21      1.35      0.43
Cocoa      10      4.39      1.27      0.40

Difference = mu GliricidiaHt(m) - mu CocoaHt(m)
Estimate for difference:  4.822
95% CI for difference: (3.582, 6.062)
T-Test of difference = 0 (vs not =): T-Value = 8.21  P-Value = 0.000  DF = 17
```

B. Mean tree dry mass of cocoa and *G. sepium* shade trees



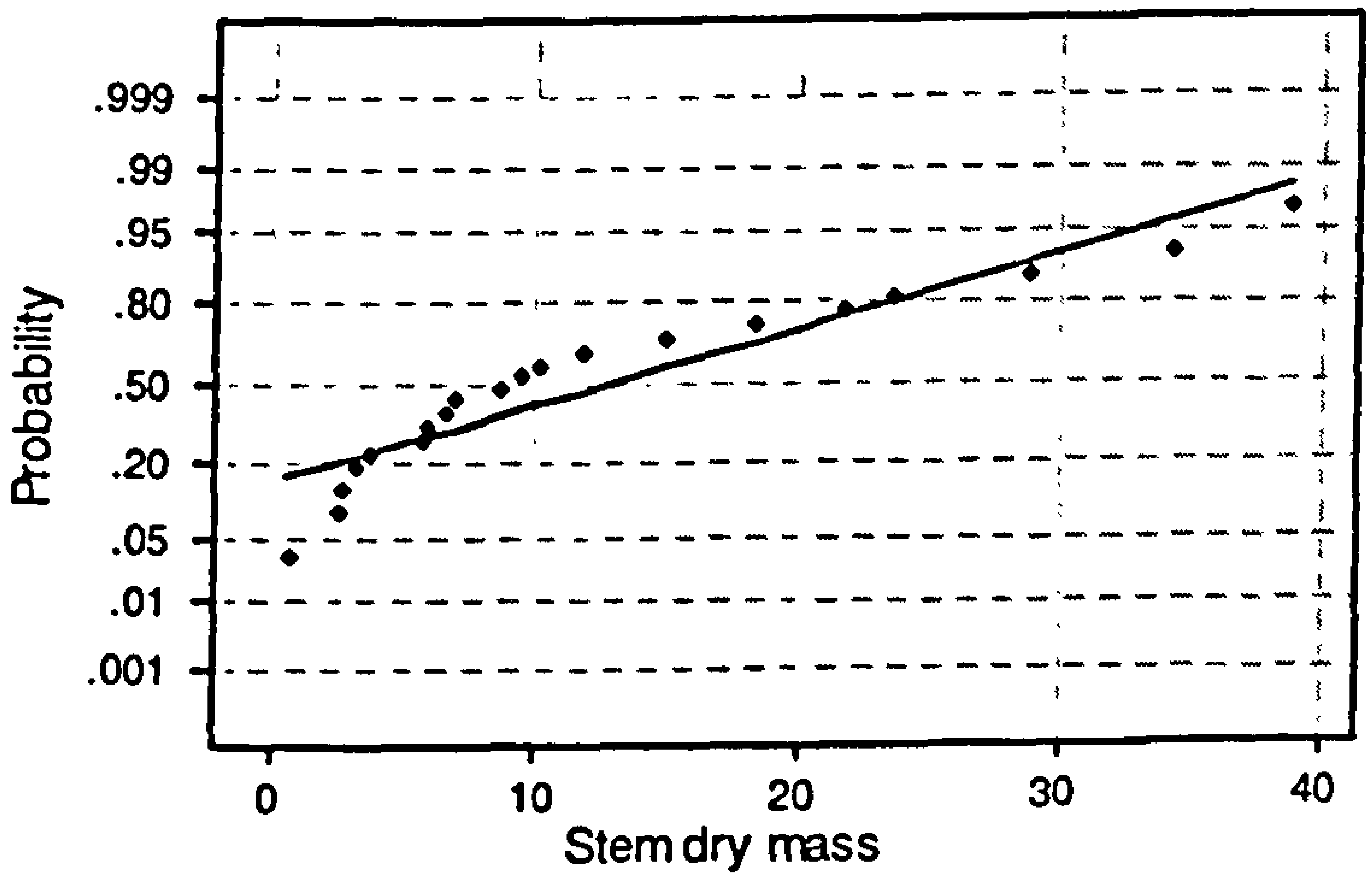
Average: 29.7814
StDev: 29 8498
N: 20

Kolmogorov-Smirnov Normality Test
D+: 0.202 D-: 0.164 D : 0.202
Approximate P-Value: 0.039

Two-Sample T-Test and CI: *G. sepium* Tree Wt (kg), Cocoa Tree Wt (kg)

```
              N       Mean      StDev   SE Mean
G. sepium  10       47.6      33.3         11
Cocoa      10      11.99      8.37        2.6

Difference = mu GsTotTreeWt(kg) - mu CoTotTreeyWt(kg)
Estimate for difference:  35.6
95% CI for difference: (11.4, 59.8)
T-Test of difference = 0 (vs not =): T-Value = 3.28  P-Value = 0.008  DF = 10
```

C. Stem dry mass of cocoa and *G. sepium* shade trees

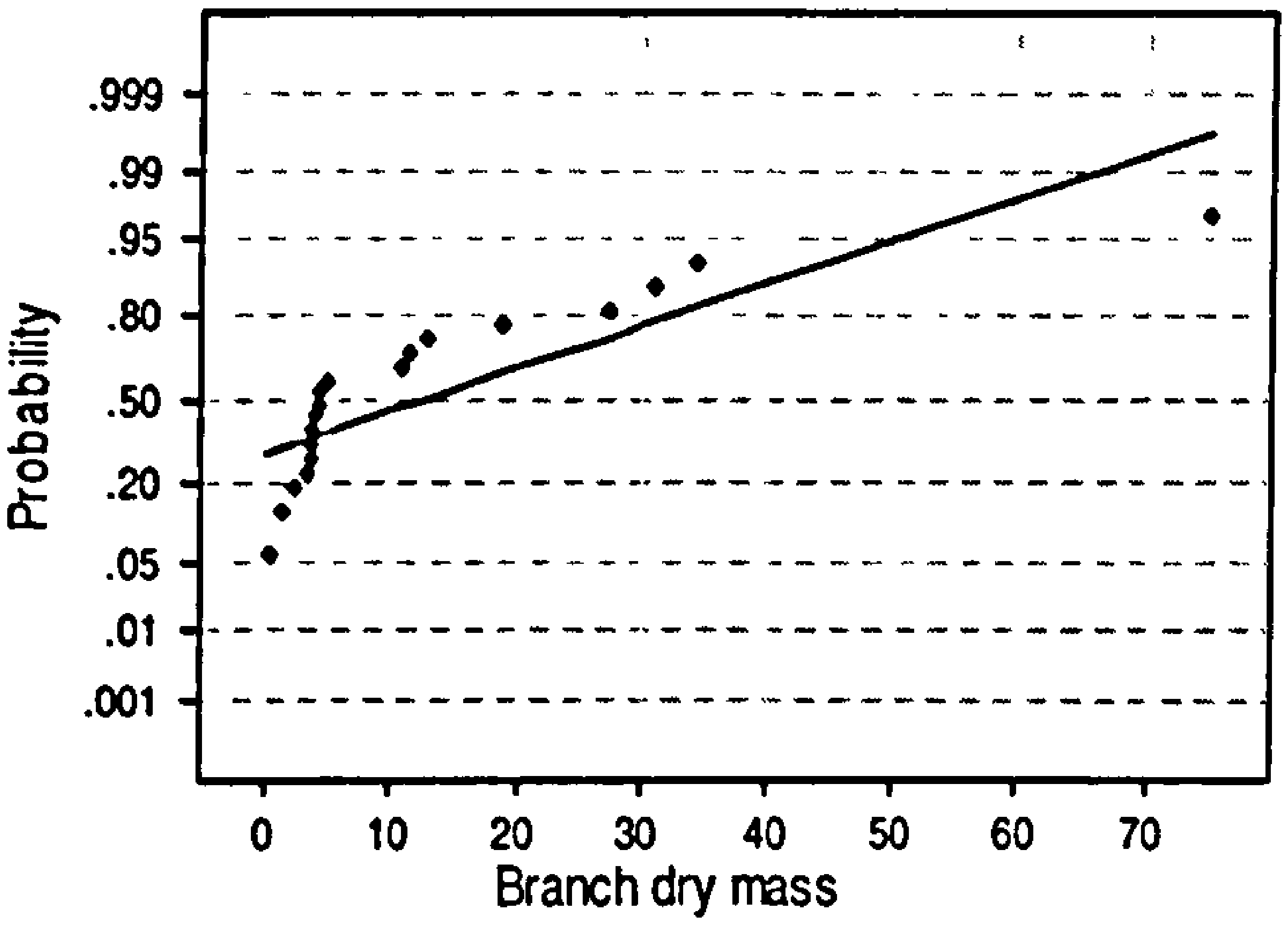


Average: 12.8258
StDev: 11.2331
N: 20

Kolmogorov-Smirnov Normality Test
D+: 0.200 D-: 0.136 D : 0.200
Approximate P-Value: 0.041

Two-Sample T-Test and CI: Cocoa Stem dry mass (kg), G. sepium Stem Wt(kg)

```
              N       Mean      StDev   SE Mean
Cocoa       10      4.93       3.02      0.95
G. sepium   10       20.7       10.9        3.4

