BIOMASS PRODUCTION AND NUTRIENT ACCUMULATION IN AN AGE SERIES OF *Caesalpinia sappan* Linn. PLANTATIONS

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THESIS

**Submitted in partial fulfillment of the
requirement for the degree of**

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DECLARATION

I hereby declare that this thesis entitled "**Biomass Production and Nutrient Accumulation in an Age Series of *Caesalpinia sappan* Linn. Plantations**" is a bonafide record of research done by me during the research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society to me.

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LIST OF SPECIAL ABBREVIATIONS

R^2	**Coeficient of Determination**
Ht	**Height**
agb	**Above ground biomass**
Av.Temp.	**Average Temperature**
R.f.	**Rain fall**
Pl.No.	**Plantation Nunber**
OB	**Over Bark**
NPP	**Net primary productivity**
UB	**Under Bark**
Yr	**Year**
Ha	**Hectare**

Dedicated
to

My beloved parents

&

Family members

Introduction

INTRODUCTION

The high rate of population growth, both human and livestock, results in indiscriminate exploitation of natural resources, for meeting the increasing demand for food, fodder and fuel. The existing tree cover is not sufficient to meet the requirement of major and minor forest products and for environmental conservation. Though National Forest Policy (1988) demands that 33 per cent area should be under forest, only 19.47 per cent of the total geographical area (329 million ha) of the country has actual vegetation cover (Gill *et al.*, 2004). Out of this, only 82.8 per cent is remaining actual forest and rest is wasteland. As population of India is growing fast, per capita forest area is slumping down for 0.075 Ha (ICFRE, 2000).

Forest is the main source of raw drugs, which are collected by the tribal and local communities. The increased demand leads to the over exploitation of these valuable plants resulting in the depletion of many species in several forest areas. India exports about 71,485 tonnes of medicinal plant product worth Rs.18, 00 million (Shiva *et al.*, 1996). About four per cent increase in the export of the medicinal plants over a 10-year period is also recorded. It is estimated that about 20,000 species of plants are used as medicines in the third world countries (Pushpangadan, 1999). Despite these facts, cultivation of medicinal plants is a rare practice in the country. Hence, it was felt necessary to utilize the medicinal plants in a judicious manner. Thus in order to provide regular and sustainable supply of drug raw materials, domestication of the medicinal plants is essential. In recent times, domestication and commercialization of medicinal plants in farm fields got importance for more profit and other reasons. Further more, while some of the medicinal plants are known as potential plants for the reclamation of the waste and degraded land (CSIR, 1990), many are regarded as suitable for introduction in agroforestry systems (Busarua and Tiwaru, 1997; Solanki and Shukla, 1997; Gill *et al.*, 1998 and Sasidharan and Muraleedharan, 2003).

Although every part of the plant has some medicinal value, man has been able to utilize only those plants and those parts that are well established for their medicinal properties. Where one part of the tree has medicinal value than its other parts may also have the same property but the amount of principal medicinal component may differ. So the increasing trend of total utilization of trees has created the need to estimate total biomass production in weight basis rather than conventional volume estimate. Therefore estimation of biomass stands as a prerequisite for better resource utilization. For biomass studies several plantations were established on different habitats to examine its production potential and also the total biomass so as to identify proper variety, habitat and the management practices leading to higher production (Pathak and Gupta, 1987). Primary productivity and biomass gain of a plant or in an ecosystem varies with the availability of resources and characteristics of environment in which they grow. Climate inter alia is the strongest ecological factor in determining primary production. Ecosystem productivity is an index, which integrates the cumulative effects of the many processes and interaction. Net production by an individual plant is the amount of organic matter that it synthesises and accumulates in tissue per unit time (Whittaker and Marks, 1975 and Booth and Mac Murtrie, 1988).

Since measurement of biomass of all trees in a given location is usually impracticable, relationships between component masses and easily measured variables of individual trees are commonly developed and used in prediction. Though attempts have been made to develop prediction equations for estimating biomass of fast growing species in India (Gurumurthi and Rawat, 1989 and Dash et al. 1991) and abroad (Thauitsa, 1990 and Dudley and Fowns, 1991), their applicability was confined to the relevant agro climatic zones. Therefore, there is an imperative need to develop prediction equations for estimating biomass of plantation ecosystems (Chaturvedi and Singh 1982, Negi *et al.*, 1983, Rawat and Singh 1988 and Rana *et al.*, 1989) and man-made short rotation forestry plantations (Bargali 1990 and Lodhiyal 1990).

Estimation of the essential mineral elements in plants is an important aspect in the study of ecosystem structure. In the case of fast growing species it becomes more essential to study the geochemical cycle of the essential elements in support of their survival in future. Geochemical cycle also provides a basis to evaluate the productivity of the ecosystem. In the forest ecosystem, uptake, retention and distribution of biogenic salts in the plant body is influenced by several factors such as age, type of tree species

(Mohsin *et al.*, 2005). Nutrient distribution data provide useful information in assessing the significance of elements in physiological processes in the trees, which affect their overall growth and vitality (Khanna and Ulrich, 1991).

Caesalpinia sappan Linn. belongs to family Caesalpiniacae grows as a small tree. It is cultivated as a medicinal tree in South East Asia including south India, Srilanka, Burma, Indonesia and Malaysia. The wood is bitter and used for fever, bilousness, ulcers, Urinary concentrations, blood complaints, hemorrhages, and wounds. The wood is astringent and decoction of the wood is used in treating dysentery, diarrhea, and in certain skin affections (Troup, 1983). It is consumed internally for certain skin disease. It is also used to improve complexion. Because of its cooling effect, the powdered wood is used as an ingredient in boiled drinking water (Sivarajan and Balachandran, 1994). It also used to the production of red dye, which is obtained from its heartwood. The dye brazilin is oxidized to 'Brazilian' by atmospheric oxygen (Hill, 1952). The brazilian dye is used for facials which are resistant to light, heat and water as well as being non-irritant. The oil obtained from leaves of the tree has antibacterial activity on both gram positive and gram negative bacteria and antifungal activity against *Asperigillus nidulans* (Indrayan, 2002).

In India *Caesalpinia sappan* is widely planted in plantations as well as cultivated in the agroforestry systems and field boundaries. The wood underbark is commercially utilized for the dye and other ingredients of medicinal importance. The amount of wood produced at different ages is the major concern of the farmer. At present, data on biomass, productivity and nutrient accumulation of these plantations are not available and therefore this study was undertaken in the three districts of Kerala. The present investigation was taken up with the following objectives.

1. To study the biomass production of *Caesalpinia sappan* plantations on an age series.
2. To estimate the productivity of *Caesalpinia sappan,*
3. To establish regression models to predict biomass of *Caesalpinia sappan* and
4. To study the nutrient accumulation in biomass.

Review of Literature

REVIEW OF LITERATURE

2.1. The species

2.2.1. *Caesalpinia sappan* Linn

Caesalpinie sappan L is a small thorny spreading tree, grows up to 10 m in height and the wood reaches 15-30 cm in diameter (Manilal, 2003). It is cultivated in south East Asia for the production of red dye, which is obtained from its heartwood. *Caesalpinia sappan* is coming under genus Caesalpinia of about 150 species lianes and trees, distributed in the tropical and subtropical regions.

2.2.1.1. Distribution

Sappan wood or East Indian red wood is a multipurpose tree and a natural dye yielding ornamental medicinal plant. Sappan is cultivated as a horticultural plant for its large compound leaves and bright yellow flowers. Its branches when interlated make a strong barrier, hence, it is considered as a live fencing plant. (CSIR, 1988). *Caesalpinia sappan* is a small thorny tree indigenous to the Eastern and Western Asiatic Peninsulas and Tansania, and is also cultivated in central and south India. In India it is cultivated in gardens and nurseries as a live fence plant in parts of Tamil Nadu, Kerala, Karnataka, Andhra Pradesh and West Bengal and nowhere it is found in the wild (CSIR, 1988). Most of the farmers in Kerala are planting it as an ingredient for purifying drinking water. The annual consumption of the sappan wood in various manufacturing unit of Thrissur is 76695 Kg, Palakkad, 4498 Kg and Kozhikode, 10247 Kg out of total 104442 Kg of Northern Kerala (Sasidharan and Muraleedharan, 2003). Due to excessive exploitation presently, Brazil wood is practically extinct in most parts of the country. The trade of Brazil wood is therefore likely to be banned in the immediate future, creating a major problem in the medicinal, dye and bow-making industry, which mainly relies on this wood (FAO, 1995).

2.2.1.2. Utilisation

Heartwood shows light yellow colour when freshly cut, but it quickly changes to red, the colour diffuses out easily in hot water, in about 7-10 hours and the extract become deep orange colour (Warrior *et al.*, 2002).

The chief constituent of the wood is a colourless, crystalline principle, sappanin, $C_{12}H_{10}O_4$, which is closely allied to brasilin, $C_{16}H_{14}O_5$, obtained from brazil wood, and to haematoxylin, $C_{16}H_{14}O_6$. Solutions of both brasilin and sappanin assume a carmine-red colour in contact with even traces of caustic alkalies, whereas solution of haematoxylin becomes purple. Sappanin is soluble in both alcohol and water. Sappan wood contains *brasilin*, $C_{16}H_{14}O_5$, identical with that of Brazil wood (CSIR, 1988)

The most valuable dye used in colouring leather, silk, cotton, wool, fibres of different kinds, batik, calico printing, furniture, floors, feather, food products, beverages, pharmaceuticals medicines and several handicrafts. More commonly this natural dye has been used in mat industries, where the fibres obtained from sedges (Korai) are coloured by Sappan dye prior to weaving. Super fine and silk mats dyed with sappan are world famous handicrafts (Badami *et al.*, 2004). Before the synthesis of aniline dyes, the heartwood of several tropical trees was used to produce blue, purple, and red dyes. The wood yields a valuable red dye, which is also prepared from the pods and from the bark (Manilal, 2003).

Pods contain 40 per cent tannin and can be used in the place of Sumac. They impart uniform tan and a soft touch to the leather. The bark and fruit walls contain 44 percent tannin. On extraction with petroleum ether, seed yield an orange coloured fixed oil. Volatile oil (0.16 to 0.25 %), tannin (19 %) is present in the leaves. phellandrene, terpene, and methyl alcohol are the important constituents in the volatile oil. The wood is used in carpentry. The timber, which has straight grains, is of great value under the name of Pernambuco for making violin bows. The dye brazilin, is oxidized to 'Brazilian' by atmospheric oxygen (Hill, 1952). The oil obtained from leaves of the tree has antibacterial activity on both gram positive and gram negative bacteria and antifungal activity against *Asperigillus nidulans* (Indrayan, 2002).

2.2.1.3. Medicinal properties

Besides the medicinal properties, the heartwood of Sapppanwood is bitter, astringent, sweet, acrid, refrigerant, vulnerary, depurative, constipating, sedative and haemostatic. The plant is one of the ingredients of an indigenous drug 'Lukol' which is administered orally for the treatment of non-specific lecorrhoea (Channegowda, 1999). Decoction of the wood is a powerful astringent and emmengogue. It is prescribed as a tonic for diarrhoea and dysentery (Troup, 1983). The decoction is also administered in cases of haemorrhage, especially from the lungs. It is commonly given to women after confinement, chiefly as a tonic. It is useful for wounds, ulcers and diabetes. The decoction is considered useful in some forms of skin diseases. It is also used as a diuretic. Because of its cooling effect, the powdered wood is used as an ingredient in boiled drinking water for its antithirst, blood purifying, antidiabetic, improvement of complexion and several other properties. (Sivarajan and Balachandran, 1994).The roots, stems, and seeds are used as sedatives and vulnerary. The seeds are used as a stomachic in Indo-China. The leaves are prescribed for sapraemia.

2.2. Biomass production

Biomass production potential of fast growing species assumes greater importance in all tree-planting programmes. However, it differs enormously with species, site characteristics and stand management practices. Biomass productivity helps into draw value conclusion on carbon sequestration potential of tree species. Assessment of biomass production not only facilitates choice of species but also to asses the impact of deforestation and regrowth rates on the global carbon cycle (Deans *et al.*, 1996). Biomass production potential of trees varies considerably owing to variations in species-site relationships, rotation age-stand density interactions and cultural treatments (Landsberg *et al.*, 1995). The production by a plant community is the reflection of its capacity to assimilate solar energy under some set of environmental conditions. Different plant communities have different rates of biomass production, based on their efficiency (Rai, 1984). Trees play an important role in the global carbon cycle and they are important as potential carbon pools and sinks (Cannel and Dewar, 1994 and Schimel *et al.*, 2001). Plants can modify their efficiency of resource acquisition through their carbon allocation between above and belowground components (Bloom *et al.*, 1985 and Tilman, 1988).

2.2.1. Plantation

A plantation may be afforested land or a secondary forest established by planting or direct seeding. A gradient exists among plantation forests from even-aged, single species monocultures of exotic species with various objectives to mixed species, native to the site with both production and biodiversity objectives. This gradient will probably also reflect the capability of the plantation forest to maintain normal local biological diversity (FAO, 2000).

Biomass production is increasing with increasing age. It was revealed by many studies conducted in different species globally. The biomass of 2- to 8 year-old plantations of *Eucalyptus tereticornis* hybrid growing in the tarai region of Central Himalaya was increased from 7.7 t/ha in the 2-yr-old to 126.7 t/ha in the 8-yr-old plantation (Bargali *et al.,* 1992). Biomass accumulation ratio ranged from 0.81 to 5.93. Lodhiyal (1995) also estimated total plantation biomass of 5 to 8year-old poplar (*Populus deltoides* clone 'D-121') plantations growing on 4 sites in the Tarai belt of Uthar Pradesh, it is increased from 84.0 t ha^{-1} in the 5 year-old to 170.0 t ha^{-1} in the 8-year-old plantation. The total standing tree biomass of shisham (*Dalbergia sissoo*) increased with increasing age and diameter from 53.09 at 3 years to 160.04 t ha^{-1} at 7 years (Das and Chadurvedi, 2003). Negi *et al.* (1995) found the biomass production of 10- 30 age sequence of *Tectona grandis* has produced 74. t ha^{-1} to 164.1 t ha^{-1}. The biomass production in an age series of *Csusuarina equisetifolia* plantations in Puri, Orissa, ranged from about 19 t ha^{-1} (5 year) to 130 t ha^{-1} (15 years) with 76 per cent to 83 per cent being contributed by the above ground biomass. Vidyasagaran (2003) also reported biomass production of *Casurina equesitifolia* at an age of 2 year is 42.3 t ha^{-1} and at 9 years, it was increased to 366.82 t ha $^{-1}$, which shows the above ground biomass increased 9 times from 2 years to 9 years in the plantations of central Kerala.

Tandon *et al.* (1988) reported the biomass production of 3-9 year age series of *Eucalyptus grandis* is 75.59 - 1040 kg tree^{-1}. Singh and Sharma (1976) estimated the biomass production of *Eucalyptus tereticornis* at an age series of 5-9 are 53.18-197.5 kg tree^{-1}. Pathak *et al.* (1981) studied the biomass accumulation in *Leucaena leucocephala* in age sequence and reported 5.92 and 23.86 kg tree^{-1} at the age of 3 and 4 years and arrived at an average biomass of 37.3 kg tree^{-1} at the age of 5 years. Sharma and Ambasht (1991) found that biomass production of an age sequence of Himalayan alder (*Alnus nepalensis*) Plantation was estimated from 106 t ha $^{-1}$ in 7 year old stand to 606 t ha $^{-1}$ in 56 year old stand. Rawat and Negi (2004) estimated the biomass production of *Eucalyptus tereticornis* is varied from 11.9 t ha^{-1} in three years to 146 t ha $^{-1}$ in 9 year old plantation in moist regions. In Dry tropical region it varied from 5.65 t ha^{-1} in 5 year old plantation to 135.5 t ha^{-1} in 9 year old plantations. Singh and Toky (1993) found the biomass in 4 year old stands above ground biomass was markedly higher for *Leucaena leucocephala* (112 t ha $^{-1}$) and *Eucalyptus tereticornis* (96 t ha $^{-1}$) than for *Acacia nilotica* (53 t ha^{-1}) in 8 year old stands values were 126 t ha $^{-1}$, 102 t ha^{-1} and 77 t ha -1 respectively.

The productive capacity of many fast growing trees exhibits substantial variability. Jayaraman *et al.* (1992) reported that *Casuarina equisetifolia* plantations growing in the west coast areas of Kerala are highly productive and can produce biomass of 190 t ha^{-1} at age of 4.5 years. Similar studies had been done by Geyer and Walawender (1997) and Long (1987). Ceulemans (2004) calculated the biomass of 10 year old Scots pine (*Pinus sylvestris* L.) was 13.38 kg for 4.5-5.6m tall trees with an average dbh of 7.16 cm. Kunhamu *et al.* (2006) conducted a study in a seven-year-old *Acacia mangium* Willd stand in Thiruvazhamkunnu to characterise biomass accumulation on per ha basis and reported that the biomass ranged from 5.58 t ha^{-1} to 97.58 t ha^{-1} among different girth classes.

The biomass production in an age series of *Bambusa bambos* plantations in India was estimated and compared with its interspecies natural stands and between genera of natural and plantation stands. The total biomass ranged from 2.3 t ha^{-1} (1 year) to 297.9 t ha^{-1} (6 years) (Shanmughavel *et al.*, 2001). The above ground biomass of 20 year old

Bamboosa bambos raised in hedgerows was also estimated by Kumar *et al.* (2005), bamboo clumps averaged 2417 kg per clump with an average per ha-accumulation of 241.7 t ha^{-1}.