Difference = mu CoStemWt(kg) - mu GsStemWt(kg)
Estimate for difference:  -15.79
95% CI for difference: (-23.76, -7.82)
T-Test of difference = 0 (vs not =): T-Value = -4.41  P-Value = 0.001  DF = 10
```



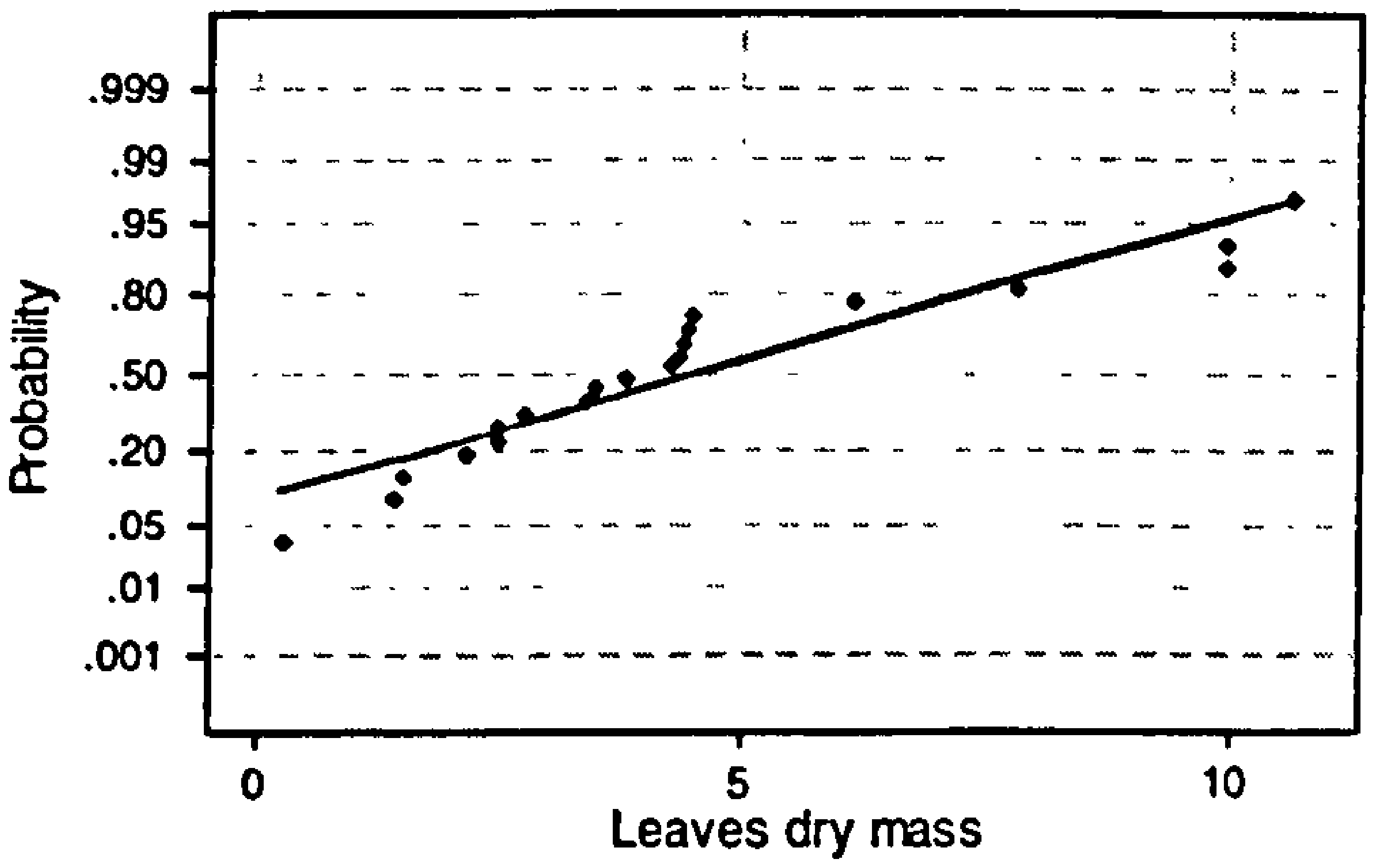
Average: 12 6991
StDev: 18 0457
N: 20

Kolmogorov-Smirnov Normality Test
D+: 0.272 D-: 0.216 D : 0.272
Approximate P-Value < 0.01

Mann-Whitney Test and CI: Cocoa Branch dry mass (kg), Glricidia Branch dry mass (kg)

```
Cocoa Branch        N =  10     Median =        3.37
Gliricidia Branch   N =  10     Median =       15.61
Point estimate for ETA1-ETA2 is      -13.26
95.5 Percent CI for ETA1-ETA2 is (-27.78,-6.82)
W = 71.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0126
The test is significant at 0.0126 (adjusted for ties)
```

Probability Plot For Leaves dry mass of Cocoa and G. sepium trees



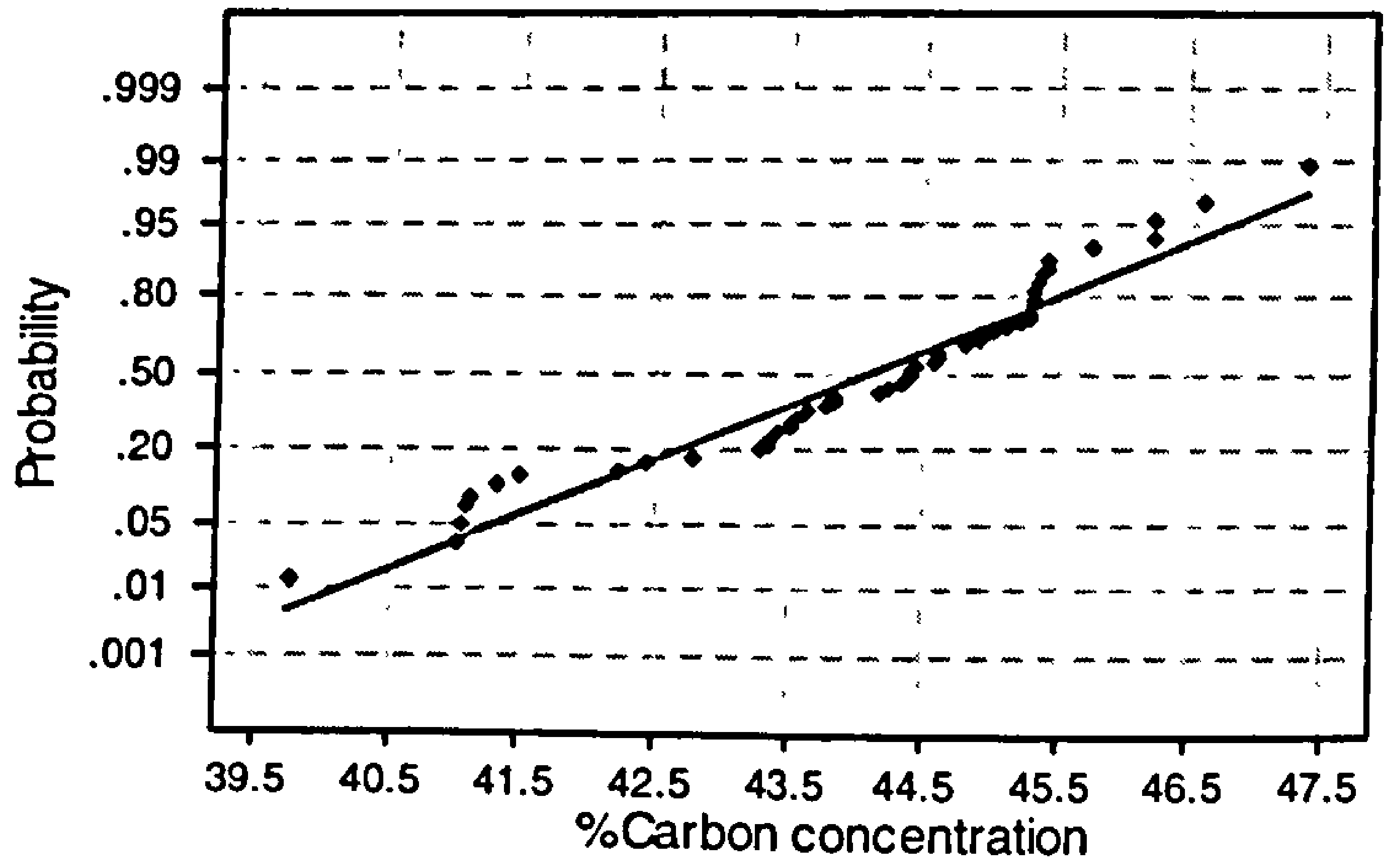
Average: 4 51341
StDev 2.97729
N: 20

Kolmogorov-Smirnov Normality Test
D+: 0.254 D-: 0.117 D : 0.254
Approximate P-Value < 0.01

Mann-Whitney Test and CI: CoLeaves), GsLeaves

```
CoLeaves   N =  10     Median =      3.128
GsLeaves   N =  10     Median =      4.315
Point estimate for ETA1-ETA2 is     -0.676
95.5 Percent CI for ETA1-ETA2 is (-2.787,3.571)
W = 97.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.5708

Cannot reject at alpha = 0.05
```

Appendix 8.2: Normal probability plots and statistical analysis for nutrient concentrations in biomass fractions of cocoa and *G. sepium* trees.



Average: 44 0917
StDev: 1.58816
N: 54

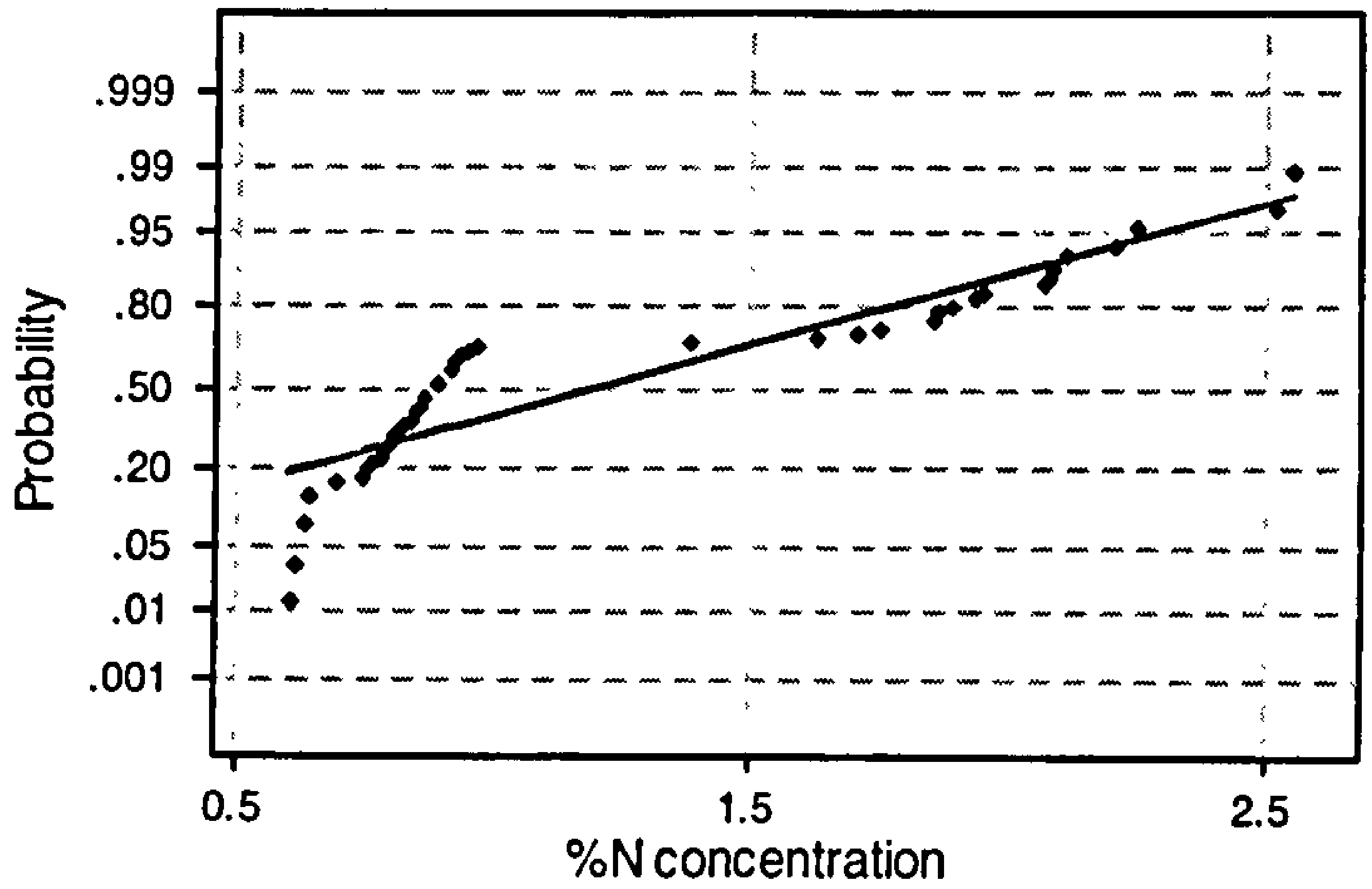
Kolmogorov-Smirnov Normality Test
D+: 0.111 D-: 0.117 D : 0.117
Approximate P-Value: 0.064

Two-Sample T-Test and CI: Mean % C concentration in stem tissues of *G. sepium* and cocoa.

```
             N      Mean      StDev    SE Mean
G. sepium    9     45.40       1.19       0.40
Cocoa        9     45.3300    0.0415      0.014

Difference = mu GScarb. - mu CScarb.
Estimate for difference:  0.071
95% CI for difference: (-0.848, 0.990)
T-Test of difference = 0 (vs not =): T-Value = 0.18  P-Value = 0.863  DF = 8
```

Two-Sample T-Test and CI: Mean % C concentration in branch tissues of *G. sepium* and cocoa.

```
             N     Mean      StDev    SE Mean
G. sepium    9    44.600     0.538      0.18
Cocoa        9    44.409     0.864      0.29

Difference = mu GBcarb. - mu CBcarb.
Estimate for difference:  0.191
95% CI for difference: (-0.542, 0.924)
T-Test of difference = 0 (vs not =): T-Value = 0.56  P-Value = 0.583  DF = 13
```



Average: 1.19111
StDev: 0.595285
N: 54

Kolmogorov-Smirnov Normality Test
D+: 0.318 D-: 0.160 D : 0.318
Approximate P-Value < 0.01

Mann-Whitney Test and CI: Mean % N concentration in stem tissues of *G. sepium* and cocoa.

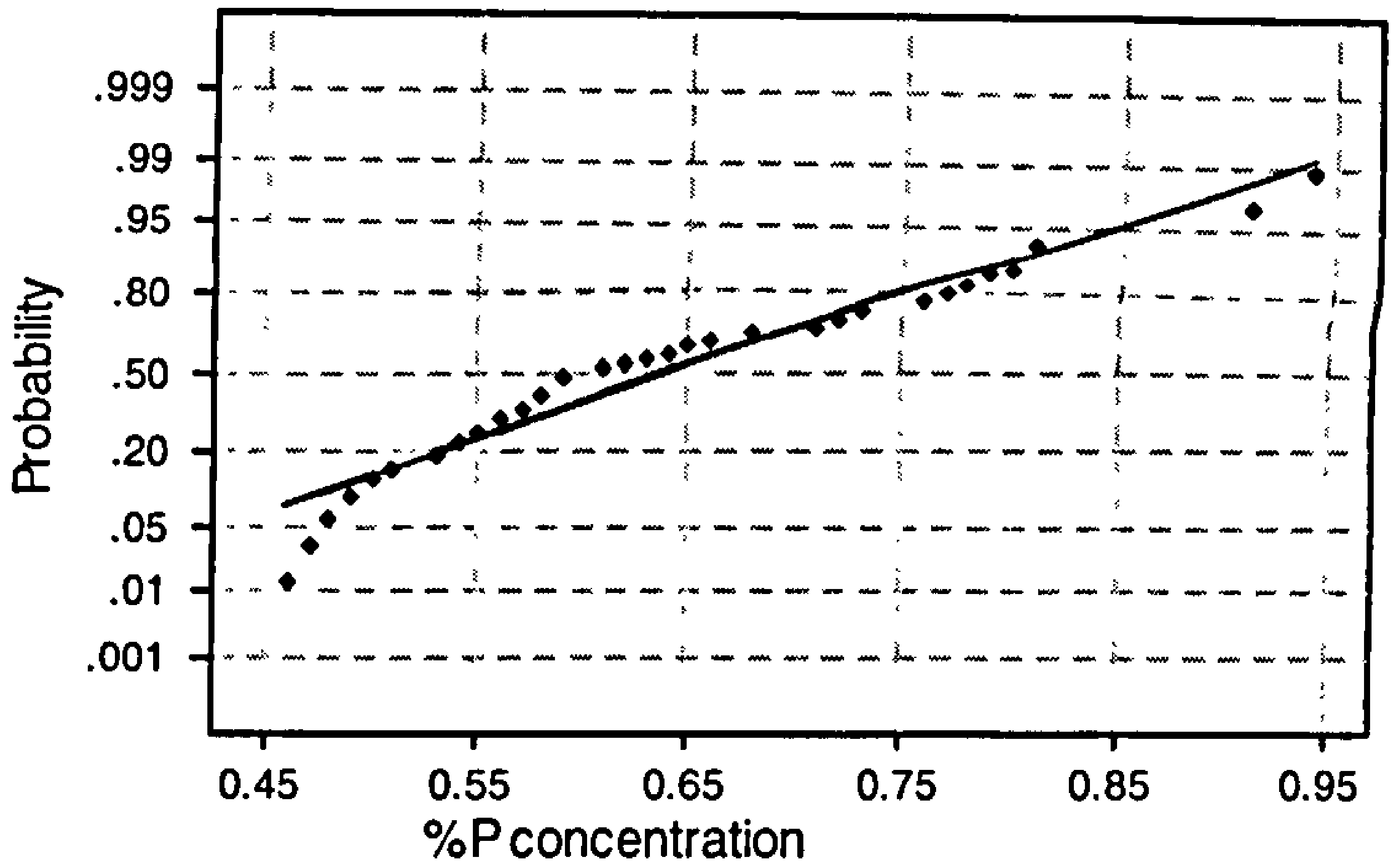
```
G. sepium          N =   9     Median =      0.85000
Cocoa              N =   9     Median =      0.63000
Point estimate for ETA1-ETA2 is      0.22000
95.8 Percent CI for ETA1-ETA2 is (0.17999,0.26001)
W = 126.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0004
The test is significant at 0.0004 (adjusted for ties)
```

Mann-Whitney Test and CI: Mean % N concentration in branch tissues of *G. sepium* and cocoa.

```
G. sepium          N =   9     Median =      0.91000
Cocoa              N =   9     Median =      0.78000
Point estimate for ETA1-ETA2 is      0.13000
95.8 Percent CI for ETA1-ETA2 is (0.09002,0.17003)
W = 125.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0006
The test is significant at 0.0006 (adjusted for ties)
```

Mann-Whitney Test and CI: Mean % N concentration in leaf tissues of *G. sepium* and cocoa.