Comparative productivity of *Acacia auriculiformis* and *Casuarina equisetifolia* was studied by Kushalapa (1987) in high rainfall areas of Karnataka, which revealed that the above ground biomass of *Casuarina equisetifolia* was 108.3 t ha^{-1} at the age of 9 years. Adu-Anning *et al.* (1995) assessed the above ground biomass accumulation of 34 year old *Anogeissus leocarpus*, 16 year old *Tectona grandis* and 10 year old *Azadirachta indica*, in the Sudin Savanna of Ghana are 29.1, 8.6 and 7.7 kg ha^{-1} respectively. The biomass production of seven tree species adapted to the semi arid conditions of south India are evaluated by Ponnammal and Gnanam (1988) reported that the greatest above-ground production was produced by *Leucaena leucocephala* (45.52 t ha^{-1}) followed by *Samanea saman, Erythrina variegata* and a local variety of *L. leucocephala*, all of which produced more than 30 t ha^{-1}, *Acacia auriculiformis, Adenanthera pavonina* and *Gliricidia maculata* produced much less than 30 tha^{-1}, while *Albizia lebbeck* produced 27.4 t ha^{-1}. (Deshraj and Raj, 1991) also compared the biomass of eight species in Gujarat, maximum dry weight of biomass recorded for *Albizia lebbeck (*26.10 t ha^{-1}) while the lowest was for *Tamaridus indica* (5.43 t ha^{-1}). Gopikumar (2000) compared the biomass production of four multipurpose species. The results showed that *Albizia falcataria* produced highest biomass compared to *Artocarpus hirsutus*, *Artocarpus heterophyllus* and *Erythrina indica.* Biomass production of the 11 multipurpose tree species was compared on sandy loam soils in Andhra Pradesh (Rao *et al.*, 2000) showed that *Dalbergia sissoo* yielded maximum biomass (214.6 t ha^{-1}) followed by *Leucaena leucocephala* (187.8 t ha^{-1}) and *Acacia auriculiformis* (162.4 t ha^{-1}).

2.2.2. Natural forest

At present the greatest advances in woodland production ecology is being made by studies of primary production in forests known regionally to be the most productive. (Ovington, 1962). High producing forest plantations in Europe generally attain a biomass of approximately 350 x 10^{3} kg ha^{-1} at about 50 years of age, corresponding to an average annual accretion of dry matter of 7 x 10^{3} kg ha^{-1} (Ovington, 1965). Yamakure *et al.*

(1986) estimated the biomass of fall virgin tropical lowland evergreen rain forest dominated by *Dipterocarpus* sp in sebulu, Indonesia is 509 ha $^{-1}$ in a 1.0 ha plot. Singh *et al.* (1987) elucidates total biomass in a *shorea –Madhuca* tropical decideom forests were 53965 kg ha^{-1}. Subedi (2004) found the above ground biomass of *Quercus semecarpifolia* forest that extends throughout the temperate region in Nepal has been carried out at six different localities are 479.17, 357.53, 462.6, 356.02, 272.15 and 304.21 t ha^{-1}. Deepak (1999) estimated aboveground tree biomass for five forest stands purposively sampled in a larger study to represent different harvesting intensities in Nepal's Schima-Castanopsis dominated warm-temperate forests. He found that mean standing-alive biomass ranged from a minimum of 16 t ha^{-1} in the severely disturbed forest to a maximum of 479 t ha^{-1} in a relatively undisturbed forest. Estimates of mean cut biomass ranged from a minimum of 24 t ha^{-1} in a second reference forest to a maximum of 183 t ha^{-1} in the severely disturbed forest. The biomass estimates in the relatively undisturbed, reference forests are well above the 95 per cent upper confidence interval of the global mean.

2.2.3. Agroforestry

Considerable species variation for biomass production were reported by Kumar *et al.* (1998), in a study to know the rates of biomass accumulation by multipurpose trees in woodlot and silvipasture experiments of three age-sequence in Kerala, India. Biomass was highest for *Acacia auriculiformis* 141, 184 and 326 t ha^{-1} at 5, 7 and 8.8 years respectively. *Paraserianthus falcataria* registered the second highest biomass yield of 183 t ha^{-1} and *Leucaena*, the lowest (93.4 t ha^{-1}). Singh Rana (2004) found the biomass of three clones (IC, D-121,G-3) of *populus deltoids* at 4, 6, and 8-10 years age in central Himalayan Tarai region varies from young 32-42 t ha $^{-1}$ to nature stands 120-170 t ha^{-1}. Swamy and Puri (2005) stated that at age 5 years total stand biomass in Agrisilvicultural system was 14.1 t ha^{-1} plantations has 35 per cent higher than Agrisilvicultural system. Wang *et al.* (1991) reported that, *Casuarina equisetifolia* accumulated above ground biomass of 199 t ha^{-1} at age 5.5 years. Roy *et al.* (2006) estimated the biomass production of eight year old trees *Azadirachta indica* on farm boundaries is 21 t ha^{-1}. Sharma *et al.*

(2003) compared the biomass of different provenances of *Acacia catechu* was maximum 54.58 kg/tree in Pi (Lathiani-2). Biomass production potential of *Albizia lebbeck* was evaluated by Roy (1988) under silvopasture system and found out average biomass production per tree was 164.8 kg, giving an annual production of 5.16 t ha^{-1} with a population of 300 trees/ha when sampled at age 9 years.

2.2.6. Rotation

Rotation length markedly influences the yield and regeneration methods (Evans, 1982). Singh (1978) studied rotation as influenced by stand stocking in *Casuarina equisetifolia* and found that Casuarina could be worked on 7 years rotation, if basal area development is maintained at a growth level of basal area index six. To increase the production in a coppiced crop, thinning is essential as the lower stand density gives a better chance for high leaf production and consequently higher biomass (Thaiutsa, 1990).

2.3. Productivity

Productivity is the rate at which biomass synthesised is an important ecological parameter. Net production by an individual plant is the amount of organic matter that synthesises and accumulation in tissue per time (Whittaker and Marks, 1975). Biomass Productivity of trees varies with species-site relationships, rotation age-stand density interactions and cultural treatments (Landsberg *et al.*, 1995).

2.3.1. Plantation

The productive capacity of many fast growing trees exhibits substantial variability. Verma *et al.* (1987) reported that in *Casuarina equisetifolia,* productivity increased in higher age group and non photosynthetic above ground biomass productivity at different ages were 2137, 3438, 3147, 7378, 5796 and 6602 kg $ha^{-1}yr^{-1}$ for 5, 7, 9, 11, 13 and 15 years respectively. Bargali *et al.* (1992) found that net primary productivity (NPP) of 2 to 8 yr-old plantations of *Eucalyptus tereticornis* hybrid growing in the tarai region of Central Himalaya were 8.6 tha^{-1} in the 2 year old to 23.4 t ha^{-1} in the 8-yr-old plantation. Lodhiyal (1995) reported the net primary productivity (NPP) of 5 to 8 year-old poplar (*Populus deltoides* clone 'D-121') plantations growing on four sites in the Tarai belt of Uttar Pradesh, the production was 16.8 t ha^{-1} year^{-1} in the 5 and 6 year-old to 31.8 t ha^{-1} in the 8 year old plantation. Vidyasagaran (2003) also reported productivity of *Casurina equesitifolia* plantations at an age 2 years is 21.2 t ha $^{-1}$ yr^{-1} and at 9 years it is increased to 40.8 t ha $^{-1}$ yr $^{-1}$ in the coastal plains of central Kerala. Maximum mean annual biomass production (MABP) was also maximum for *Dalbergia sissoo* (23.8 t ha^{-1}) followed by *Leucaena leucocephala* (20.9 t ha^{-1}) and *Acacia auriculiformis* (18.0 t ha^{-1}) (Rao *et* al., 2000). The mean annual biomass production in an age series of *Bambusa bambos* plantations was 49.6 t ha^{-1} over the 6 year period. The mean periodic increment and net primary production was highest in the 5th year, during which a peak of 124.1 t ha^{-1} yr^{-1} in net primary production was obtained (Shanmughavel *et al.*, 2001). Kunhamu *et al.* (2006) also conducted an experiment in a seven-year-old *Acacia mangium* Willd stand in Thiruvazhamkunnu to characterize total above ground biomass production per ha and reported that for all the size classes together the MAI was 35.04 t ha^{-1}yr^{-1}.

Comparative analysis of biomass productivity of five tropical tree species was studied by Lugo *et al.* (1990) and found that the rates of stem production at age 5.5 years were 27.8, 20.4, 10.1, 7.7 and 5.5 t ha^{-1}yr^{-1} for *Casuarina, Albizia, Eucalyptus*, exotic *Leucaena* and native *Leucaena* respectively. Harmand *et al.* (2004) estimated the mean aerial woody biomass of three tree fallows, *Acacia Polycantha, Semna siamea*, and *Eucalyptus camaldulensis* of five year age are ranged 5-30 t ha^{-1} year $^{-1}$, 3.81 t ha^{-1} year $^{-1}$ and 5.73 t ha $^{-1}$ year $^{-1}$ respectively. Singh and Toky (1993) also recorded the highest above ground biomass productivity 33 t ha^{-1} yr $^{-1}$ for *Leucaena leucocephala* followed by 29 ha^{-1} yr^{-1} for *Eucalypustus tereticornis* and 14 t ha^{-1} yr^{-1} for *Acacia tortilis* in 4 year old stands in the arid climatic zone of Western India. While in 8 years, the values decreased to 29, 21 and 14 ha^{-1} yr^{-1} respectively. Singh and Rana (2004) also found the Net productivity of three clones (IC, D-121, G-3) of *populus deltoids* at 4,6 and 8-10 year old are in an order D-121 (23 t ha $^{-1}$ yr $^{-1}$) G-3 (21 ha^{-1} yr^{-1}), IC (14 ha $^{-1}$yr^{-1}). Gurumurthi *et al.* (1984) reported a net primary production (NPP) of 30 t ha^{-1} year $^{-1}$ for *Prosopis juliflora* and 38 t ha^{-1} year^{-1} for *Leucaena leucocephala*. Mishra *et al.* (1986) reported net primary production of *Leucaena leucocephala* plantation was 38 t ha $^{-1}$ yr^{-1} in a subhumid region of india.

2.3.2. Natural forest

Productivity of the natural ecosystem showed variation under different climatic and edaphic conditions. Sharma and Ambasht (1991) revealed the primary production of *Alnus nepalensis* plantation in Kalimpong forest division of the Eastern Himalayas is reduced to 25 t ha $^{-1}$ year $^{-1}$ in 7 years and 13 t ha -1 year $^{-1}$ in 56 year stands. Singh *et al.* (1987) estimated the net primary production of *Shorea-Madhuca* tropical deciduous forests were 53401 kg ha^{-1} yr^{-1}. Pathak and Gupta (1987) found the Net productivity of k.500 *Leucaena leucocephala* on moist wasteland at jhansi was 3408 t ha $^{-1}$yr^{-1} at 2 years of age with a density of 40000/ha.

Shanmughavel *et al.* (2001) studied The NPP in an age series of *Bambusa bambos* plantations in India and compared with its interspecies natural stands and between genera of natural and plantation stands. The mean periodic increment and net primary production was highest in the 5th year, during which a peak of 124.1 t ha^{-1} yr^{-1} in net primary production was obtained. Gurumurti *et al.* (1984) reported a net primary production (NPP) of 30 t ha $^{-1}$ y $^{-1}$ for *Prosopis juliflora* and 38 t ha $^{-1}$ y $^{-1}$ for *Leucaena leucocephala.*

2.3.3. Agroforestry

In a coffee and cocoa production system interplanted with *cordia alliodora* and *Erythrina poeppigiana* of Latin America, it was estimated that the tree component alone gave about 10 t ha $^{-1}$ y $^{-1}$ of biomass (Russo and Busowski, 1986). In a hedgerow intercropping system in Nigeria, *Gliricidia sepium* produced 3 to 4.5 t ha $^{-1}$ year $^{-1}$ (Yamoah *et al.*, 1986). Nigam and Roy (2006) conducted an experiment in 12 year old *Acacia tortilis* under silvo pastorial system, the mean woody biomass was 4.79 ha $^{-1}$ yr $^{-1}$ and the total aerial biomass production was 4.95 t ha^{-1} yr $^{-1}$.

2.4. Partitioning of biomass

The biomass accumulation ratio (biomass/net production, BAR) for different tree components increased with increasing ages (Lodhiyal, 1995). Biomass partitioning among various tree components also vary considerably with species and age. Generally, bole fraction accounts bulk of the total tree biomass. For *Eucalyptus grandis* planted at different age sequence in Kerala, India, Tandon *et al.* (1988) reported that the percentage contribution of bole biomass varied from 28 per cent to 86 per cent over a period of 3 to 9 years. However, the percentage contribution of leaf, twig and branches decreased with increasing age and diameter. For *Tectona grandis*, the bole fraction accounted 64.6 per cent of the total above ground biomass at the age of 10 years, which declined to 60.2 per cent at the end of 30th year. However, branch wood proportion substantially increased from 8.3 to 35.15 per cent over the years. Root biomass accounted 28.5 per cent of the total tree biomass (Negi *et al.*, 1995).

The linear increase of the total biomass of all compartments was reported with the age of the plantation in the above-ground biomass (Shanmughavel *et al.*, 2001). Karmacharya and Singh (1992) described the above ground biomass which was ranged from 25.7 to 76.9 t ha^{-1} in an age series of 4 to 30 years. The proportion of woody biomass was 56 per cent of the total at 4 yr old, increasing to 91 per cent of the total by 30 year old *Tectona grandis* Plantations. The proportion of leaf biomass decreased from 34 per cent of the total at 4 year old to 7 per cent at 30 year old plantations. The share of bole decreased from 54 per cent of total net production at 4 year old to 44 per cent of the total at 30 years old with increase in age. The reproductive parts comprised 2 per cent of biomass but accounted for 9 per cent of net production at 30 years old. The allocation of the various components to the different trees in the central Himalayan forest was revealed considerable variation among three species (Rane *et al.*, 1989). For *Shorea robusta* 61.3 per cent biomass was allocated to bole, 10.5 per cent to the branches, 4.7 per cent to the twigs and 2.6 per cent to the leaves. While in Chir pine –Sal mixed forest the branches, twig and leaf were 43.9, 26.9, 10.5 and 3.5 per cent respectively. Osman *et al.* (1992) revealed 72-76 per cent is allocated to stem and 9-12 per cent to leaves in four year old *Acacia auriculiformis* plantation.

The component wise dry matter production of 3 to 7 year old plantation of shisham (*Dalbergia sissoo*) in Pusa (Samastipur), Bihar was estimated by Das and Chaturvedi (2003). The total standing tree biomass increased with increasing age and diameter from 53.09 (3 years) to 160.04 t ha^{-1} (7 years). Leaf, bole, branch and root constituted 1, 58-61, 24-26 and 13-15 per cent of the total tree biomass. Vidyasagaran (2003) also reported the above ground biomass production of *Casurina equesitifolia* increased 9 times from 2 years to 9 years. Out of this bole biomass 12 times, bark and branch 6 times and twig and needle 3 times increased at age of 9 years. Shanmughavel *et al.* (2001) reported the biomass production in an age series of *Bambusa bambos* plantations and compared with its interspecies natural stands and between genera of natural and plantation stands. In the above ground biomass, the percentage contribution of culms (81 %), branches (14 %) and leaves (1 %) was 96 per cent, whereas in the below-ground rhizome contribution was 4 per cent of the total biomass.

The relative allocation of biomass or energy to various above ground parts is a decisive factor that reflects the success of an organism in an environment (Gadgil and Solbrig, 1972). Kunhamu *et al.* (2006) conducted a seven-year-old *Acacia mangium* Willd stand in Thiruvazhamkunnu to characterise stem wood which was accounted for bulk of the above ground biomass (65-75 %) followed by branch wood (12.5-25.2 %), foliage (5.0-6.5 %) and twigs (4.1-6.5 %). In the total dry matter recorded including roots of *Acacia nilotica.* Gurumurti *et al.* (1986) indicated that, stem wood was 30 per cent and branches 35 per cent; root biomass was 9 per cent at 1 year while it was 26 per cent at 5th year. Wang *et al.* (1991) studied the biomass partitioning in five tropical tree taxa in a 5.5 year old plantation in Puerto Rico. They found that *Casuarina equisetifolia* accumulated 70.8 percent biomass in its bole, 17.4 per cent in the branch and 10.9 percent in the leaves. In *Leucaena leucocephala* var. Puerto Rico, the respective values were 72.7, 15.4 and 11.5 percent.

The partitioning of dry matter between different components namely, leaf, reproductive parts, bole, branch wood and roots are a matter of considerable importance in agroforestry. Verma *et al.* (1987) reported that in *Casuarina equisetifolia*, the proportion of bole to agb ranged from 40 per cent to 70 percent. Similar range was reported in

Eucalyptus hybrid by Negi and Sharma (1985). Patel and Singh (1994) studied biomass distribution in some agroforestry tree species including *Casuarina equisetifolia* and reported that accumulation of biomass in different tree species was highest in stem, branch, twigs and roots and least in leaves and bark. Tandon *et al.* (1993) reported that in *Populus deltoides,* among different biomass components, bole contributed the maximum (65 to 73 %) and root biomass contributed between 10 to 21 per cent towards above ground biomass. Maghembe *et al.* (1986) reported values of 14.8 per cent (foliage) and 50.4 per cent (bole) in *Leucaena leucocephala* plantation.