```
G. sepium          N =   9     Median =       2.1100
Cocoa              N =   9     Median =       1.8500
Point estimate for ETA1-ETA2 is       0.3000
95.8 Percent CI for ETA1-ETA2 is (0.0399,0.5701)
W = 113.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0171
The test is significant at 0.0171 (adjusted for ties)
```



```
Average: 0.638704
StDev: 0.120221
N: 54
```

```
Kolmogorov-Smirnov Normality Te
D+: 0.130  D-: 0.075  D : 0.130
Approximate P-Value: 0.032
```

Two-Sample T-Test and CI Mean % P concentration in stem tissues of *G. sepium* and cocoa.

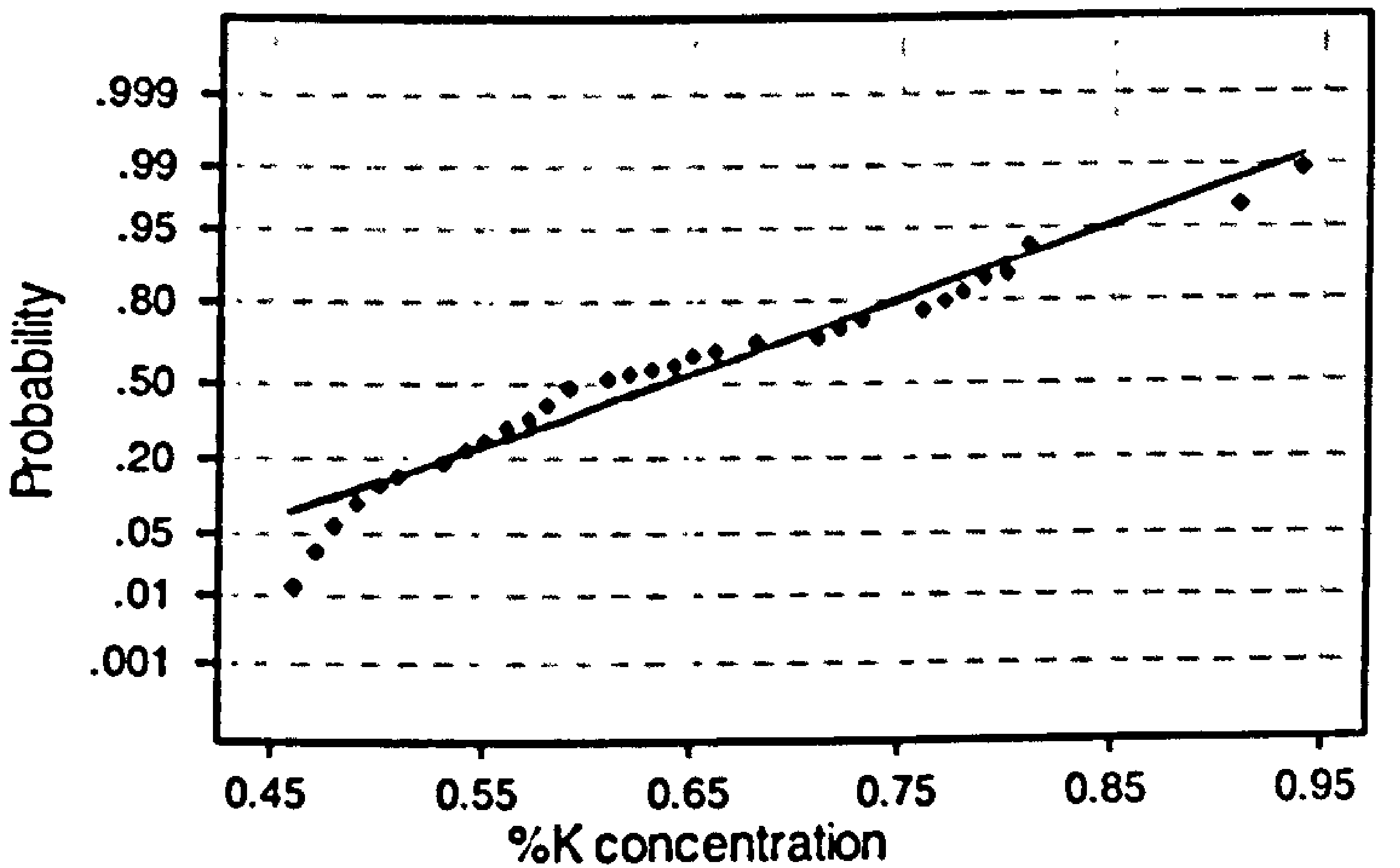
```
             N     Mean      StDev    SE Mean
G. sepium    9    0.0700    0.0212    0.0071
Cocoa        9    0.0433    0.0158    0.0053

Difference = mu GS - mu CS
Estimate for difference:  0.02667
95% CI for difference: (0.00775, 0.04558)
T-Test of difference = 0 (vs not =): T-Value = 3.02  P-Value = 0.009  DF = 14
```

Two-Sample T-Test and CI: Mean % P concentration in branch tissues of *G. sepium* and cocoa.

```
             N     Mean      StDev    SE Mean
G. sepium    9    0.0878    0.0291    0.0097
Cocoa        9    0.0544    0.0230    0.0077

Difference = mu GB - mu CB
Estimate for difference:  0.0333
95% CI for difference: (0.0070, 0.0597)
T-Test of difference = 0 (vs not =): T-Value = 2.70  P-Value = 0.016  DF = 15
```

Two-Sample T-Test and CI: Mean % P concentration in leaf tissues of *G. sepium* and cocoa.

```
             N     Mean      StDev    SE Mean
G. sepium    9    0.1378    0.0277    0.0092
Cocoa        9    0.1322    0.0484     0.016

Difference = mu GL - mu CL
Estimate for difference:  0.0056
95% CI for difference: (-0.0350, 0.0461)
T-Test of difference = 0 (vs not =): T-Value = 0.30  P-Value = 0.770  DF = 12
```



Average: 0.638704
StDev: 0.120221
N: 54

Kolmogorov-Smimov Normality Test
D+: 0.130 D-: 0.075 D : 0.130
Approximate P-Value: 0.032

Two-Sample T-Test and CI: Mean % K concentration in stem tissues of *G. sepium* and cocoa.

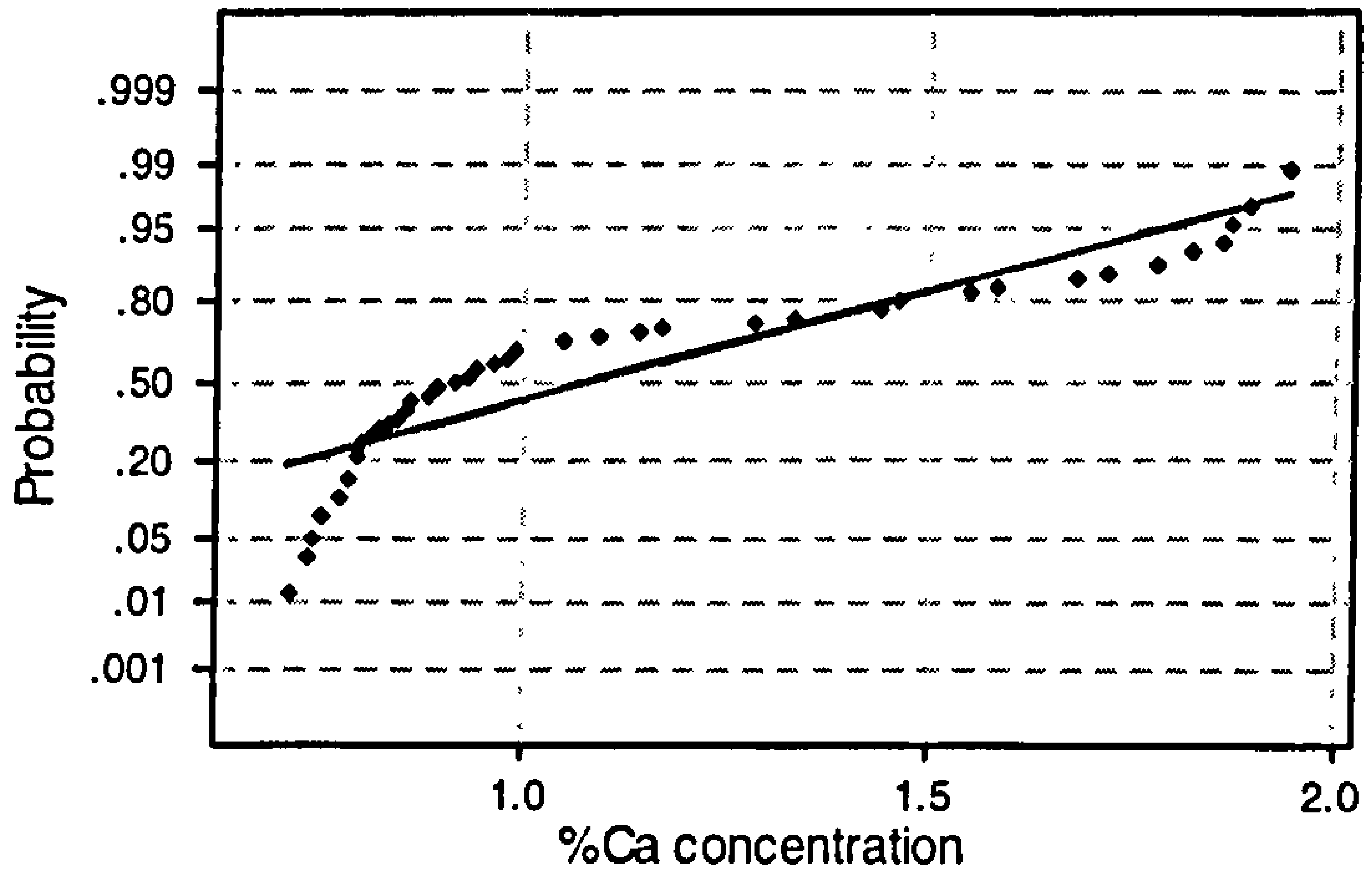
```
              N      Mean     StDev   SE Mean
G. sepium     9    0.4878    0.0172    0.0057
Cocoa         9    0.5656    0.0219    0.0073

Difference = mu GS - mu CS
Estimate for difference:  -0.07778
95% CI for difference: (-0.09752, -0.05803)
T-Test of difference = 0 (vs not =): T-Value = -8.40  P-Value = 0.000  DF = 15
```

Two-Sample T-Test and CI: Mean % K concentration in branch tissues of *G. sepium* and cocoa.

```
              N      Mean     StDev   SE Mean
G. sepium     9    0.5656    0.0219    0.0073
Cocoa         9    0.6433    0.0218    0.0073

Difference = mu GB - mu CB
Estimate for difference:  -0.0778
95% CI for difference: (-0.0997, -0.0558)
T-Test of difference = 0 (vs not =): T-Value = -7.56  P-Value = 0.000  DF = 15
```

Two-Sample T-Test and CI: Mean % K concentration in leaf tissues of *G. sepium* and cocoa.

```
              N      Mean     StDev   SE Mean
G. sepium     9    0.7633    0.0381     0.013
Cocoa         9    0.8067    0.0753     0.025

Difference = mu GL - mu CL
Estimate for difference:  -0.0433
95% CI for difference: (-0.1053, 0.0186)
T-Test of difference = 0 (vs not =): T-Value = -1.54  P-Value = 0.152  DF = 11
```



Average: 1.08593
StDev: 0.378425
N: 54

Kolmogorov-Smirnov Normality Test
D+: 0.239 D-: 0.160 D : 0.239
Approximate P-Value < 0.01

Mann-Whitney Test and CI: Mean % Ca concentration in stem tissues of *G. sepium* and cocoa.

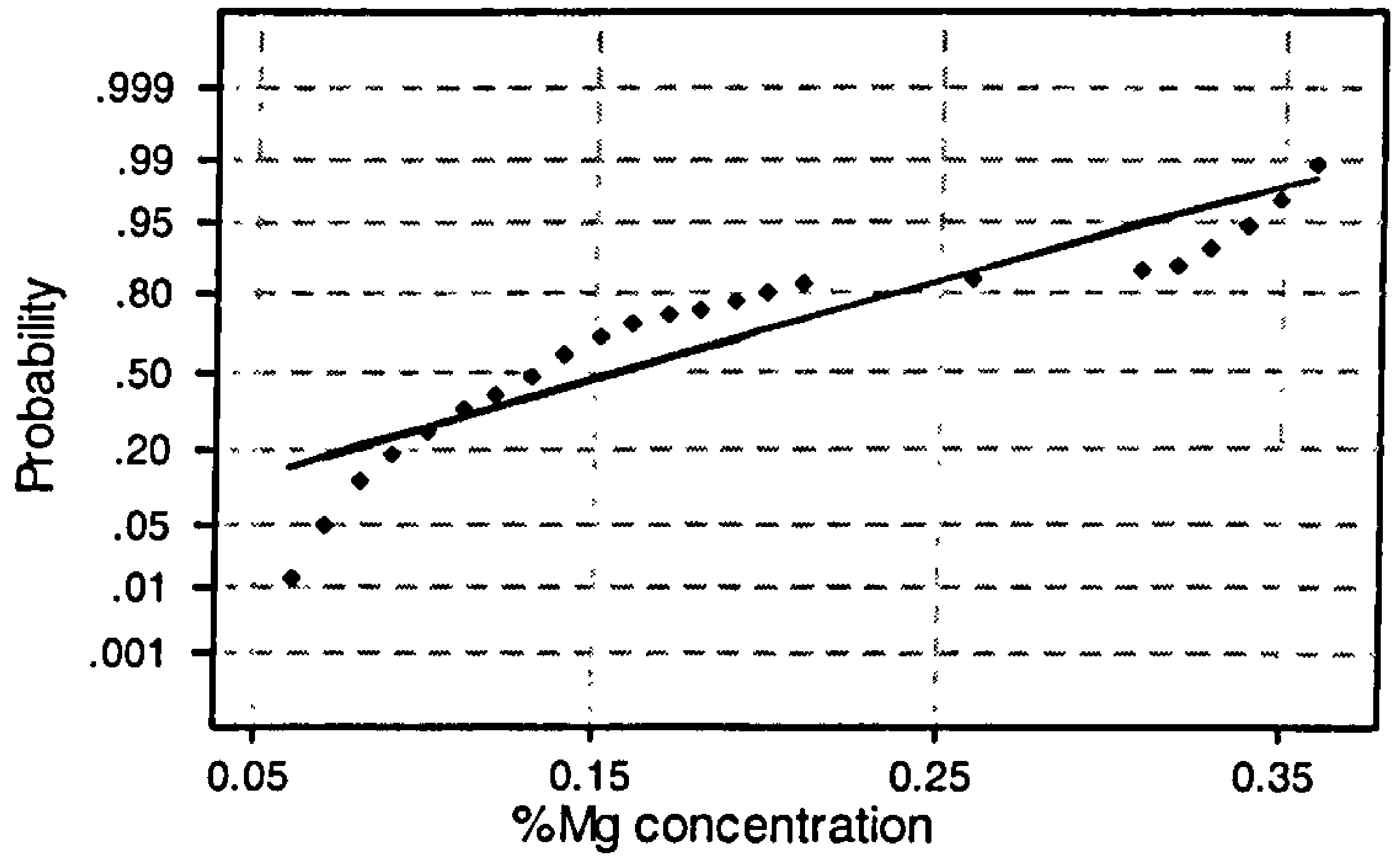
```
G. sepium          N =   9     Median =      0.81000
Cocoa              N =   9     Median =      0.78000
Point estimate for ETA1-ETA2 is     0.03000
95.8 Percent CI for ETA1-ETA2 is (-0.03000,0.07998)
W = 99.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.2332
The test is significant at 0.2320 (adjusted for ties)

Cannot reject at alpha = 0.05
```

Mann-Whitney Test and CI: Mean % Ca concentration in branch tissues of *G. sepium* and cocoa.

```
G. sepium          N =   9     Median =       0.9300
Cocoa              N =   9     Median =       0.8900
Point estimate for ETA1-ETA2 is      0.0300
95.8 Percent CI for ETA1-ETA2 is (-0.0700,0.1401)
W = 90.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.7239
The test is significant at 0.7235 (adjusted for ties)

Cannot reject at alpha = 0.05
```

Mann-Whitney Test and CI: Mean % Ca concentration in leaf tissues of *G. sepium* and cocoa.

```
G. sepium          N =   9     Median =       1.8200
Cocoa              N =   9     Median =       1.3300
Point estimate for ETA1-ETA2 is      0.4300
95.8 Percent CI for ETA1-ETA2 is (0.2700,0.6600)
W = 122.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0013
The test is significant at 0.0013 (adjusted for ties)
```



Average: 0.157593
StDev: 0.0844948
N: 54

Kolmogorov-Smirnov Normality Test
D+: 0.192 D-: 0.124 D : 0.192
Approximate P-Value < 0.01

Mann-Whitney Test and CI: Mean % Mg concentration in stem tissues of *G. sepium* and cocoa.

```
G. sepium          N =   9     Median =      0.10000
Cocoa              N =   9     Median =      0.13000
Point estimate for ETA1-ETA2 is    -0.02000
95.8 Percent CI for ETA1-ETA2 is (-0.05001,0.00001)
W = 64.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0703
The test is significant at 0.0688 (adjusted for ties)

Cannot reject at alpha = 0.05
```

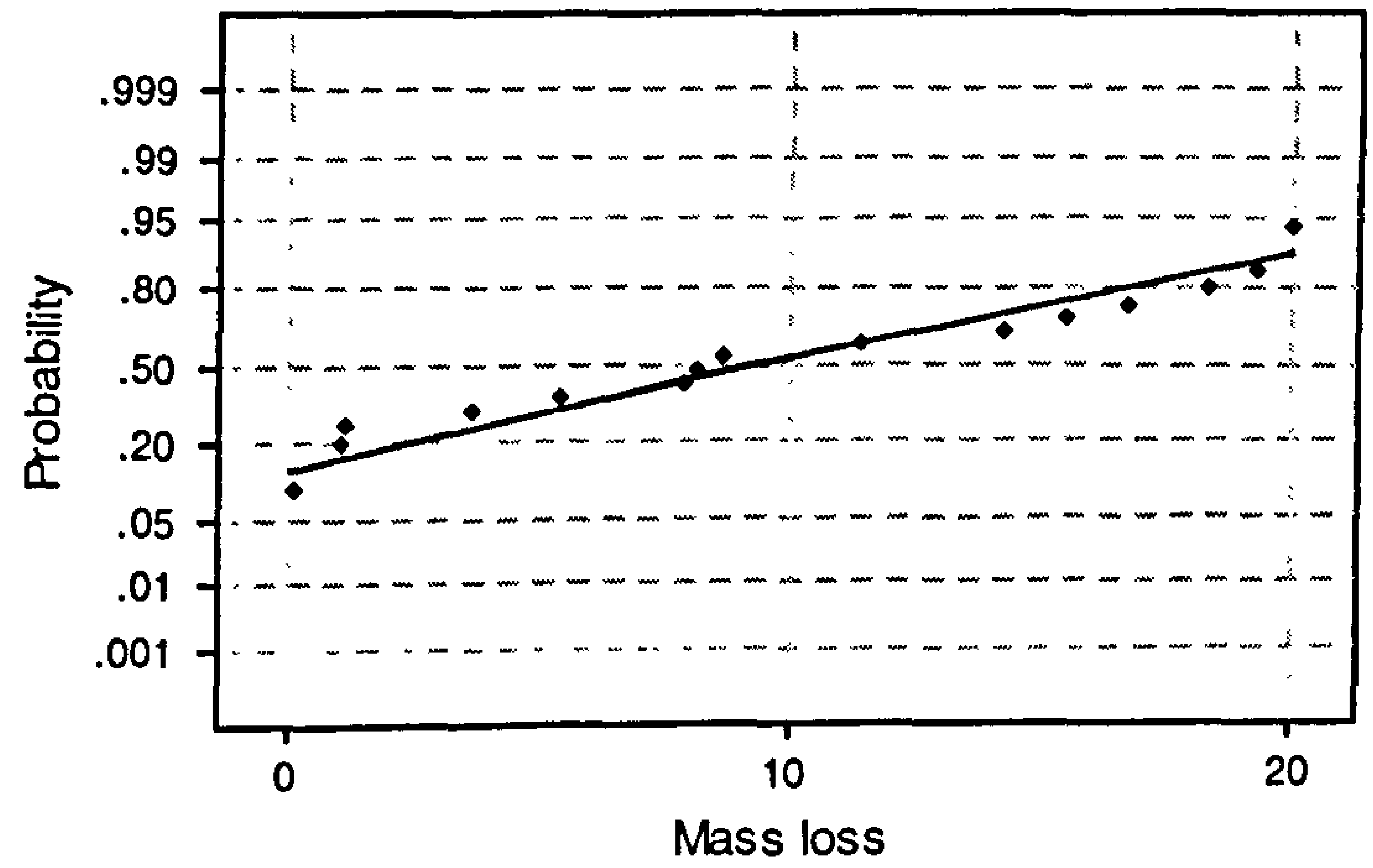
Mann-Whitney Test and CI: Mean % Mg concentration in branch tissues of *G. sepium* and cocoa.