The biomass partition of the 15 multipurpose tree species grown in an agroforestry system is compared in Gujarath (Jaimini and Tikka, 2001). Among these, *Albizia lebbeck* had the maximum trunk and branches weight while *Acacia nilotica* and *A. nilotica var. cupressiformis* had the minimum values for these attributes. The highest twig weight per tree was observed in *Dalbergia sissoo* while minimum values were evident in *Moringa oleifera.* In four multi-purpose tree species, George (1993) observed that foliage has the least biomass yields (ranging from 5.2 % in Leucaena to 8.5 % in Casuarina) and the boles with the highest relative allocation of total biomass (ranging from 66.59 % for Leucaena to as much as 71.74 % for Casuarina) Xiao *et al.* (2004) reported the 33.9 per cent of the biomass were allocated to the stem, 25 per cent to the branches, 22 per cent to the needles, and 17.8 per cent in 10 years old *Pinus sylvestris* L. trees. Kumar *et al.* (2005) estimated that highest biomass accumulation was observed in the live culms (82 %) followed by thorns and foliage (13 %) and dead culm accounted 5 per cent of the biomass accumulation in 20 year old *Bambusa Bambos* hedge rows.

Shujauddin and Kumar (2003) found that stem wood contribution is 70 per cent and foliage contributed the least 7 per cent in 8.8 year° *Ailanthus triphysa* plantation. Swamy and Puri (2005) found that at 5 years the leaves, stem, branches and roots contributed 4.1, 65.2, 10.0 and 20.71 per cent of the total standing biomass (17.2 t ha^{-1}). Konopka *et al.* (2000) reported that the 40 year old trees of Japanese Blue Pine (*Pinus thumbergii*) growing on sandy soil produces 70.4 per cent stem, 9.9 per cent of branches with needles, below ground stump 6.5 and roots represent 13.2 per cent of total biomass.

Adu-Anning *et al.* (1995) assessed the leaf component 1, 5 and 8 percent and woody component 97, 95 and 92 per cent in 34 year old *Anogessus leiocarpus*, 16 year old *Tectona grandis* and 10 year old *Azadirach indica* of total above ground biomass. Roy *et al.* (2006) found the allocation of biomass as minor timber, firewood, and fodder is 66, 24 and 10 percent of total biomass production of 21.1 t ha^{-1} of eight year old *Melia azaderach* planted on farm boundaries. Sharma *et al.* (2003) found the variation in the biomass of leaves, twigs and branches from 1.225 kg/tree, 4.762kg/tree and 11.62-42.13 kg/tree respectively in the different provenances of *Acacia catechu.*

2.5. Biomass prediction

Since measurement of the biomass of all trees in given locations is usually impracticable, relationships between component masses and easily measurable variables of individual trees are commonly developed and used in prediction. The dry weight is determined through destructive sampling and related by regression analysis to easily measurable tree dimensions such as dbh or combination of dbh and height. Stand biomass, volume etc can be estimated with reasonable accuracy by developing regression equation using easily measurable variables such as DBH and Height. Such a relationships needs to be developed for individual site owing to large variation in species - site interactions (Wittwer and Immel, 1978).Many studies have been done to quantify biomass of aboveground compartments of trees (Baker *et al.*, 1984; Rai, 1984; Whitesell *et al.*, 1988; Halenda, 1989; Paramathma, 1992; Latif and Habib, 1993; Grundy, 1995 and Montagu *et al.*, 2005).

Allometric equations of 2 to 8 year old plantations of *Eucalyptus tereticornis* hybrid growing in the Tarai region of Central Himalaya was studied by Bargali (1992). The above- and below-ground components of trees and shrubs were developed for each stand. Lodhiyal (1995) also predicted 5 to 8 year old poplar (*Populus deltoides* clone 'D-121') plantations growing on four sites in the Tarai belt of Uttar Pradesh.

Multiple regression models were found to be suitable for predicting biomass of many species including *Casuarina equisetifolia* as reported by Dash *et al.* (1991) and Ghan *et al.* (1993). Nwonwu (1997) conducted a comparison of *Gmelina arborea* yields in the derived and Guinea Savanna zones of Nigeria. Data on tree age, height, standing stems, and basal area volume production were collected for different age classes of *Gmelina arborea* in trial plots in the 2 zones. Volume production was regressed on each of the other variables separately to choose variables that will be fitted into a multiple regression equation suitable for prediction (based on the R^2 value). Age, height and basal area were finally chosen and were included in the multiple regression models from which the most predictive variable was chosen on the basis of the significance of the beta coefficients. El-Osta *et al.* (1992) calculated the regression equations for predicting biomass (based on diameter at breast height and height) assessed as part of a large afforestation programme using multipurpose species, 17 species were used to establish four trials located along the North West coast of Egypt. Kunhamu *et al.* (2006) find out regression equations linking above ground biomass dry weight, tree volume with GBH (cm) and tree height (m) in a seven year old *Acacia mangium.* Willd stand in Thiruvazhamkunnu, India. In their study prediction equations based on single variable gave good fit with high R^2 values.

Kumar *et al.* (2005) calculated allometric relationship linking clump biomass and culm number with clump diameter of 20 year old hedge rows of *Bamboosa bambos.* Ardiansyah (2005) also conducted a study in District I of PT WKS Jambi, Nigeria. Aboveground biomass of *Acacia mangium* and *A.crasicarpa* was estimated using an allometric equation that relates dry biomass as independent variable to their stem heights as dependent variable. Using field plot data, empirical regression models were established to determine dry biomass of industrial forest plantation using vegetation index of Landsat data. The best models were non-linear exponential and polynomial types, and explained more than 85 percent variability in data.

A study was conducted on *Morus alba* to establish a suitable prediction model for green leaf and total branch wood yield under three management practices in the Doon valley of Uttar Pradesh; Coppicing, pollarding and lopping (Charansingh *et al.,* 1998). Yield data were collected annually in October to November over 9 yr (1986-94), and used as dependent variables, with year (1- 9) as the independent variable, in test prediction equations. Gurumurthi and Rawat (1989) estimated both dbh and height as independent variables gave best equations for predicting biomass of *Casurina equisetifolia.* The Diameter and height are used as predictor variable for the biomass prediction equations. For *Eucalyptus pilularis*, Montagu *et al.* (2005) observed that using dbh alone as the predicator variable produced the most stable relationship. The inclusion of height as a second predictor variable decreased the performance of the general model dbh alone can be an independent variable for the purpose of prediction of biomass (Dudley and Fownes, 1991; Ghan *et al.*, 1993; Tandon *et al.*, 1993 and Rana *et al.*, 2001).

The quadratic prediction model of leaf branch yield with two variables (dbh and crown diameter) was a reliable predictor of leaf branch yield of thirteen agroforestry species suitable to Himalayan areas was estimated by Gupta *et al.* (1990). Christine (1992) estimated biomass of 6 to 7 year old *Acacia mangium* plantations using allometric regression and found that the total biomass could be estimated within a relative error of 4 per cent. Many workers reported that standard deviation and coefficient of determination were the major criteria for the selection of best regression model (Pande *et al.*, 1988; Gupta *et al.*, 1990 and Deans *et al.*, 1996).

Logarithmic transformation of equation was observed to give best prediction for biomass in many species (Negi and Sharma, 1987 and Kushalapa, 1987). Khan and Pathak (1996) reported the prediction of biomass in Leucaena leucocephala (Lam) ranging from 3.5 to 7.5 years growth, Transformate Y=log (l+x) was used for normality of data. Khan *et al.* (1995) calculated statistical analysis for biomass of three multipurpose trees, *Acacia tortilis, Hardwickia binata,* and *Leucaena leucocephala* planted under agro-Silvi pasture and farm forestry experiments. Logarithmic transformation was most suitable for *Acacia tortilis* and *Hardwickia binata* while square root function transformation was most suitable for *Leucaens leucocephala.*

In allometric regressions, the parameters may not be always suitable for comparing different models because the dependant variables differ from one model to another. Therefore, it is possible to compare the different models by an index developed by Furnival (1961). Thapa (2005) developed prediction models for above ground wood of some fast growing trees *Acacia auriculiformis, Acacia catechu, Dalbergia sissoo, Eucalyptus camaldulensis* and *Eucalyptus tereticornis* was conducted on a five and half years old 'Fuelwood Species trial under short rotation'. The lowest Furnival Index (FI) was the main criteria for selecting a model. Among the six models tested, the transformed model Ln W= a + b Ln DBH from a power equation W = a DBH_b was selected. With the exclusion of branch wood models, R^2 is higher in a range of 88.7 per cent for oven dry stem wood of *Acacia catechu* to 99.3 per cent for above ground wood model of *Dalbergia sissoo*. However, R^2 is less than 80 per cent in branchwood (green and oven dry) of *Acacia auriculiformis, Eucalyptus camaldulensis*, and *Eucalyptus tereticornis* showing moderate relationship between branchwood and DBH. In the case of *E. tereticornis*, precision is more than 49 per cent per cent which leads to low reliability in biomass estimation resulting in true biomass deviation in a range of about 49.51 per cent to 56.74 per cent. Kushalapa (1993) reported that in the prediction of standing biomass of *Eucalyptus hybrid*, coefficient of determination alone is not suitable for comparing different weighted and transformed model because the dependant variables differ from one model to another and therefore the best model for predicting aboveground biomass and components was selected based on equation with maximum coefficient of determination and lowest Furnival index values.

Ceulemans (2004) reported the allometric relationship of the 10 year old Scots Pine (*Pinus sylvestris*) trees describing the branch and needle biomass at the branch level, as well as biomass of stems, branches, needles, coarse roots, small roots and total biomass at the tree level. At the branch level, the relationship of branch diameter branch length and whorl positions were best to predict branch and needle biomass and found 96 per cent of the observed variation. Allometric relationship with dbh was the best to estimate biomass of above ground biomass. Ajith *et al.* (2003) formed the statistical model for estimating the woody biomass of *Acacia tortilis* planted in field boundaries under semi arid conditions, on the basis of DBH, 10 Linear Functions, 20 Non-linear functions namely exponential gompertz, allometric and logistic and combined were used.

For the prediction of the biomass of tree regression equations were used widely. Roy *et al.* (2005 and 2006) calculated the biomass prediction equation based on regression analysis with D^2 DBH and D^2H were developed in eight year old *Melia azadirach* planted on farm boundaries. The relationship of bole and total aerial biomass was found to be strong with all the predictor variables whereas relationship of foliage was strong with D^2 and D^2H only. Rana *et al.* (1993) applied two regression models to assess differences in per tree biomass estimation of similar aged plantations 4,6 and 8-10 year stands of three cotton wood clones (*Populus deltoides* 1C,D-121, G-3 clones) planted in Tarai region of central Himalaya. The mean per cent variation in biomass estimation (kg tree $^{-1}$) of different components for three ages combined are within the permissible limits. They concluded that dbh should be preferred over the model having D^2 H as independent variable. Kumar *et al.* (1998) accepted biomass equation for fast growing species in a woodlot and silvopastoral experiment. They developed species-specific equation for a specific age-class and management regime and evolved generalized biomass equation that are independent of tree age, location or management regime.

2.6. Nutrient accumulation

Nutrient dynamics and biogeochemical cycling are fundamental properties of ecosystems that can be altered by large-scale human activities such as nutrient enrichment and atmospheric carbon dioxide increases. Management of entire ecosystems is emerging as the most effective and cost-effective means of protecting natural resources. The biogeochemical cycling of nutrients is one of the fundamental properties of ecosystems. Understanding biogeochemical cycling requires analysis of input and output vectors, and the processes by which elements are recycled within ecosystems (Faulkner and Euliss, 2006).

2.6.1. Nutrient concentration

The significant differences in nutrient percentages by tree component that was unrelated to age or site. Ranasinghe (1992) studied the distribution of nutrients in *Eucalyptus camaldulensis* plantations ranging in age from two to fourteen years, at two sites in the dry zone of Sri Lanka. There were high nutrient concentrations in leaves and bark, the lowest concentrations were in the bole (without bark). Kumar *et al.* (1998) reported marked variations in nutrient concentration of tissue fractions among species and age classes in a woodlot experiment involving nine tropical fast growing species and they observed that mineral element concentration decreased in the order: foliage>branches>roots>bole. Shujauddin and Kumar (2003) showed that foliar N, P, K concentrated was highest, followed by branch wood, course roots and stem wood.

Sharma (1993) reported that dynamics of four macro-nutrients were studied in an age series (7, 17, 30, 46 and 56 years) of Himalayan alder (*Alnus nepalensis*) plantations in the Kalimpong forest division of the eastern Himalayas, West Bengal. Concentrations of nutrients were in the order N>K>Ca>P in most tree components and in under storey vegetation. There was an inverse relation between nutrient concentrations of perennial parts and diameter at breast height. Xue (1996) also reported that in *Cunninghamia lanceolata*, among different nutrients, Ca constituted highest concentration (0.07 per cent to 1.37 per cent) and P the least (0.005 per cent to 0.08 per cent). Singh (1994) made similar observation in *Cryptomeria japonica* and by Singh (1982) in *Pinus patula*.

Concentration of certain nutrients showed a definite trend with increase in age. Wright and Will (1958) reported that Scots and Corsican pine growing on sand dunes exhibited decreasing pattern of some nutrients with age. Increasing trend of nutrient contents with plantation age was largely in the order of nitrogen> potassium> calcium> magnesium> phosphorus (Kadeba, 1991). Bargali (1992) reported that nutrient dynamics in 2 to 8 year old plantations of *Eucalyptus tereticornis* previously investigated for dry matter dynamics in Uttar Pradesh, India. He found that nutrient concentrations changed in the order herb>shrub>tree. Nutrient concentrations in different components of these vegetation types also decreased with plantation age. Nutrient content in trees and shrubs increased and in herbs it decreased with increase in plantation age. Lodhiyal (1995) reported on nutrient dynamics in 5 to 8 year-old poplar (*Populus deltoides*) clone 'D-121' plantations in the Tarai belt of Uttar Pradesh. The nutrient concentrations in different layers of the vegetation were in the order: tree > shrub > herb.

The distribution of nutrients was studied in *Bambusa bambos* plantations of different ages growing in Kallipatty, Tamil Nadu. The percentage distribution of nutrients in different biomass components varied. Ranking for major element concentrations was in the sequence K > N > Mg > Ca > P in branches, culms and rhizomes, N > K > Mg > Ca > P in leaves (Shanmughavel and Francis, 1996 and 2001).

2.6.2. Nutrient accumulation

A direct result of high biomass accumulation rate is that the nutrient accumulation rates are also correspondingly high. The component wise nutrient distribution of 3 to 7 year old plantation of shisham (*Dalbergia sissoo*) in Pusa was studied (Das and Chaturvedil, 2003). They reported that nutrient content of the standing tree increased with plantation age because of an increase in dry matter accumulation. Higher amount of N, P, K, Ca and Mg was accumulated in bole and branches.

The nutrient distribution in 4, 6, 8, 12 and 14 year old plantations of *Pinus kesiya* was found by Pande *et al.* (1987) based on the analysis of sample felled mean trees for a range of diameter classes, indicated that harvesting stem biomass (68 per cent) at 12 yr old would remove nearly 6.9 kg N, 7 kg P, 33 kg K and Ca, and 47 kg Mg per ha. A substantial amount of nutrients was accumulated in the foliage (36 per cent of N, 34 per cent of P, 36 per cent of K, 9 per cent of Ca, and 15 per cent of Mg) and it is suggested that this should be left on site to minimize nutrient loss after harvesting. Morris (1992) reported that Biomass (t/ha DM) and nutrient content were determined by field sampling of eleven 1 to 2 years old *Pinus patula* stands in a high-yielding section of Usutu Forest. Treating these stands as an age series sample of a single yield class, the pattern of accumulation over time at the rotation age (17 years) the biomass contained 551 kg/ha N, 73 kg/ha P, 383 kg/ha K, 238 kg/ha Ca and 88 kg/ha Mg. Annual rates of nutrient accretion into biomass peaked at 6 to 8 years, when the rate of canopy development was greatest.

Sharma (1993) reported that dynamics of four macro-nutrients were studied in an age series (7, 17, 30, 46 and 56 years) of Himalayan alder (*Alnus nepalensis*) plantations in the Kalimpong forest division of the eastern Himalayas, West Bengal. The relative contributions of standing state of nutrients in different tree components of mature plantations were in the order; bole>branch>below-ground part>twig and leaf>catkin. Lodhiyal (1995) reported on nutrient dynamics in 5 to 8 year-old poplar (*Populus deltoides*) clone 'D-121' plantations in the Tarai belt of Uttar Pradesh. The standing state of nutrients was in the order: tree > herb > shrub. Soil, litter and vegetation, respectively, accounted for 80-89, 2-3 and 9-16 per cent of the total nutrients in the system.

The distribution of different nutrients in different life forms, their allocation in different tree components and nutrient cycling in some teak forests of Satpura Plateau are revealed (Pande, 2004). The allocation of nutrients was higher for bole and lowest for leaves, irrespective of sites. The accumulation of nutrients in bole was higher for disturbed and mature sites whereas the trend was reverse for leaves. The contribution of teak in total tree biomass nutrients were 62.7, 70.1, 84.6 and 99.9 per cent for site I, II, III and IV respectively. The young and undisturbed sites showed higher contribution of nutrients in teak. Caldeira *et al.* (2002) quantified the nutrient content of the *Acacia mearnsii* De Wild. Provenance Bodalla, Brazil at the age of 28 months. Among the nutrient contents are contributed 42.6 per cent of the dry matter accounted for leaves and living and dead branches, which in turn account for 74 per cent of N, 72 per cent of P, 63 per cent of K, 68 per cent of Ca, 69 per cent of Mg, and 74 per cent of S of the above-ground biomass. The trunk (bark and wood) represents the remaining 57.4 per cent of the total above-ground biomass, out of which 26 per cent of N, 28 per cent of P, 37 per cent of K, 32 per cent of Ca, 31 per cent of Mg, and 26 per cent of S were accumulated. Mohsin *et al.* (2005) estimated the concentration of N, P, K (kg $ha^{-1}yr^{-1}$) in different components of *populus deltoids* at 2-3 and 6-7 ages under Agronomy systems. It is observed that N, P, K in different ages decreased with increase in age of plantations.

The distribution of nutrients was studied in *Bambusa bambos* plantations of different ages growing in Kallipatty, Tamil Nadu. The maximum amount of all nutrients per hectare occurred in the culms, followed by branches, rhizomes and leaves. Harvesting the above-ground biomass of 286 t ha^{-1} at 6 yr old would result in the removal of 2377, 234, 2599, 1188 and 1330 kg/ha of N, P, K, Ca and Mg, respectively. Culms formed 85 per cent of the total biomass and accounted for 58-69 per cent of all nutrients in the plants (Shanmughavel and Francis, 1996 and 2001).

2.6.3. Nutrient use efficiency

The above-ground nutrient productivity decreased with the increase in plantation age, as a result of which the nutrient use efficiency increased with increasing plantation age. (Bargali, 1995). He attempted to examine the use of N, P and K in an age series of 1 to 8 year old *Eucalyptus tereticornis* plantations in the Tarai belt of Uttar Pradesh. Various parameters like nutrient uptake, nutrient reabsorption before leaf abscission, nutrient use efficiency (g g^{-1}), and above-ground productivity per unit leaf nutrient (g g^{-1} leaf nutrient yr^{-1}) were calculated. The foliage nutrient concentration and fractional nutrient reabsorptions before leaf abscission decreased with the increase in plantation age.

The uptake, accumulation and distribution of nutrients in the plant body are affected by several factors such as age, species, soil conditions, spacing, climate etc. (Ovington, 1965). Singh (1994) reported that nutrient use efficiency shows an increasing trend with increase in age. He observed that in *Cryptomeria japonica*, the quotient for nutrient use efficiency was 82 at age of 7 years and it increased to 131 at age of 40 years. Bhatnagar (1966) found that in *Casuarina equisetifolia*, uptake of nitrogen was inversely correlated with the availability of light and the uptake of potassium and phosphorus on the other hand exhibited a regular trend. Nutrient contents increased much more than nutrient uptake rates (Gholz and Fisher, 1985).

Comparing the nutrient use efficiency and biomass production of five tropical trees, Wang *et al.* (1991) have shown that *Casuarina equisetifolia* with the highest growth rate had the highest nutrient efficiency for N, P, K and Mg and *Leucaena leucocephala* var K8 had the least efficiency for N, K Ca and Mg. For most nutrients, stem wood and large branches were the most important nutrient sinks followed by small branch, bark and then leaves.

2.6.4. Nutrient drain

Nutrient losses accompanying biomass harvest has been of great concern in the recent years, especially, in the context of planting high-yield species followed by whole-tree harvesting (Bormann and Johnson, 1983).Verma *et al.* (1987) studied nutrient distribution in different aged plantations of *Casuarina equisetifolia* and found that the harvesting of utilisable biomass would result in the removal of 59 per cent N, 50 per cent P, 63 per cent K, 65 per cent Ca and 66 per cent Mg of the total amount of nutrients retained in the aboveground biomass. Pande *et al.* (1987) found that in *Eucalyptus* hybrid, harvesting of utilizable biomass at the age of 10 years would result in the removal of 52 per cent N, 70 per cent P, 66 per cent K, 78 per cent Ca and 67 per cent Mg.

Kumar *et al.* (2005) estimated the nutrient export (N, P, K) of hedge row raised 20 year old *Bambusa bambos*, varied, highest in live culms, followed by leaves + twigs and dead culms. Average N, P, K, and removal were 9.22, 1.22 and 14.4 kg per clump respectively.

According to Hopman *et al.* (1993) that analysed ecosystem in south eastern Australia, nutrient removals from wood generally represented only a small percentage of available soil reserves. Nutrient content of bark was higher compared to stem wood and therefore, export of nutrients as a result of harvesting was significantly reduced by on-site debarking.

Materials and Methods

MATERIALS AND METHODS

The present study was conducted in an age series of *Caesalpinia sappan* plantations grown in three districts of Kerala viz., Trichur, Kozhikode and Palakkad which are situated between 9° 55' to ll° 50' N and 75° 50' to 76° 53' E. Nine plantations belong three age groups ranging from 5 to 7 years were studied for biomass production, productivity and nutrient accumulation and these plantations were raised and maintained by farmers and government agencies.

3.1. Location, climate and soil

Caesalpinia sappan plantation of Palakkad district is located at low rainfall dry agro climatic zones of the state. It receives about 960 mm annual rainfall and remains dry for most of the months. The mean maximum temperature is 44^0 C and mean minimum temperature is 21.1^0 C. The soil is inceptisol. The plantations selected in Thrissur district are situated in the humid zone in the central part of the state. The annual average rainfall is 2550 mm. The mean maximum temperature is 32^0 C and mean minimum temperature is 21^0 C .The soil is laterite alluvium and acidic. Kozhikode district is situated in the humid zone in the northern part of the state. The average rainfall is 3266 mm. the mean maximum temperature is 39^0 C and mean minimum temperature is 21^0 C. The details of these plantations, climate and edaphic factors pertaining to study area are given in Table I. The area receives an average annual rainfall of 3229 mm, of which about 73 per cent is received from southwest monsoon, about 25 per cent from northeast monsoon and remaining from summer showers. Average annual temperature of the area is 28.5^0 C. Maximum temperature (39.2^0 C) is recorded in March and minimum (19.9° C) in the month of December. March is considered the hottest month and December the coldest. Average relative humidity of the area is 73.5 per cent. The location of the plantations is shown in Fig 1.

Table 1. The location, growth, climatic and soil parameters of the study areas

Plot.. No	District	Locality	Age	Av. Dbh	Av. Height	No. of trees /ha	Av.RF (mm)	Temp (^oC)	Soil Type
1	Palakkad	Oottara	5	5.56	5.91	1111	960	21.1-44.0	Inceptisol (Black soil)
1		Kollengode	6	6.14	5.66	1111			
1		Mechira	7	7.12	6.37	1000			
2	Thrissur	Arayiram	5	6.11	5.96	1111	2550	21.0 - 32.0	laterite alluvium
2		Kuttanallur	6	7.06	6.51	1111			
2		Amballur	7	7.44	6.69	1111			
3	Kozhikode	Ulliyeri	5	6.23	6.18	1111	3266	21.0-39.0	Laterite
3		Perambra	6	7.64	6.77	1000			
3		Moypoth	7	7.99	7.02	1111			

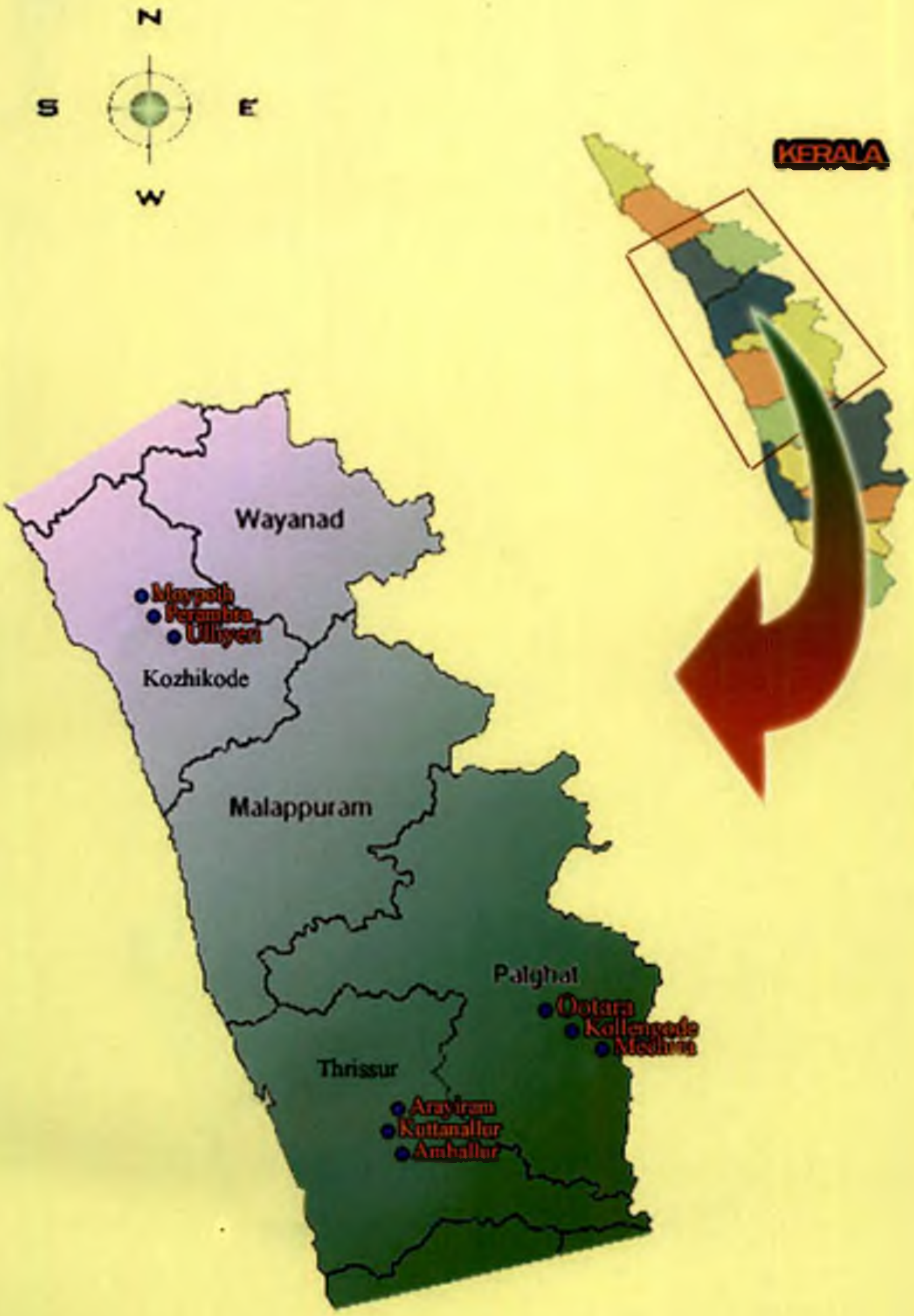

Fig.1. Map showing study sites

3.2. The species

3.2.1. *Caesalpinia sappan* Linn. Syn. *Biancaea sappan* Todaro.

Family: *Caesalpinaceae*

Local names: *sappan wood*, *bukum wood* (Engl.). Pathimukham, Cappannam, sappannam (Mal)

3.2.1.1. Morphology

Sappan is a small thorny spreading tree, grows up to 10 m in height and the wood reaches 15-30 cm in diameter. It bears 3-4 seeds, ellipsoid, and brown to black coloured. The leaves are compound, and up 50 centimeters long. The pinnae are about 20, opposite, and 10 to 20 centimeters long. The leaflets are 20 to 30, obliquely oblong to oblong-rhomboid rounded at the apex. The flowers are yellow, on terminal and axillary panicles, and 2 to 2.5 centimeters in diameter. Stamens waxy white, filaments densely wooly at the base .The fruit a woody pod is oblong to oblong-ovate, about 7 centimeters long, and 3.5 to 4 centimeters wide, hard, shinning, with a hard, recurved beak at the upper angle. (Manilal, 2003). The leaves persist year long but defoliates only for a short period of 10-15 days in a year. As the older stems are removed, others grow up and take their place.

3.2.1.2. Flowering and Fruiting

Within a year's time the plant reaches a height of 3-5 m and begins to bloom in July-August and continues till December. Flowers are golden yellow in colour and are cross-pollinated by bees, butterflies and insects. Fruit set starts after 5-15 days of flowering (August to November). They come to maturity in three months' time. Only few seeds mature. (Warrior *et al.*, 2002)

3.2.1.3. Soil conditions

It grows well in all kinds of soil and lush growth is obtained in red soil and it withstands any amount of drought. East Indian sappanwood occurs at low to medium altitudes in India and Southeast Asia with rainfall ranging from 700-4,300 mm and mean temperatures of 24-28^{0}C. It is adaptable to clay soil and calcarious rocks but does not tolerate water logging. Being fond of sandy soil, it is commonly grown throughout whole of Malabar, and it freely grows in Travancore of Kerala (Manilal, 2003).

3.2.1.4. Physical and Anatomical features

The freshly cut wood is yellowish white, but becomes red on exposure to the air. According to the British Pharmacopoeia, in transverse section, well-marked concentric rings, numerous narrow medullary rays, and large vessels, straight grains are observed. It does not have odour, however taste slightly astringent. It communicates to alcohol (90 %) and to water a red color, which becomes carmine-red, but not purple, upon the addition of solution of sodium hydroxide (distinction from Logwood), low wood density is 600 Kg / m^3 and high wood density is 780 Kg/ m^3.

3.3. Estimation of biomass production

3.3.1. Dry matter production of sample trees

Field studies were confined to sample plots in the plantations employing stratified average tree technique (Madgwick, 1971). Sample plots of size 10 m x 10 m were laid out and diameter at breast height (dbh) of each tree in the sample plot was recorded. Height of trees was also recorded by using Clinometer. When the main shoot is forked below BH level (1.37m) and then such branches were also treated as stem wood. A general view of the experimental trees raised in different plantations is depicted in Table 1 to 6.

The trees were grouped into three diameter classes by frequency distribution method and an average tree of each diameter class (Girth classes) was selected for sampling. A total of 21 trees were harvested for estimating above ground biomass. Trees were felled at the ground level during November 2005 to February 2006 with the help of

Plate.1.Five year old *C.sappan* plantation standing at Arayiram, Thrissur

Plate.2. Five year plantation at Ulliyeri, Kozhikode

Plate.3. Six year old plantation at Kuttanallur, Thrissur

Plate.4. Six year old plantation at Perambra, Kozhikode

Plate 5. Seven year old plantation at Mechira, Palakkad

Plate. 6. Seven year old plantation at Moypoth, Kozhikode

a bow saw and total height, bole height was recorded. The above ground biomass was separated in to main stem, branches (above 5 cm (ob) and below 20 cm (ob) twigs (below 5-cm girth (ob) leaves and fruits. The main bole was limited to 5-cm girth (ob). Fresh weights of all the above components were recorded immediately after felling using appropriate spring scales. (To either nearest 0.1 kg or 100 Kg) (Plates 7 to 9)

Triplicate samples (100 gm each) of stem wood, branch wood, twigs, foliage and fruits were collected from all the felled trees and were transferred to laboratory in double-sealed polythene bags for dry weight estimation and chemical analysis. The main bole was cut into 2 m logs to facilitate weighing and a 5-cm thick disc was taken from the cut ends (Plate 10). The bark and wood of the disc were separated and fresh weight recorded in the field. All the discs and bark were packed in paper bags and taken to laboratory for dry weight estimation and chemical analysis. All the samples were brought to the laboratory and oven dried at 70°C to constant weight and dry weight of different components was recorded for moisture estimation. Dry weight of wood and bark of each log was estimated using mean wood: bark ratio of two successive discs. The dry weight of each log was totalled separately to obtain the dry weight of bark and wood of the main bole. Estimates of dry weight biomass were obtained from the fresh weights of various tissue types and their corresponding moisture contents. The frequency (as percentage) of stems belonging to various girth classes in the entire stand was recorded to calculate the number of trees per ha in each girth class. Biomass of tree parts was summed to obtain the total above ground biomass per tree. The average biomass of component parts per tree was multiplied by the number of trees ha^{-1} to get biomass on hectare basis.

$$\text{Moisture percentage} = \frac{\text{Fresh weight (g)} - \text{Dry weight (g)}}{\text{Fresh weight (g)}} \times 100$$

$$\text{Dry Matter} = \frac{\text{Dry Weight of the sample (g)}}{\text{Fresh Weight of the sample (g)}} \text{ X Fresh weight of the tree (kg)}$$

Plate 7. Two meter long billets of sappan wood

Plate 8. Twigs and leaves separated for weighing

Plate 9. Fruits separated for weighing

Plate 10. Discs collected for moisture estimation

3.4. Biomass prediction

The biomass data (dry weight) of all the components of 21 sample trees were used to compute the biomass on unit area basis. Equations were developed for predicting biomass of different components of trees and volume at tree level using dbh (Gbh) and height of trees as predictor variables. These equations can then be applied to develop estimates of stand level biomass for which such measurements are available. For this, statistical package SPSS (Version 10) was resorted. The following family equations were evaluated.