```
G. sepium          N =   9     Median =      0.11000
Cocoa              N =   9     Median =      0.10000
Point estimate for ETA1-ETA2 is     0.01000
95.8 Percent CI for ETA1-ETA2 is (-0.01998,0.04999)
W = 96.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.3538
The test is significant at 0.3521 (adjusted for ties)

Cannot reject at alpha = 0.05
```

Mann-Whitney Test and CI: Mean % Mg concentration in leaf tissues of *G. sepium* and cocoa.

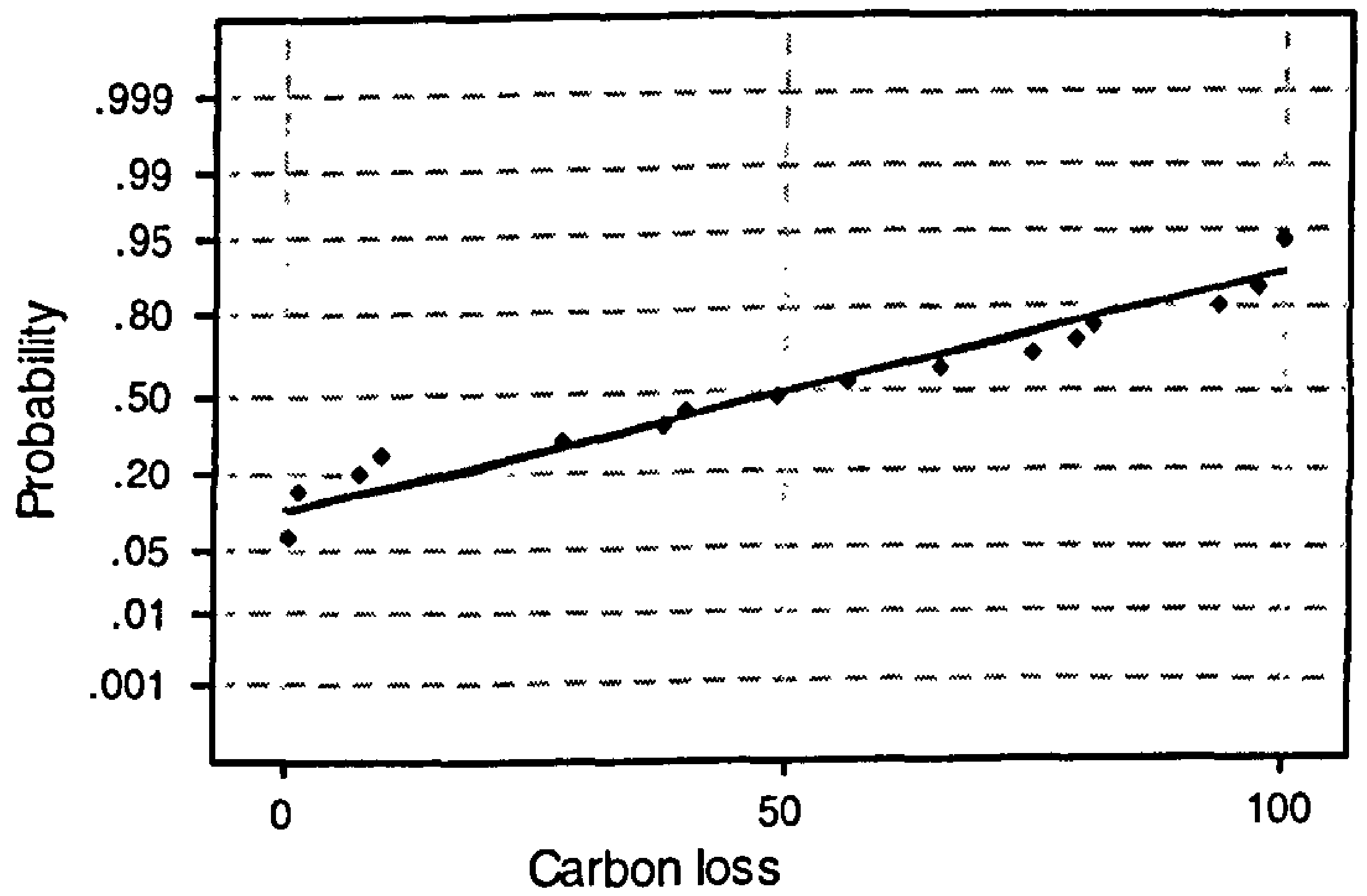
```
G. sepium          N =   9     Median =      0.18000
Cocoa              N =   9     Median =      0.33000
Point estimate for ETA1-ETA2 is    -0.15000
95.8 Percent CI for ETA1-ETA2 is (-0.17999,-0.13002)
W = 45.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0004
The test is significant at 0.0004 (adjusted for ties)
```

Appendix 8.3: Normal probability plots and statistical analysis of decomposition and nutrient release patterns in decomposing leaf litter of cocoa and *G. sepium* in Bontomuruso.



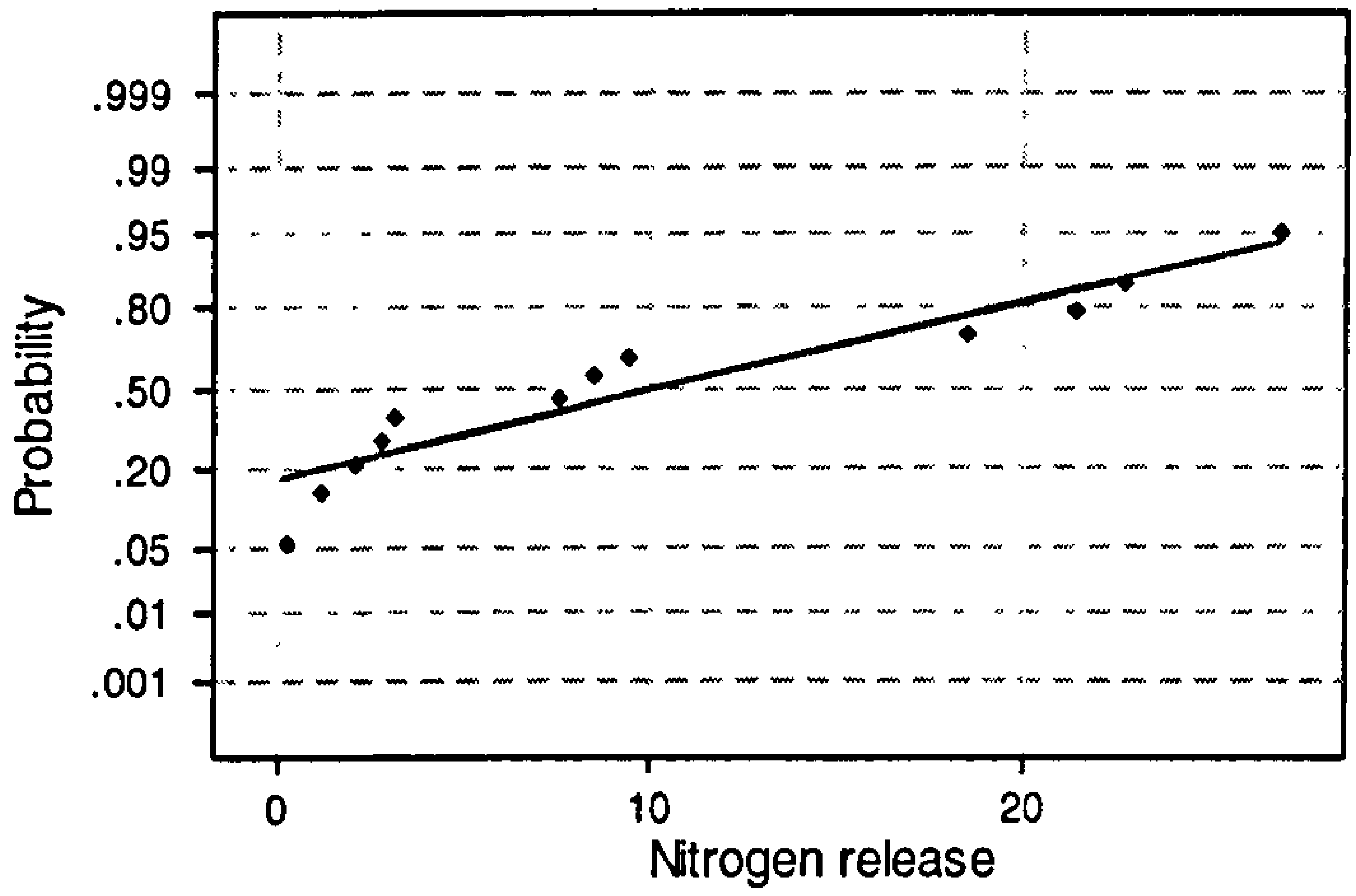
Average: 9 53556
StDev: 7.58746
N: 18

Kolmogorov-Smirnov Normality Test