1. $W = b_o + b_l D$

2. $W = b_o + b_l D + b_2 D^2$

3. $W = b_o + b_l D^2$

4. $\mathrm{In}\ W = b_o + b_l \mathrm{In}\ D$

5. $W/D^2 = b_o + b_l (l/D) + b^2 (l/D^2)$

6. $W = bo + b_l D^2 H$

7. $W = bo + b_l D^2 + b_2 H + b_3 D^2 H$

8. $W = bo + b_l D^2 + b_2 DH + b_3 D^2 H$

9. $\mathrm{In}\ W = b_o + b_l \mathrm{In}\ D + b_2 \mathrm{In}\ H$

10. $\mathrm{In}\ W = b_o + b_l \mathrm{In}\ D^2 H$, where

w = Weight (kg)

D = diameter at breast height (cm)

H = Height (m)

b_o = a constant

b_1, b_2 and b_3 = regression coefficients

The best fitting model in each case was selected using adjusted R^2, Furnival index and characteristics of residuals. Non-significant terms were eliminated while fitting the models. Furnival index for each model is then obtained by multiplying the corresponding values of the square root of mean square error with the inverse of the geometric mean of the derivatives of the independent variables with respect to y.

3.5. Phytochemical analysis

Triplicate samples of each biomass components were analyzed for Nitrogen (N), Phosphorus (P) and Potassium (K). The oven-dried samples were powdered and passed through sieves of size ranges from 5mm to 2mm.

3.5.1. Nitrogen

Nitrogen was estimated following the micro-Kjeldahl digestion and distillation method (Jackson, 1958).

3.5.2. Phosphorus

Phosphorus was estimated after digesting the samples in triple acid mixture (HNO_3 and H_2SO_4 and $HCLO_4$ in 10:1:3) and determined following the vanado-molybdo phosphoric yellow colour method by Spectrophotometer (Jackson, 1958).

3.5.3. Potassium

Potassium was estimated after digesting the samples in triple acid mixture (HNO_3 and H_2SO_4 and $HCLO_4$ in 10:1:3) and determined by flame photometry (Jackson, 1958).

Total nutrient accumulation on per tree basis was calculated by multiplying the oven dry biomass of tree components with the mean biomass of each plant part by the corresponding nutrient concentrations was obtained. Average nutrient accumulation per tree was extrapolated to a hectare by multiplying frequency per ha.

3.6. Statistical analyses

The data were analyzed by analysis of variance technique The 'MSTAT' statistical package was used for statistical analyses. Statistically significant means were subjected to DMRT and ranked.

Results

RESULT

4.1. Biomass production

Biomass production is the total quantity of biomass present at a particular time in an ecosystem. Such studies are important to know the ecological and economical productivity.

4.1.1. Growth Parameters

The field studies were conducted in nine sample plots from three age groups (Table 2 and Appendix 1). The growth parameters like diameter at breast height (dbh) and height (ht) along with dry weight of components were recorded from each sample plot of nine plantations and the mean values are given in the Table 2. In five year old plantation the diameter varies from 5.56 cm to 6.23 cm whereas at 6 years diameter varied from 6.14 cm to 7.64 cm. At age seven year it was varied from 7.12 cm to 7.99 cm. The variation in diameter showed almost the same trend in all age groups, however, no substantial difference had been found. In 5 year old plantations height ranged from 5.91 m to 6.18 m. At age 6 year height was ranging from 5.66 m to 6.77 m and in 7 years it ranged from 6.37 m to 7.02 m. But there was no significant difference in height within age groups except at age 6 year which had shown significant difference between age 5 and age 6 years and age 6 and age 7 years.

The diameter and height increased with increasing age. Diameter at age 5 year was 5.96 cm and at 7 year it was 7.52 (Table 3 and appendix 2). A significant difference of diameter at age 5 year with other two ages has been noticed. The height also increased from 6.02 m to 6.69 m when the age increased from 5 to 7 year. The significant difference in height was shown between ages 5 and 7, but not between 5 and 6 as well as 6 and 7 years.

Table 2. Plot wise average dbh and height at different ages

Age (years)	Average DBH (cm)				Average height (m)			
	Plot 1	Plot 2	Plot 3	CD (0.05)	Plot 1	Plot 2	Plot 3	CD (0.05)
5	5.56^a	6.11^a	6.23^a	0.987	5.91^a	5.96^a	6.18^a	0.735
6	6.14^a	7.06^a	7.64^a	1.390	5.66^b	6.51^{ab}	6.77^a	0.864
7	7.12^a	7.44^a	7.99^a	1.424	6.37^a	6.69^a	7.02^a	0.897

Values with same superscript do not differ significantly between themselves

Table 3. Mean values of dbh and height under different age groups

Age (years)	DBH (cm)	Height (m)
5	5.96^b	6.02^b
6	6.95^a	6.32^{ab}
7	7.52^a	6.69^a
CD (0.05)	0.454	0.457

Values with same superscript do not differ significantly between themselves

4.1.2. Above ground biomass

The trees were selected from different plots based on diameter class frequency distribution. Dry matter production of sample trees was estimated from the samples collected. It was seen that a variation in above ground biomass (agb) and also in the biomass components between ages. Biomass of average trees (average of same ages) are depicted in Table 4 and Appendix 3. Analysis of variance of agb showed that age 5 year is significantly different to an agb at age 7 year, but variation was not observed between age groups 5 and 6 and 6 and 7. In all age groups, total agb and biomass components increased with increasing age. At age 5 years total agb was 21.43 kg, whereas at age 6 years it increased to 34.02 kg and at 7 years it was 39.92 kg. The significant difference in agb from 5 to 7 years showed considerable increase in average tree biomass as indicated with their homogenous mean values. In general, the biomass indicated an increasing trend with increasing ages (Fig. 2).

Table 4. Mean values of biomass components (kg tree^{-1}) of dry weight at different ages

Age (Years)	Bole*	Bark^{ns}	Branch*	Twig**	Leaves^{ns}	Fruits**	Total agb*
5	8.55^{b}	0.98^{a}	5.10^{b}	2.42^{b}	2.05^{b}	2.33^{b}	21.43^{b}
6	14.75^{ab}	1.46^{a}	9.16^{ab}	3.05^{b}	2.42^{ab}	3.19^{b}	34.02^{ab}
7	16.24^{a}	1.83^{a}	8.89^{a}	4.70^{a}	3.57^{a}	4.69^{a}	39.92^{a}
CD (0.05)	7.592	0.725	4.483	1.556	1.385	1.174	15.764

* Significant at 5% level, ** significant at 1% level, ns - non significant

Values with same superscript do not differ significantly between themselves

In the case of biomass components of average tree between age groups also showed variation. There was a significant difference between each component from 5 year to 7 year old plantations. But, between 5 and 6 years as well as 6 and 7 years, as indicated in the total aboveground biomass, it showed no significant difference. The bole produced the biomass 8.55 kg at age 5 years, 14.75 kg at age 6 years and 16.24 kg at age 7 years and it also showed that biomass, at age 5 years was significantly different compared to age 7 years. The branch and leaves also indicated significant difference at

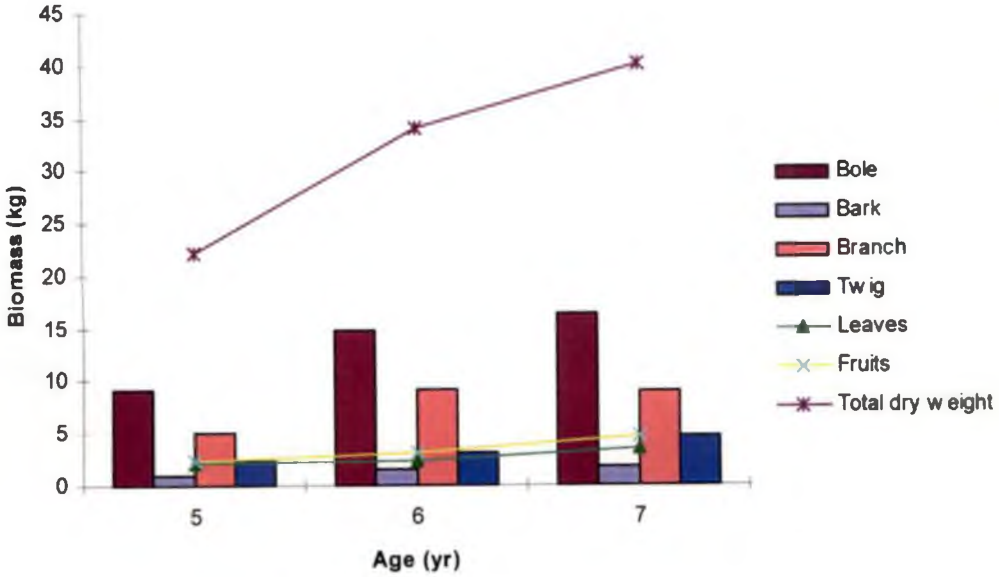

Fig. 2 Relation between age and biomass components of sample trees

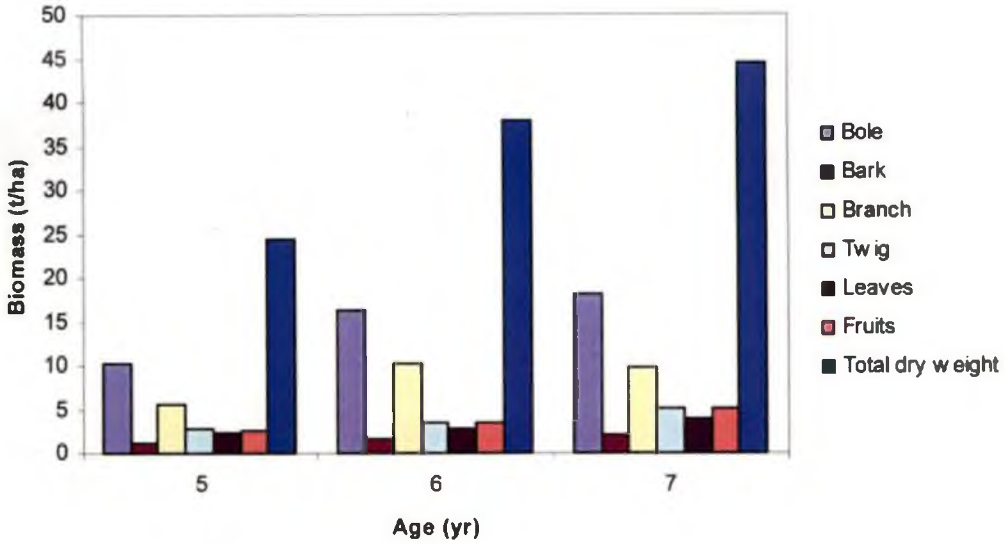

Fig. 3 Relation between Age and biomass of plantations

age 5 years to age 7 years, but in 5 and 6 years as well as 6 and 7 years showed no substantial difference. In twigs and fruits, at age 7 years, biomass showed significant different from 5 and 6 year old plantations. The twig produced at age 5 years was 2.42 kg, at age 6 years was 3.05 kg and at age 7 years produced 4.70 kg. At age 5 years fruit has got the biomass 2.33 kg, at age 6 years increased to 3.19 kg and at age 7 years produced 4.69 kg. In bark, there was no significant difference in biomass between 5, 6 and 7 ages. Biomass components in all age group had shown an increasing trend from 5 year to 7 years. In all age groups, bole has acquired maximum biomass and bark has lowest. At age 5 years the components showed the decreasing order as bole > branch > twig > fruits > leaves > bark, whereas at age 6 years fruit biomass was more compared to twigs with an increasing order as bole > branch > fruits > twig > leaves > bark. But at age 7 years showed the same order as indicated at age 5 years.

4.1.3. Percentage distribution

Percentage distribution of biomass components to agb is depicted in Table 5 and Figures 4 to 6. Among the percentage of biomass distributed to different components, bole constituted highest biomass and bark the lowest in all age groups. At age 5 years the percentage distribution sequence was in the order bole > branch > twig > fruit > leaves > bark, whereas at age 6 years, percentage of fruit was more than twig. The distribution order were bole > branch > fruit > twig > leaves > bark. But in 7 years the twig and fruit percentage was equal. The sequence of distribution was in the order: bole > branch > twig = fruit > leaves > bark. The bole biomass percentage at age 5 years was recorded 39.89 per cent and increased to 43.35 per cent at age 6 years. At age 7 years, the bole biomass was decreased to 40.68 per cent. The similar trend was noticed in branches. The bark biomass at age 5 years produced 4.57 per cent and at age 6 years it decreased to 4.29 per cent. Further it increased to 4.58 per cent at age 7 years. The fruit and twig also showed the same trend as bark. In leaf, it decreased with increasing age. It was decreased from 9.28 percent from 5 year to 7.12 per cent at age 6 year and increased to 8.94 per cent at age 7 years.

Table 5. Percentage biomass of each component under different ages

Age (Years)	Bole	Bark	Branch	Twig	Leaves	Fruits
5	39.89	4.57	23.79	11.29	9.57	10.87
6	43.35	4.29	26.93	8.95	7.12	9.37
7	40.68	4.58	22.28	11.76	8.94	11.76

4.2. Biomass production per unit area

The biomass production per unit area is given in the Table 6 and Fig. 3. The dry matter production per unit area basis is a function of age, density, and growth parameters like diameter at breast height and height. As a result conspicuous variation in the agb and biomass of different components are observed in different age groups.

Variation in total agb and biomass components are observed between ages. It was increased with increase in age. The agb at age 5 year was significantly different to age 7 years. The agb at age 5 years was observed 23.81 t ha^{-1}, increased to 37.80 t ha^{-1} at age 6 year and further increased at age 7 year to 44.36 t.ha^{-1}. This showed no significant difference as indicated their homogenous mean values at age 6 and 7. Similarly, bole, branch and leaves showed the same difference as agb. The bole biomass at age 5 years was recorded 9.50 t ha^{-1} and it increased to 16.39 t ha^{-1} at age 6 years. Further at age 7 years, the bole biomass increased to 18.04 t ha^{-1}. The branch biomass produced at age 5 years was 5.67 t ha^{-1} and at 6 years, it increased to 10.18 t ha^{-1}. At age 7 years, decrease of branch biomass has been noticed and recorded 9.88 t ha^{-1}. The leaf biomass at age 5 years was produced 2.28 t ha^{-1} and at 6 years as 2.69 t ha^{-1}, and which further increased to 3.97 t ha^{-1}. In the case of twig and fruit, age at 7 years was significantly different with ages 5 and 6 years. The twig biomass at 5 years was recorded 2.69 t ha^{-1} and it increased

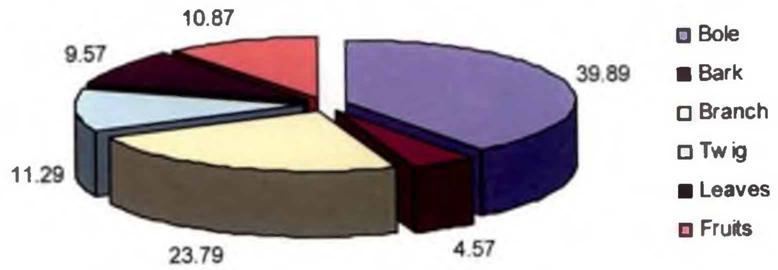

Fig. 4 Percentage contribution of biomass components at 5 year old plantation

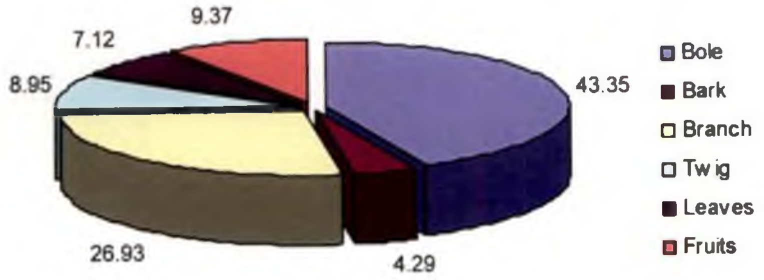

Fig.5 Percentage contribution of biomass components at 6 year old plantation

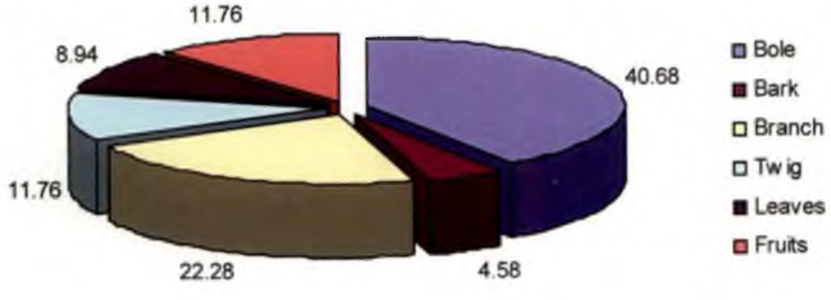

Fig. 6 Percentage contribution of biomass components at 7 year old plantation

to 3.39 t ha^{-1} at age 6 years. At age 7 years, it reached to 5.22 t ha^{-1}. The fruit biomass was observed at age 5 years was 2.59 t ha^{-1}, which increased to 3.54 t ha^{-1} at age 6 years and again increased to 5.21 t ha^{-1} at age 7 years. In bark biomass, no significant difference has been observed. Bark biomass at age 5 years was recorded 1.08 t ha^{-1} and at 6 years it increased to 1.62 t ha^{-1} and further increased to 2.03 t ha^{-1} at age 7 years. The above figures indicated that significant variation in agb and biomass components between age groups when age increased from 5 to 7 years

Table 6. Biomass production of plantations at different ages (t ha^{-1})

Age (Years)	Bole*	Bark^{ns}	Branch*	Twig**	Leaves*	Fruits**	Total agb*
5	9.50^{b}	1.08^{a}	5.67^{b}	2.69^{b}	2.28^{b}	2.59^{b}	23.81^{b}
6	16.39^{ab}	1.62^{a}	10.18^{ab}	3.39^{b}	2.69^{ab}	3.54^{b}	37.80^{ab}
7	18.04^{a}	2.03^{a}	9.88^{a}	5.22^{a}	3.97^{a}	5.21^{a}	44.36^{a}
CD (0.05)	8.485	1.468	4.980	1.727	1.539	1.306	17.514

* Significant at 5% level, ** significant at 1% level, ns - non significant

Values with same superscript do not differ significantly between themselves

Anova of agb showed that 5 year old plantations are significantly different from 7 year old plantations. The difference in age between 5 and 6 as well as 6 and 7 showed no significant difference. Biomass of bole, branch and leaves also showed the same difference. Whereas, biomass of fruits and twigs at the age 5 and 6 years significantly varied from 7 year old plantations. In bark, no significant difference was showed between ages.