D+: 0.144 D-: 0.121 D : 0.144
Approximate P-Value > 0.15



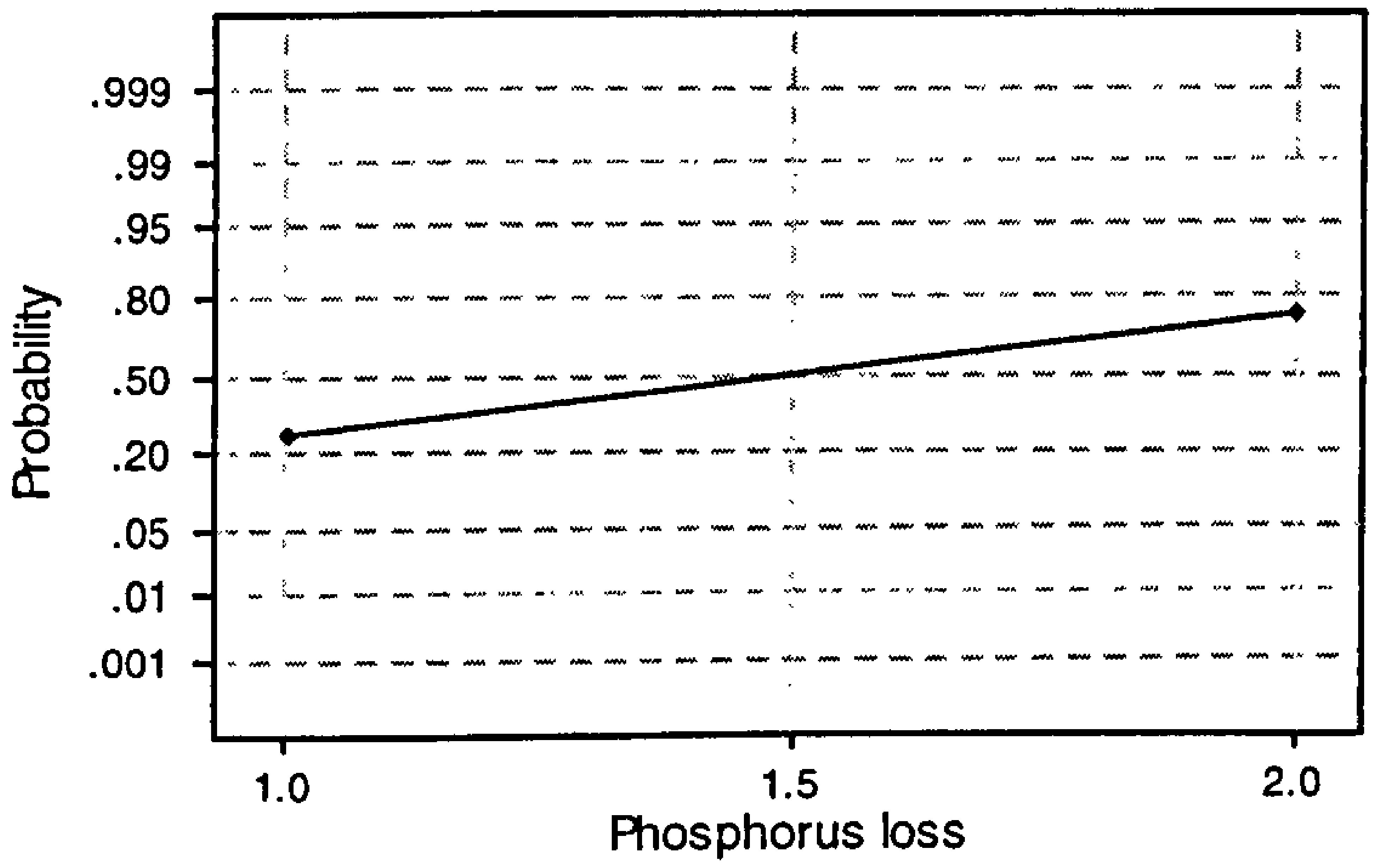
Average: 51.0894
StDev: 37.1717
N: 18

Kolmogorov-Smirnov Normality Test
D+: 0.146 D-: 0.126 D : 0.146
Approximate P-Value > 0.15



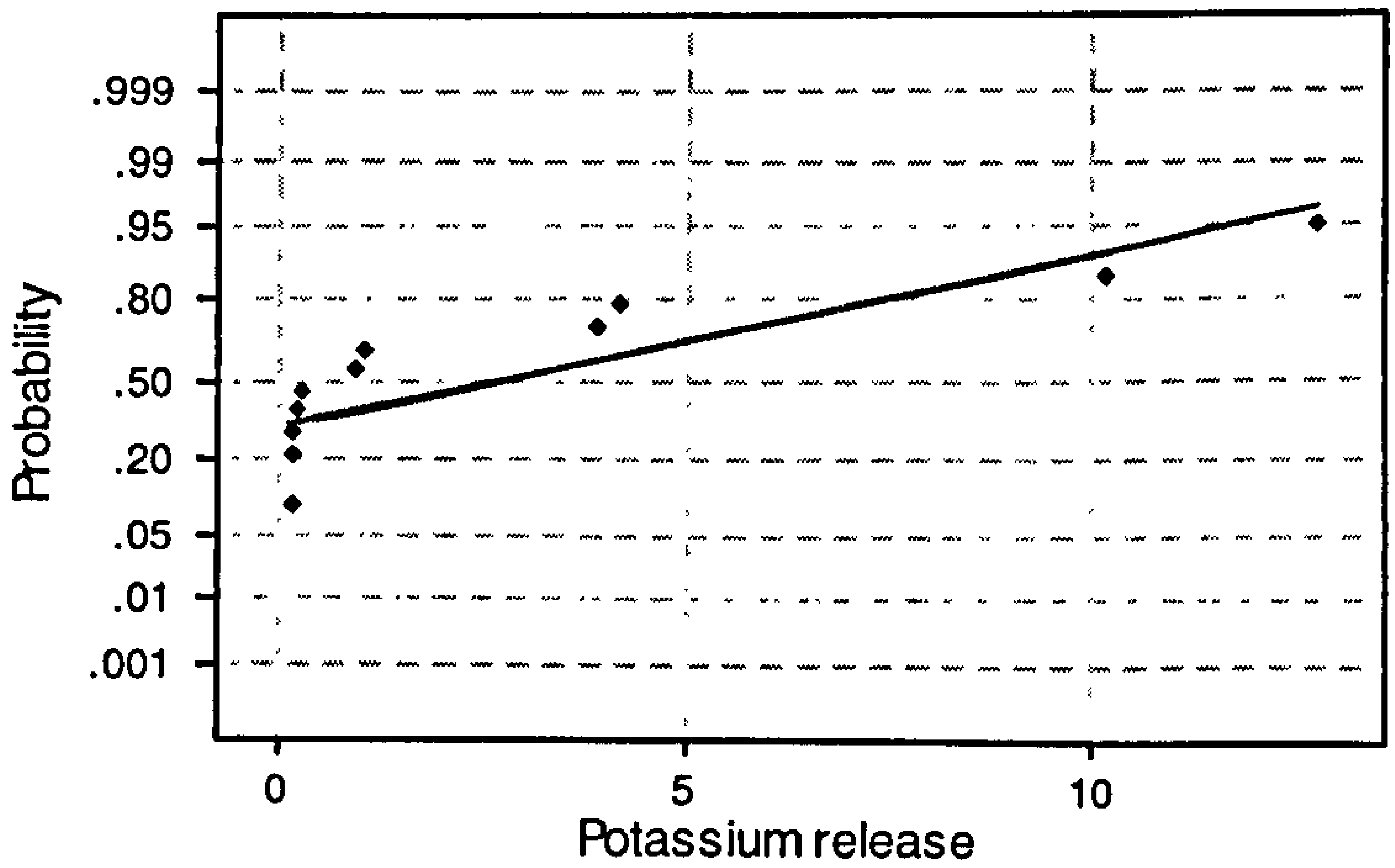
Average: 10.2825
StDev: 9.52112
N: 12

Kolmogorov-Smirnov Normality Test
D+: 0.207 D-: 0.142 D : 0.207
Approximate P-Value > 0.15



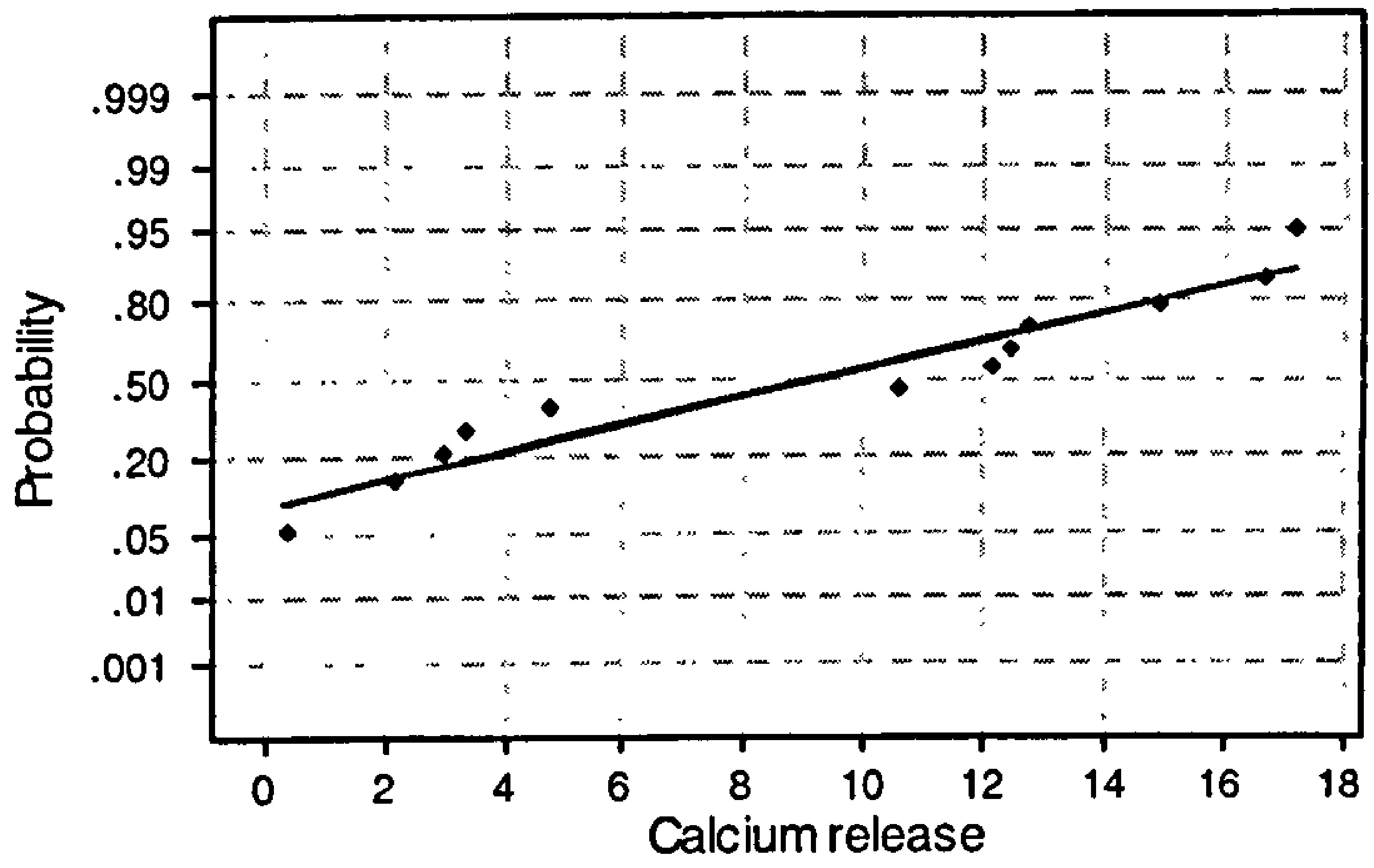
Average: 1.5
StDev: 0.522233
N: 12

Kolmogorov-Smirnov Normality Test
D+: 0.122 D-: 0.122 D : 0.122
Approximate P-Value > 0.15



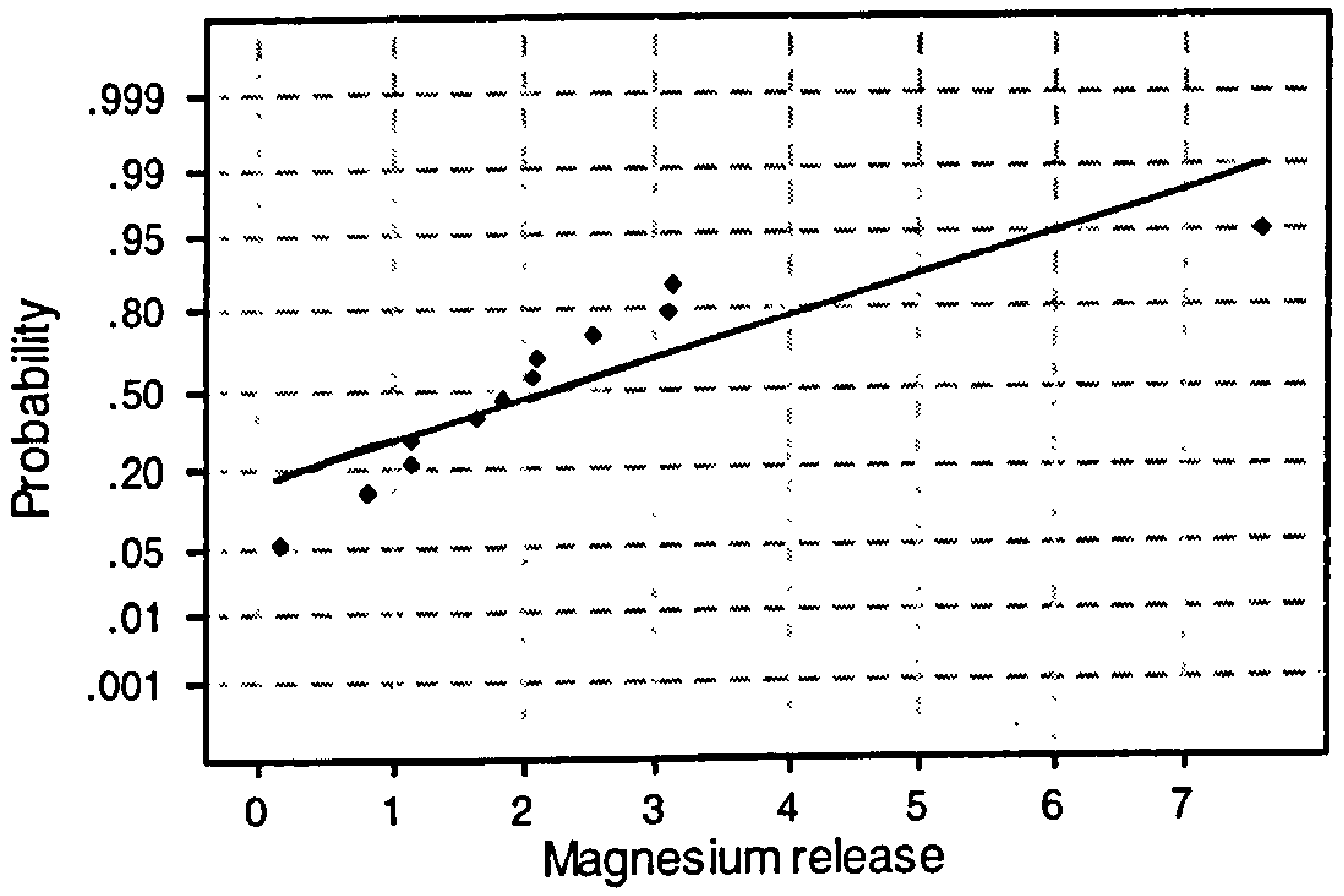
Average: 2.83083
StDev: 4.33254
N: 12

Kolmogorov-Smirnov Normality Test
D+: 0.328 D-: 0.224 D : 0.328
Approximate P-Value < 0.01



Average: 9.18083
StDev: 6.08870
N: 12

Kolmogorov-Smirnov Normality Test
D+: 0.184 D-: 0.185 D : 0.185
Approximate P-Value > 0.15



Average: 2.25583
StDev: 1.90196
N: 12

Kolmogorov-Smirnov Normality Test
D+: 0.245 D-: 0.140 D : 0.245
Approximate P-Value: 0.047

Two-Sample T-Test and CI: Mass loss in decomposing leaf litter of cocoa and *G. sepium*.