In all age groups bole was recorded maximum biomass and bark the lowest as indicated in the tree level biomass. At age 5 years the components showed an increasing order in biomass production as bole > branch > twig > fruits > leaves > bark, whereas at age 6 years fruit biomass was more compared to twigs and the increasing order as bole > branch > fruits > twig > leaves > bark. But at age 7 years showed the same trend as indicated at age 5 years.

Above ground biomass production study in an age series ranged from 5-7 years indicated maximum above ground biomass production at age 7 years. The components also showed the same trend. It was noted that increment in agb was maximum between 5 and 6 year age and it decreased between 6 and 7 year old plantations. It indicated that though the biomass of components increased with increase in age, the differences in their allocation is less pronounced in 6 and 7 years. It revealed that the agb and biomass components showed a levelling off at 6 years as indicated by their homogenous mean values.

4.3. Productivity

Productivity is considered as the rate of net primary production or the rate of production of organic matter less than that used in respiration. The productivity (t ha^{-1} yr^{-1}) of 3 ages of *C. sappan* plantations was estimated and presented (Table 7 and Fig. 7). It was seen that productivity of the agb as well as biomass components varied between age groups. The productivity of agb increased from 4.77 t ha^{-1} yr^{-1} at age 5 years to 6.30 t ha^{-1} yr^{-1} at age 6 years and 6.34 t ha^{-1} yr^{-1} at 7 years. But the difference was not significant between above age groups. The data also indicated that maximum difference in agb was noticed between ages 5 and 6 but it decreased between age 6 and 7. Difference in productivity considerably reduced between ages 6 and 7 (0.04 t ha^{-1} yr^{-1}).

The biomass components also showed the same trend as agb except in the fruits. At age 5 years the productivity of fruit was 0.52 t ha^{-1} yr^{-1} which was significantly different from 0.74 t ha^{-1} yr^{-1} at age 7 years. An increasing trend was recorded in bark, twig and fruits with increasing ages. In bole and branches, productivity increased from age 5 years (2.04 t ha^{-1} yr^{-1} for bole and 1.13 t ha^{-1} yr^{-1} for branches) to age 6 years (2.73 t ha^{-1} yr^{-1} for bole and 1.70 t ha^{-1} yr^{-1} for branches) and it again decreased at age 7 years (2.58 t ha^{-1} yr^{-1} for bole and 1.41 t ha^{-1} yr^{-1} for branches). But in leaves, productivity decreased from 0.46 t ha^{-1} yr^{-1} at age 5 years to 0.45 t ha^{-1} yr^{-1} at age 6 years and increased to 0.57 t ha^{-1} yr^{-1} at age 7 years.

Table 7. Biomass productivity of plantations at different ages (t ha^{-1} yr^{-1})

Age (Years)	Bole^{ns}	Bark^{ns}	Branch^{ns}	Twig^{ns}	Leaves^{ns}	Fruits*	Total agb^{ns}
5	1.90^{a}	0.22^{a}	1.13^{a}	0.54^{a}	0.46^{a}	0.52^{b}	4.77^{a}
6	2.73^{a}	0.27^{a}	1.70^{a}	0.56^{a}	0.45^{a}	0.59^{ab}	6.30^{a}
7	2.58^{a}	0.29^{a}	1.41^{a}	0.75^{a}	0.57^{a}	0.74^{a}	6.34^{a}
CD (0.05)	1.211	0.112	0.734	0.250	0.224	0.194	2.528

ns – Non significant, * significant at 5 % level

Values with same superscript do not differ significantly between themselves

Among the biomass components, bole showed maximum biomass while bark lowest as indicated by biomass per unit area. At age 5 years, the components showed an increasing order as bole > branch > twig > fruits > leaves > bark, whereas at age 6 years fruit biomass was more compared to twigs and the increasing order as bole > branch > fruits > twig > leaves > bark. But at age 7 years the same trend is followed as indicated at age 5 years and was in the order: as bole > branch > twig > fruits > leaves > bark.

Productivity of agb and components on tree basis is illustrated in Table 8 and Fig. 8. It was estimated by dividing the biomass on unit area basis at different ages with their corresponding age. It indicated that at age 5 years, productivity was 4.29 kg tree^{-1} yr^{-1} and increased to 5.67 kg tree^{-1} yr^{-1} and it further increased to 5.70 kg tree^{-1}yr-1 at age 7 years. The above figures indicated that agb productivity increased from 5 years to 6 years with increasing age reached to a culmination at age 6 years as observed by the productivity on a unit area basis. The components like bole, bark, branch, twigs, leaves and fruits showed the same trend as shown agb productivity. The above findings revealed that productivity of total above ground biomass and biomass components showed no significant difference between ages except in fruits. In fruits, at age 5 years biomass varied significantly from the age at 7 years. This indicated that, there was a levelling off in productivity of agb as well as biomass components from age 6 years to age 7 years.

Among the biomass components bole showed maximum biomass and bark showed the lowest as indicated in biomass per unit area. At age 5 years the components showed an increasing order as bole > branch > twig > fruits > leaves > bark, whereas at age 6 years fruit biomass was more compared to twigs and the increasing order as bole > branch > fruits > twig > leaves > bark. But at age 7 years showed the twig and fruit productivity same and the increasing sequence was in the order, bole > branch > twig = fruits > leaves > bark.

Table 8. Biomass productivity of plantations at different ages (kg tree^{-1} yr^{-1})

Age (Years)	Bole^{ns}	Bark^{ns}	Branch^{ns}	Twig^{ns}	Leaves^{ns}	Fruits*	Total agb^{ns}
5	1.71^{a}	0.20^{a}	1.02^{a}	0.48^{a}	0.41^{a}	0.47^{b}	4.29^{a}
6	2.46^{a}	0.24^{a}	1.53^{a}	0.51^{a}	0.40^{a}	0.53^{ab}	5.67^{a}
7	2.32^{a}	0.26^{a}	1.27^{a}	0.67^{a}	0.51^{a}	0.67^{a}	5.70^{a}
CD (0.05)	1.342	0.127	0.815	0.285	0.257	0.203	2.805

ns – Non significant, * significant at 5 % level

Values with same superscript do not differ significantly between themselves

4.4. Volume production

The volume was estimated from the plantations at different ages. It was observed that volume increased from 5 to 7 year. At age 5 years it was 0.0156 m^3 and increased to 0.0232 m^3 at age 6 years and further increased to 0.317 m^3 at age 7 years (Table 9).

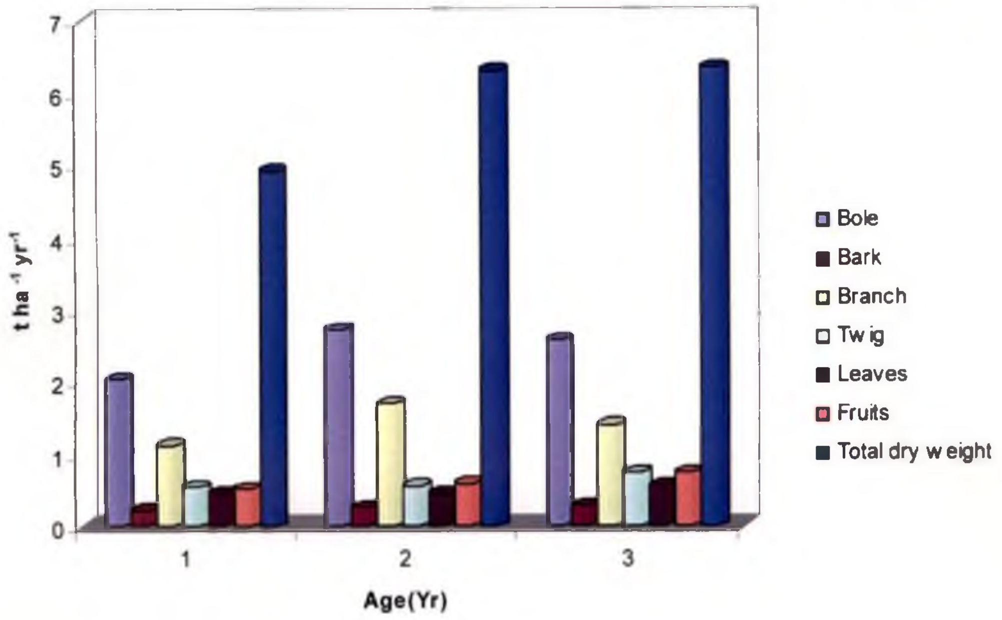

Fig. 7 Relation between age and productivity of plantation

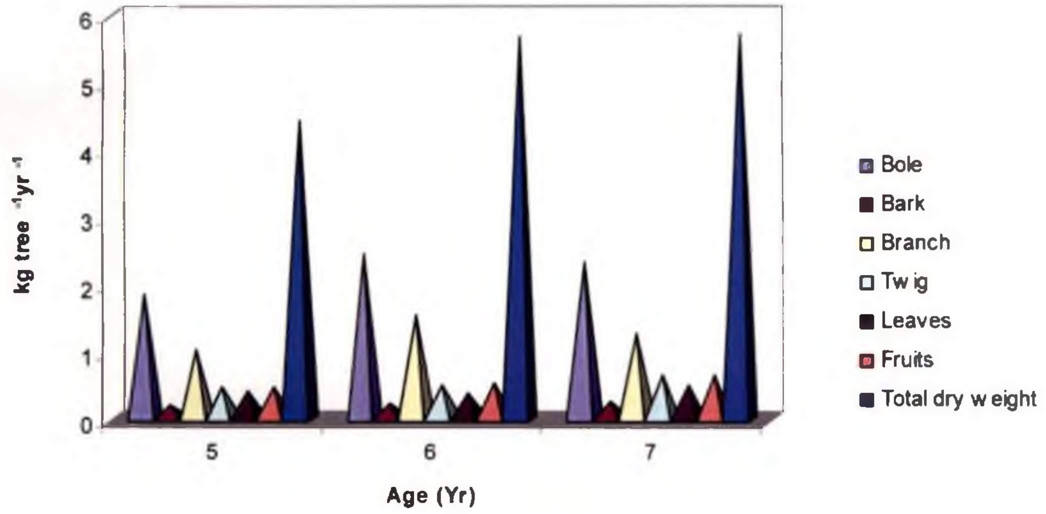

Fig. 8 Relation between age and productivity of sample trees

Table 9. Volume production at different ages

Age (Years)	Av. Dbh (cm)	Av. Height (m)	Volume (m^3)
5	19.42	5.52	0.0156
6	23.14	6.34	0.0232
7	25.57	7.26	0.0317

4.5. Biomass prediction

The basic data obtained from the 21 trees were used to compute the biomass prediction equation for bole wood, bark, branch, twig, leaves and fruits and above ground biomass. These trees covered a wide range of variation in the growth parameters ie., diameter at breast height ranging from 3.5 cm to 11.14 and height ranging from 3.8 m to 9.3 m. simple linear regression analysis of 10 most commonly used equation were tried, of which five were with single independent variables and the remaining five with two variables (either dbh and height or derivatives of both). The ten different models are

1. $W = b_o + b_1 D$
2. $W = b_o + b_1 D + b_2 D^2$
3. $W = b_o + b_1 D^2$
4. $\text{In } W = b_o + b_1 \text{ In } D$
5. $W/D^2 = b_o + b_1 (1/D) + b^2 (1/D^2)$
6. $W = bo + b_1 D^2 H$
7. $W = bo + b_1 D^2 + b_2 H + b_3 D^2 H$
8. $W = bo + b_1 D^2 + b_2 DH + b_3 D^2 H$
9. $\text{In } W = b_o + b_1 \text{ In } D + b_2 \text{ In } H$
10. $\text{In } W = b_o + b_1 \text{ In } D^2 H$

Where,
W = Weight (kg)
D = diameter at breast height (cm)
H = Height (m)
b_0 = a constant
b_1, b_2 and b_3 = regression coefficients

When the above ten models were tried it was essential to use certain criteria to select the best model. Similarly when large number of equations was proposed for constructing weight tables, difficulty may arise in deciding the most appropriate equations or a particular data. The standard error and coefficient of determination (R^2) were not sufficient for comparing different weighted and transformed models. This is due to the fact that dependent variable is different from one model to another. However, it was made possible to compare the different models by an index developed by Furnival (1961). The model with maximum coefficient of determination and minimum Furnival index was selected to give the best fit. In all the equations dbh and height were used as independent variables and biomass of the components as dependant variable.

Different equations were tried for various components like bole wood (Under bark), bark, branch, twig, leaves, fruits and the total dry weight and coefficient of determination and Furnival index values also estimated. Along with this, the volume of *C. sappan* was also found out. The equations for the volume estimation were also calculated. Based on the data, a weight table of total biomass and bole weight are presented.

Among the ten models tried, best fit were determined by coefficient of determination and Furnival index. In each case the best for a single variable dbh and combined variables dbh and height were selected for the best fit. It indicated that single linear model (Model 1) and quadratic form of models (models 2, 3, 6, 7, 8) and exponential models (models 4, 5, 9, 10) were proved best fit for various components. The equations tried for each component are explained below.

4.5.1. Bole (UB)

Functional forms tried for predicting stem (UB) is given in Table 10 along with coefficient of determination (R^2) and Furnival index.

Among the equation with dbh alone Model 4 has higher R^2 value and low Furnival index and so it is selected as the best fitted equation. The result of those equations is given below (Appendix 5).

Model 4 $\ln W = b_0 + b_1 \ln (D)$

$\ln W = -2.200 + 2.361 \ln (D)$

Coefficient of determination $R^2 = 0.944$

Correlation Coefficient $r = 0.971$

Table 10. Models tried for predicting the bole biomass

Models	R^2	Furnival index
1. $W = b_0 + b_1D$	0.883	2.76
2. $W = b_0 + b_1D + b_2D^2$	0.936	2.10
3. $W = b_0 + b_1D^2$	0.925	2.20
4. $\ln W = b_0 + b_1\ln D$	0.944	1.62
5. $W/D^2 = b_0 + b_1 (1/D) + b_2 (1/D^2)$	0.415	1.60
6. $W = b_0 + b_1D^2H$	0.945	1.90
7. $W = b_0 + b_1D^2 + b_2H + b_3D^2H$	0.949	1.93
8. $W = b_0 + b_1D^2 + b2DH + b_3D^2H$	0.949	1.93
9. $\ln W = b_0 + b_1\ln D + b_2\ln H$	0.948	1.60
10. $\ln W = b_0 + b_1^o \ln(D^2H)$	0.943	1.63

The reliability of prediction also studied by plotting the observed and predicted values by using this equation. It has a good relation with dbh and bole biomass (Fig .9)

Among the equations with dbh and height-combined independent variables, model 6 has high R^2 and low Furnival index, and so that it is selected as the best fitted equation. The result of these equations are given below (Appendix 5)

Model 6 $W = b_0 + b_1 (D^2H)$

$W = -0.006 + 0.034 (D^2H)$

Coefficient of determination $R^2 = 0.942$

Correlation Coefficient $r = 0.945$

4.5.2. Bark

The different models tried for the prediction of the bark along with their coefficient of determination R^2 and Furnival index are tabulated in Table 11.

Table 11. Models tried for predicting the bark biomass

Models	R^2	Furnival index
1. $W = b_0 + b_1D$	0.590	0.473
2. $W = b_0 + b_1D + b_2D^2$	0.633	0.460
3. $W = b_0 + b_1D^2$	0.622	0.454
4. $\ln W = b_0 + b_1\ln D$	0.658	0.374
5. $W/D^2 = b_0 + b_1 (1/D) + b_2 (1/D^2)$	0.236	0.357
6. $W = b_0 + b_1D^2H$	0.665	0.428
7. $W = b_0 + b_1D^2 + b_2H + b_3D^2H$	0.681	0.442
8. $W = b_0 + b_1D^2 + b2DH + b_3D^2H$	0.686	0.438
9. $\ln W = b_0 + b_1\ln D + b_2\ln H$	0.710	0.354
10. $\ln W = b_0 + b_1 \ln(D^2H)$	0.697	0.352

Among the equations tried, for dbh alone, the model 4 was selected as the best fitted equation due to maximum coefficient of determination (R^2) and minimum Furnival index. The best fitted equation is given below (Appendix.6).

Model 4 $\ln W = b_0 + b_1 \ln (D)$

$\ln W = -2.635 + 1.496 \ln (D)$

Coefficient of determination $R^2 = 0.658$

Correlation Coefficient $r = 0.811$

Model 4 $\ln W = b_0 + b_1 \ln(D)$

$\ln W = -2.200 + 2.361 \ln(D)$

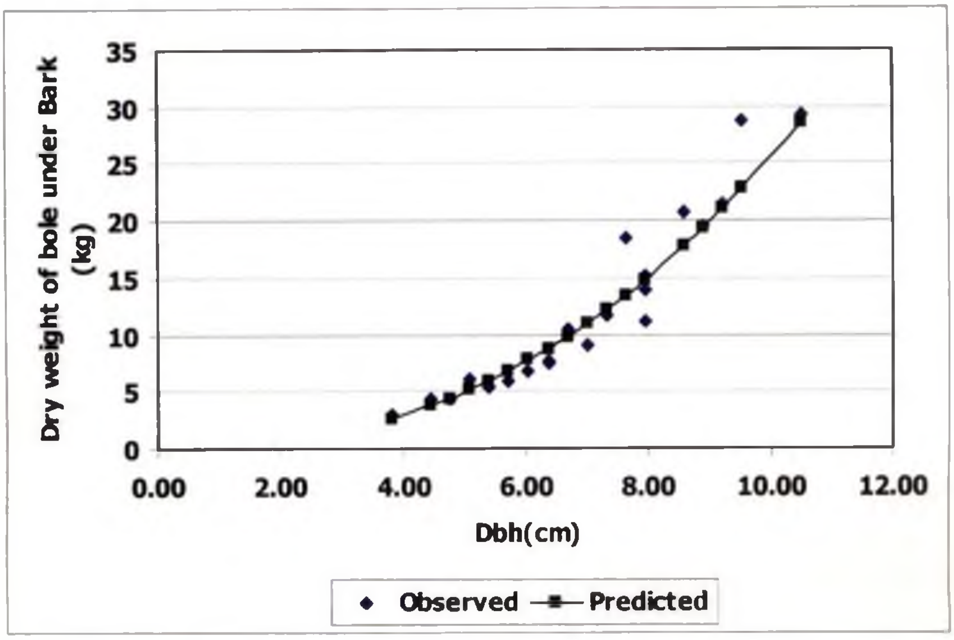

Fig. 9 Relation between dbh and bole

Model 4 - $\ln W = b_0 + b_1 \ln (D)$

$\ln W = -2.635 + 1.496 \ln (D)$

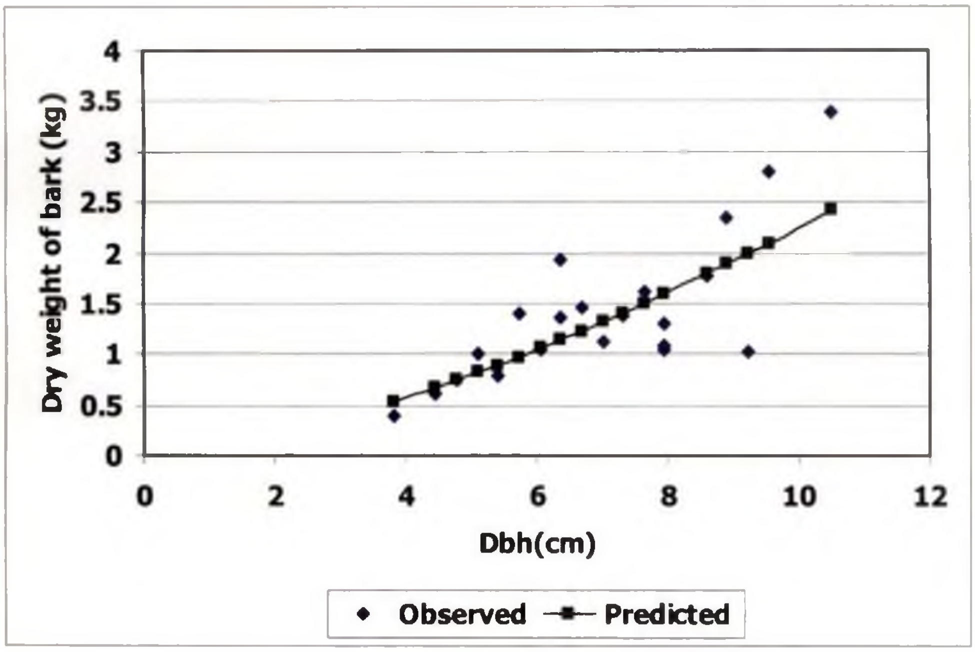

Fig.10 Relation between dbh and bark

By plotting the observed and predicted values by using this equation the reliability of prediction was studied. It indicated that dbh established a good relation with bark biomass (Fig.10).

As dbh and height was taken as independent variables, the best fitted equation was model 9 with high R^2 value and low Furnival index. The selected equation is given below (Appendix 6).

Model 9 $\ln W = b_0 + b_1 \ln (D) + b_2 \ln (H)$

$\ln W = -3.231 + 0.712 \ln (D) + 0.127 \ln(H)$

Coefficient of determination $R^2 = 0.710$

Correlation Coefficient $r = 0.842$

4.5.3. Branch

For the prediction suitable equation for branch biomass, following equations are tried and given in the Table 12 along with coefficient determination (R^2) and Furnival index.

Table 12. Models tried for predicting the branch biomass

Models	R^2	Furnival index
1. $W = b_0 + b_1D$	0.776	2.26
2. $W = b_0 + b_1D + b_2D^2$	0.794	2.22
3. $W = b_0 + b_1D^2$	0.794	2.16
4. $\ln W = b_0 + b_1\ln D$	0.810	1.80
5. $W/D^2 = b_0 + b_1 (1/D) + b_2 (1/D^2)$	0.856	2.22
6. $W = b_0 + b_1D^2H$	0.841	1.90
7. $W = b_0 + b_1D^2 + b_2H + b_3D^2H$	0.851	1.94
8. $W = b_0 + b_1D^2 + b2DH + b_3D^2H$	0.852	1.94
9. $\ln W = b_0 + b_1\ln D + b_2\ln H$	0.823	1.78
10. $\ln W = b_0 + b_1 \ln(D^2H)$	0.823	1.74

From the equations, model 4 has high R^2 value and low Furnival index with dbh as independent variable alone. So it is selected as the best fitted equation. The best fitted equation is given below (Appendix. 7). A good correlation with dbh and branch biomass had been observed by plotting the observed and predicted values by using this equation (Fig .11).

Model 4 $\ln W = b_0 + b_1 \ln(D)$

$\ln W = -2.689 + 2.322 \ln(D)$

Coefficient of determination $R^2 = 0.810$

Correlation Coefficient $r = 0.800$

Among the equations tried with dbh and height as independent variables, model 10 is selected as it indicated high R^2 value and low Furnival index. The equation is furnished below (Appendix 7).

Model 10 $\ln W = b_0 + b_1 \ln (D^2H)$

$\ln W = -3.134 + 0.860 \ln (D^2H)$

Coefficient of determination $R^2 = 0.823$

Correlation Coefficient $r = 0.907$

4.5.4. Twig

The models tried for twig along with their coefficient of determination (R^2) and Furnival index are given in the Table 13.

The best model selected in which dbh alone as an independent variable was model 3 due to high R^2 value and low Furnival index. The best equation is furnished below (Appendix 8).

Model 3 $W = b_0 + b_1 D^2$

$W = 0.04495 + 0.06076 D^2$

Coefficient of determination $R^2 = 0.780$

Correlation Coefficient $r = 0.883$

By plotting the observed and predicted values by using this equation, the reliability of prediction has been studied. It established a weak corelation with dbh and twig biomass as shown in Fig.12.

Table 13. Models tried for predicting the twig biomass

Models	R^2	Furnival index
1. $W = b_0 + b_1D$	0.753	0.90
2. $W = b_0 + b_1D + b_2D^2$	0.783	0.86
3. $W = b_0 + b_1D^2$	0.780	0.85
4. $\ln W = b_0 + b_1\ln D$	0.680	0.94
5. $W/D^2 = b_0 + b_1 (1/D) + b_2 (1/D^2)$	0.868	1.98
6. $W = b_0 + b_1D^2H$	0.738	0.92
7. $W = b_0 + b_1D^2 + b_2H + b_3D^2H$	0.793	0.87
8. $W = b_0 + b_1D^2 + b2DH + b_3D^2H$	0.793	0.87
9. $\ln W = b_0 + b_1\ln D + b_2\ln H$	0.695	0.95
10. $\ln W = b_0 + b_1 \ln(D^2H)$	0.640	1.00

The best equation selected among the equations with dbh and height as independent variables was the model 6. The best fitted model is given below (Appendix 8).

Model 6 $W = b_0 + b_1D^2H$

$W = 0.769 + 0.0067D^2H$

Coefficient of determination $R^2 = 0.738$

Model 4 - $\ln W = b_0 + b_1 \ln(D)$

$\ln W = -2.689 + 2.322 \ln(D)$

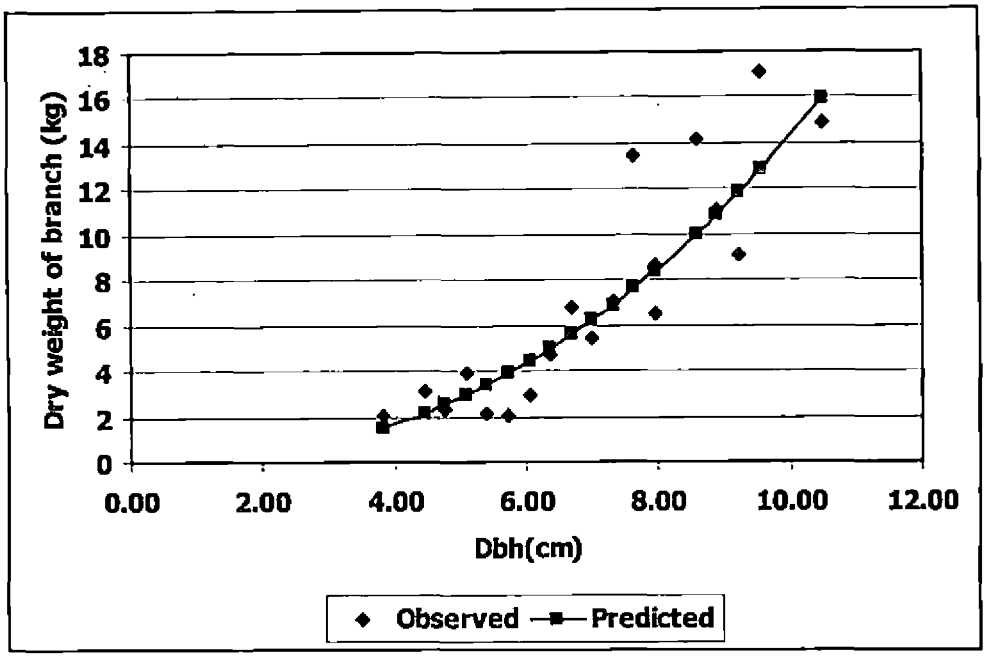

Fig.11 Relation between dbh and branch

Model 3 - $W = b_0 + b_1 D^2$

$W = 0.04495 + 0.06076 D^2$

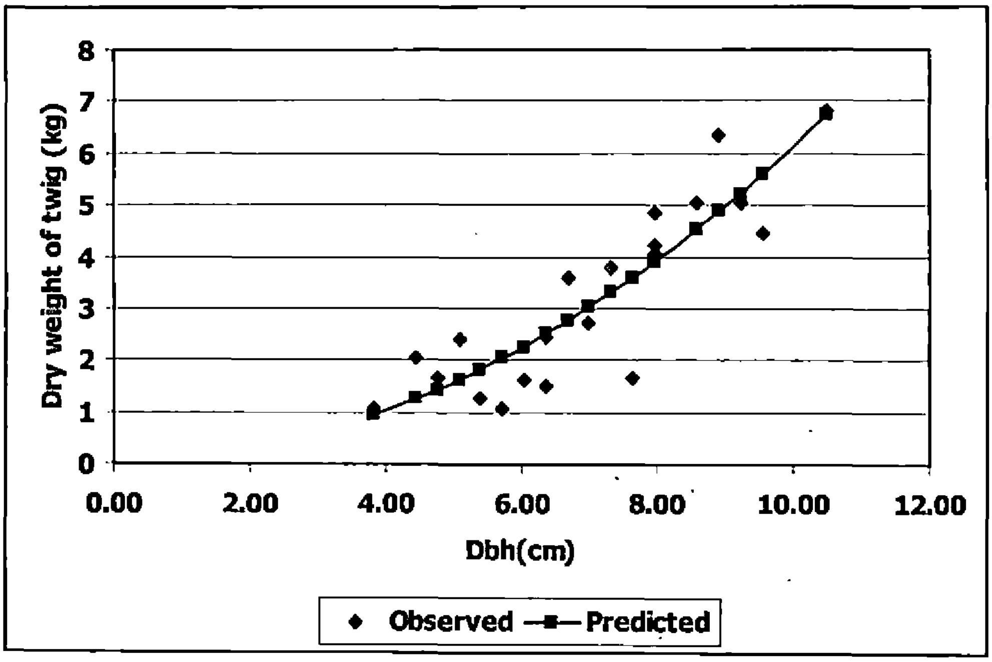

Fig. 12 Relation between dbh and twig

Correlation Coefficient $r = 0.738$

4.5.5. Leaf

Functional forms tried for predicting leaf biomass are given in the Table 14 along with R^2 value and Furnival index.

Among the models tried, model 2 has high R^2 and low Furnival index compared to other dbh alone equations. Model 2 was selected as the best fitted equation. The equation is given below (Appendix 9).

Table 14. Models tried for predicting the leaf biomass

Models	R^2	Furnival index
1. $W = b_0 + b_1D$	0.612	0.87
2. $W = b_0 + b_1D + b_2D^2$	0.676	0.82
3. $W = b_0 + b_1D^2$	0.654	0.82
4. $\ln W = b_0 + b_1 \ln D$	0.597	0.80
5. $W/D^2 = b_0 + b_1 (1/D) + b_2 (1/D^2)$	0.838	3.55
6. $W = b_0 + b_1D^2H$	0.644	0.83
7. $W = b_0 + b_1D^2 + b_2H + b_3D^2H$	0.661	0.86
8. $W = b_0 + b_1D^2 + b2DH + b_3D^2H$	0.667	0.85
9. $\ln W = b_0 + b_1 \ln D + b_2 \ln H$	0.598	0.82
10. $\ln W = b_0 + b_1 \ln(D^2H)_0$	0.591	0.81

Model 2 $W = b_0 + b_1D + b_2 D^2$

$W = 3.235 + -0.834\, D + 0.101\, D^2$

Coefficient of determination $R^2 = 0.676$

Correlation Coefficient $r = 0.822$

The reliability of prediction was also studied by plotting the observed and predicted values using this equation. It is indicated a relatively a weak corelation with dbh and leaf biomass (Fig. 13).

Even though high R^2 value and low Furnival index was shown by many equations involving dbh and height as independent variables, the parameters estimated were not significant in the above equations therefore equations for dbh and height were not selected for predicting leaf biomass.

4.5.6. Fruit

The equation tried for predicting fruit biomass depicted in table 15 with their R^2 value and Furnival index.