```
C16          N       Mean       StDev    SE Mean
Cmass        9      13.71        5.45        1.8
Glmass       9       5.36        7.31        2.4

Difference = mu (Cmass ) - mu (Glmass)
Estimate for difference:  8.36
95% CI for difference: (1.84, 14.87)
T-Test of difference = 0 (vs not =): T-Value = 2.75  P-Value = 0.016  DF = 14
```

Two-Sample T-Test and CI: Carbon loss in decomposing leaf litter of cocoa and *G. sepium.*

```
C19          N      Mean     StDev   SE Mean
Ccarbon      9      70.0      24.8       8.3
Gcarbon      9      32.2      38.9        13

Difference = mu (Ccarbon) - mu (Gcarbon)
Estimate for difference:  37.8
95% CI for difference: (4.5, 71.0)
T-Test of difference = 0 (vs not =): T-Value = 2.45  P-Value = 0.029  DF = 13
```

Two-Sample T-Test and CI: Nitrogen release pattern in decomposing leaf litter of cocoa and *G. sepium.*

```
C22          N      Mean     StDev   SE Mean
CNi          6     12.66      9.33       3.8
GNi          6      7.90      9.94       4.1

Difference = mu (CNi) - mu (GNi)
Estimate for difference:  4.76
95% CI for difference: (-7.83, 17.35)
T-Test of difference = 0 (vs not =): T-Value = 1.85  P-Value = 0.041  DF = 9
```

Two-Sample T-Test and CI: Phosphorus release pattern in decomposing leaf litter of cocoa and *G. sepium.*

```
C25          N      Mean     StDev   SE Mean
CP           6     0.962     0.422      0.17
GP           6     0.708     0.403      0.16

Difference = mu (CP) - mu (GP)
Estimate for difference:  0.253
95% CI for difference: (-0.286, 0.792)
T-Test of difference = 0 (vs not =): T-Value = 1.06  P-Value = 0.315  DF = 9
```

Mann-Whitney Test and CI: Potassium release pattern in decomposing leaf litter of cocoa and *G. sepium.*

```
GK         N =   6     Median =       0.635
CK         N =   6     Median =       0.540
Point estimate for ETA1-ETA2 is       0.070
95.5 Percent CI for ETA1-ETA2 is (-3.769,4.062)
W = 44.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.4712
The test is significant at 0.4704 (adjusted for ties)

Cannot reject at alpha = 0.05
```

Two-Sample T-Test and CI: Calcium release pattern in decomposing leaf litter of cocoa and *G. sepium.*

```
C31          N      Mean     StDev   SE Mean
CCa          6     10.65      5.55       2.3
GCa          6      7.72      6.75       2.8

Difference = mu (CCa) - mu (GCa)
Estimate for difference:  2.93
95% CI for difference: (-5.14, 11.00)
T-Test of difference = 0 (vs not =): T-Value = 0.82  P-Value = 0.433  DF = 9
```

Two-Sample T-Test and CI: Magnesium release pattern in decomposing leaf litter of cocoa and *G. sepium.*

```
C33          N      Mean     StDev   SE Mean
CMg          6     1.972     0.651      0.27
GMg          6      2.54      2.71       1.1

Difference = mu (CMg) - mu (GMg)
Estimate for difference:  -0.57
95% CI for difference: (-3.49, 2.36)
T-Test of difference = 0 (vs not =): T-Value = -1.50  P-Value = 0.047  DF = 5
```