Table 15. Models tried for predicting the Fruit biomass

Models	R^2	Furnival index
1. $W = b_0 + b_1D$	0.709	0.81
2. $W = b_0 + b_1D + b_2D^2$	0.730	0.80
3. $W = b_0 + b_1D^2$	0.729	0.78
4. $\ln W = b_0 + b_1\ln D$	0.750	0.68
5. $W/D^2 = b_0 + b_1 (1/D) + b_2 (1/D^2)$	0.801	4.88
6. $W = b_0 + b_1D^2H$	0.733	0.78
7. $W = b_0 + b_1D^2 + b_2H + b_3D^2H$	0.736	0.82
8. $W = b_0 + b_1D^2 + b2DH + b_3D^2H$	0.736	0.82
9. $\ln W = b_0 + b_1\ln D + b_2\ln H$	0.755	0.69
10. $\ln W = b_0 + b_1 \ln(D^2H)$	0.753	0.67

Model 2 $W = b_0 + b_1D + b_2D^2$

$W = 3.235 + -0.834\ D + 0.101\ D^2$

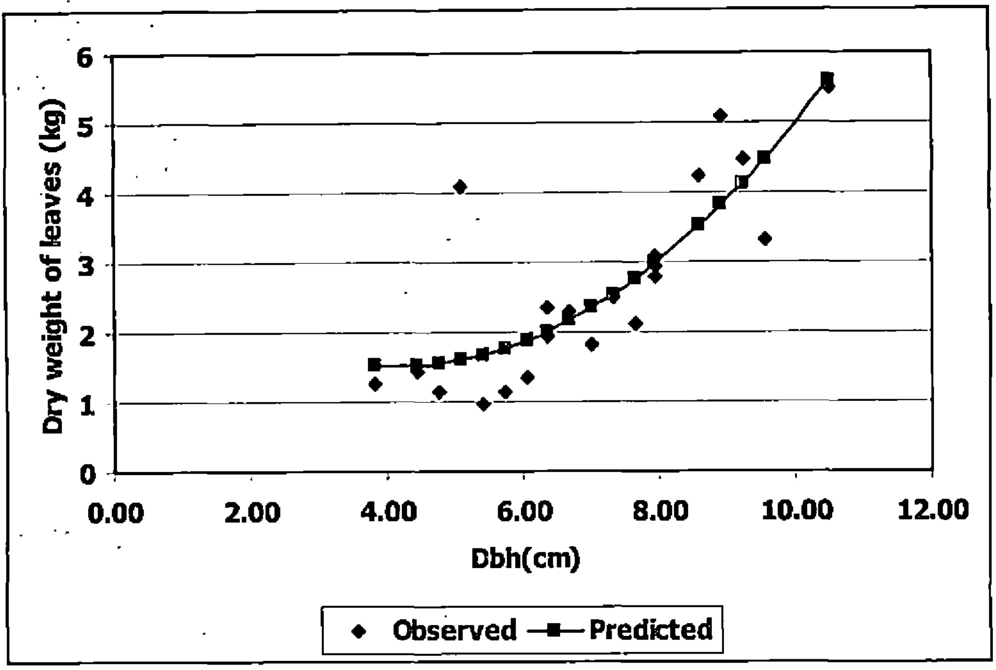

Fig.13 Relation between dbh and leaves

Model 4 $\ln W = b_0 + b_1 \ln D$

$\ln W = -1.558 + 1.396 \ln D$

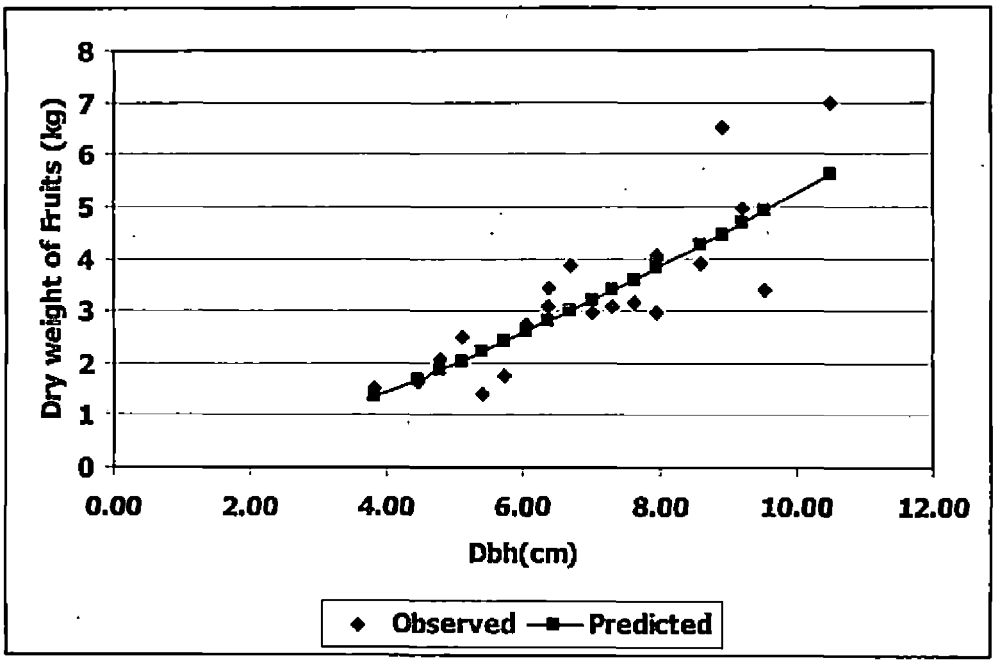

Fig.14 Relation between dbh and fruits

When the independent variable dbh alone was considered, model 4 proved high R^2 value and low Furnival index. The best-fitted equation is furnished below (Appendix 10).

Model 4 $\quad \ln W = b_0 + b_1 \ln D$

$\ln W = -1.558 + 1.396 \ln D$

Coefficient of determination $R^2 = 0.750$

Correlation Coefficient $\quad r = 0.866$

As shown by leaf, fruit biomass was also established a weak correlation with dbh (Fig.14).

In addition to dbh, when height is considered model 10 proves the best fit with high the R^2 value and low Furnival index (Appendix 10).

Model 10 $\quad \ln W = b_0 + b_1 \ln(D^2H)$

$\ln W = -1.810 + 0.514 \ln(D^2H)$

Coefficient of determination $R^2 = 0.753$

Correlation Coefficient $\quad r = 0.868$

4.5.7. Total biomass

Total of all the biomass components predicted with different equations are depicted in table 14 along with their R^2 value and Furnival index.

Model 2 indicated the best fitted equation with high R^2 value and low Furnival index for the total dry weight when the dbh alone as independent variable. The selected best fitted model is furnished below (Appendix. 11).

Table 16. Models tried for predicting the total biomass

Models	R^2	Furnival index
1. $W = b_0 + b_1D$	0.897	5.51
2. $W = b_0 + b_1D + b_2D^2$	0.940	4.34
3. $W = b_0 + b_1D^2$	0.933	4.43
4. $\ln W = b_0 + b_1\ln D$	0.904	4.97
5. $W/D^2 = b_0 + b_1(1/D) + b_2(1/D^2)$	0.171	4.41
6. $W = b_0 + b_1D^2H$	0.953	3.72
7. $W = b_0 + b_1D^2 + b_2H + b_3D^2H$	0.955	3.86
8. $W = b_0 + b_1D^2 + b2DH + b_3D^2H$	0.955	3.86
9. $\ln W = b_0 + b_1\ln D + b_2\ln H$	0.912	4.91
10. $\ln W = b_0 + b_1 \ln(D^2H)$	0.910	4.41

Model 2 $W = b_0 + b_1D + b_2D^2$

$W = 15.505 - 5.427D + 1.010D^2$

Coefficient of determination $R^2 = 0.940$

Correlation Coefficient $r = 0.969$

The reliability of prediction also studied by plotting the observed and predicted values by using this equation. It proves a strong relation between dbh and total dry weight (Fig. 15).

Among the above equations, when the dbh and height were considered as the independent variables, model 6 had come as the best fitted equation with high R^2 value and low Furnival index (Appendix. 11).

Model 6 $W = b_0 + b_1(D^2H)$

$\ln W = 3.694 + 0.07215 \ln(D^2H)$

Coefficient of determination $R^2 = 0.953$

Correlation Coefficient $r = 0.976$

It was seen that among different equations tried for dbh alone, the total dry weight had been considered the model 2 as the best fitted equation (R^2 -0.940 and Furnival index 4.34). Among the components, bole, bark, branch and fruit had shown the model 4 as the best fitted equation due to high R^2 value and low Furnival index. Few other equations with dbh alone as independent variable also gave high R^2 and low Furnival index, they were not considered because, they are derivatives of dbh and also did not show significant difference in R^2 and Furnival index. In the case of twig, the best equation selected was model 3 with R^2- 0.780 and furnival index 0.85. Whereas in leaf, the best fitted equation was model 2 with R^2 – 0.676 and furnival index 0.82. This indicated that model 4 is best for all the components except leaf and twig.

Among various models tried by considering dbh and height as independent variables, model 6 gave best fit for total dry weight and bole. In branch and fruit model 10 proved best equations as indicated by high R^2 value and low Furnival index. But in twig, model 7 and in bark model 9 gave best fit.

The reliability of various equations identified as best fit for different components revealed that a strong correlation exists between dbh and total agb, bole (UB), bark and branch while leaf, twig and fruit exhibited a weak correlation as indicated by the R^2 and Furnival index.

4.5.8. Volume prediction

The volume of all the felled trees were predicted by using different models along with their coefficient of determination R^2 and furnival index are presented in Table 17.

Among the equations tried the best equation with dbh alone was model 4 with high R^2 value and low furnival index. The selected equation is given below (Appendix.12).

Model 4 $\ln W = b_0 + b_1 \ln D$

$\ln W = 8.949 + 2.577 \ln D$

Table 17. Models tried for predicting the volume

Models	R^2	Furnival index
1. $W = b_0 + b_1D$	0.920	0.0039
2. $W = b_0 + b_1D + b_2D^2$	0.947	0.0033
3. $W = b_0 + b_1D^2$	0.946	0.0010
4. $\ln W = b_0 + b_1\ln D$	0.964	0.0025
5. $W/D^2 = b_0 + b_1 (1/D) + b_2 (1/D^2)$	0.577	0.0024
6. $W = b_0 + b_1D^2H$	0.972	0.0023
7. $W = b_0 + b_1D^2 + b_2H + b_3D^2H$	0.972	0.0024
8. $W = b_0 + b_1D^2 + b2DH + b_3D^2H$	0.972	0.0024
9. $\ln W = b_0 + b_1\ln D + b_2\ln H$	0.982	0.0018
10. $\ln W = b_0 + b_1 \ln(D^2H)$	0.982	0.0017

Coefficient of determination $R^2 = 0.964$
Correlation Coefficient $r = 0.982$

The reliability of prediction also studied by plotting the observed and predicted values by using this equation. It indicates a strong correlation with dbh and volume (Fig. 16).

While considered the dbh and height as independent variable the best fit equation with high R^2 value and low furnival index was model 10 the selected equation is given below (Appendix 12).

Model 10 $\ln W = b_0 + b_1 \ln(D^2H)$
$\ln W = -9.454 + 0.957 \ln(D^2H)$

Coefficient of determination $R^2 = 0.982$
Correlation Coefficient $r = 0.991$

4.6. Weight table

Based on the dry weight taken, the total above ground biomass with best fit equation $W = b_0 + b_1D + b_2D^2$ and bole (Under bark) with $\ln W = b_0 + b_1 \ln(D)$ had been

Model 2 $W = b_0 + b_1D + b_2D^2$

$W = 15.505 - 5.427D + 1.010D^2$

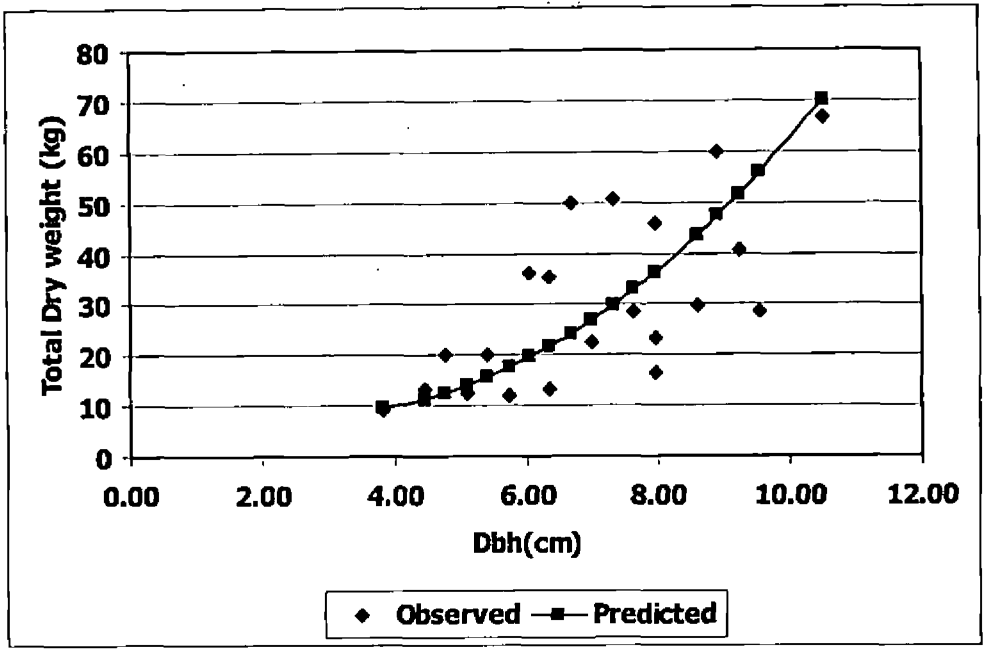

Fig. 15 Relation between dbh and total dry weight

Model 4 $\ln W = b_0 + b_1\ln D$

$\ln W = 8.949 + 2.577 \ln D$

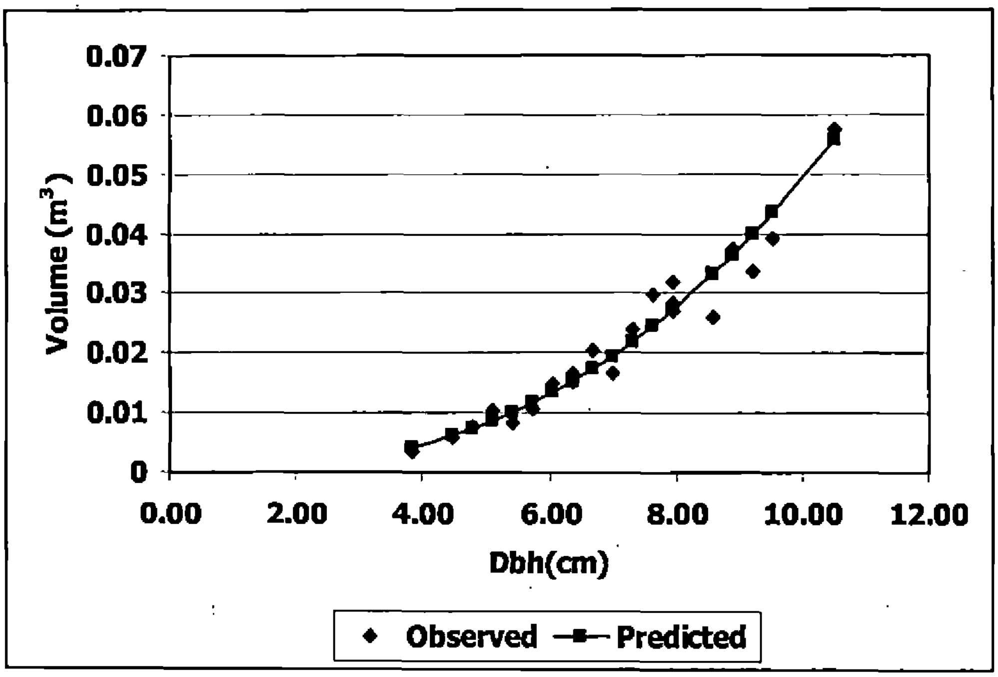

Fig. 16.Relation between dbh and volume

estimated (Appendix 15). Girth was taken as independent variable which was ranged from 12-33 cm. For each 1 cm girth, the dry weight was calculated and presented. These can be utilized to predict the values for similar plantations of *C. sappan* directly when the dbh is known. The biomass figures are obtained by substituting the values in the regression equation and multiplied by the number of trees per hectare.

4.7. Nutrient accumulation

4.7.1. Nutrient concentration in above ground biomass

The concentration of nutrients for a particular component between different sample trees at a particular age had no significant difference. However, significant variation in concentration was observed between ages.

Concentration of nitrogen, phosphorus, and potassium in various components and different ages are given in Table 18 and Fig. 17 to 19. It is observed from the above table that there was considerable variation in the concentration of various elements between different ages. Nitrogen concentration in bole, twig and fruit indicated significant difference between ages 5, 6 and 7 years. Concentration of nitrogen in branches was not significant between ages 6 and 7 years. Same is the case with leaf also. Concentration of nitrogen in bark between different ages did not show significant difference. Concentration of phosphorus in bole, branch, leaf and fruit did not show significant difference between ages 5 and 6 years but there was a significant difference between ages 6 and 7 years. Phosphorus in bark did not show variation between all age group studies, whereas a significant difference in twig concentration was noticed between ages 5, 6 and 7 years. Potassium concentration at different ages indicated significant variation between age groups studied. However, in bole the difference was not conspicuous between ages 5 and 6, but both ages 5 and 6 years significant difference with age 7 years.

Among various components studied, leaf contributed maximum concentration of nitrogen followed by bark, fruit, twig, branch and bole. This was true to the ages 5, 6, and 7 years. Concentration of phosphorus was highest in leaf followed by twigs, bark, branch, fruit and bole. Similarly leaf contributed maximum concentration of potassium followed by fruit, twig, bark, branch, and bole.

Among various elements studied, nitrogen contributed highest concentration followed by potassium and least by phosphorous in all the components at different ages (Table 18).

Table 18. Nutrient concentration of biomass component at different ages

Age (Years)	Bole	Bark	Branch	Twig	Leaf	Fruit
Nitrogen (%)						
5	0.37^{a}	0.67^{a}	0.45^{a}	0.55^{a}	1.22^{a}	0.63^{a}
6	0.30^{b}	0.56^{a}	0.38^{b}	0.49^{b}	1.16^{ab}	0.54^{b}
7	0.25^{c}	0.47^{a}	0.34^{b}	0.38^{c}	1.04^{b}	0.44^{c}
CD (0.05)	0.045	0.051	0.045	0.058	0.078	0.055
Phosphorus (%)						
5	0.06^{a}	0.11^{a}	0.10^{a}	0.16^{a}	0.20^{a}	0.10^{a}
6	0.05^{b}	0.11^{a}	0.10a^{b}	0.15^{b}	0.19a^{b}	0.09^{b}
7	0.04^{b}	0.10^{a}	0.09^{b}	0.14^{c}	0.18^{b}	0.08^{b}
CD (0.05)	0.0061	0.0243	0.0071	0.0050	0.0094	0.0071
Potassium (%)						
5	0.32^{a}	0.52^{a}	0.47^{a}	0.58^{a}	0.90^{a}	0.67^{a}
6	0.32^{a}	0.46^{b}	0.38^{b}	0.47^{b}	0.82^{b}	0.58^{b}
7	0.21^{b}	0.34^{c}	0.30^{c}	0.37^{c}	0.70^{c}	0.48^{c}
CD (0.05)	0.035	0.035	0.035	0.035	0.061	0.050

Values with same superscript do not differ significantly between themselves

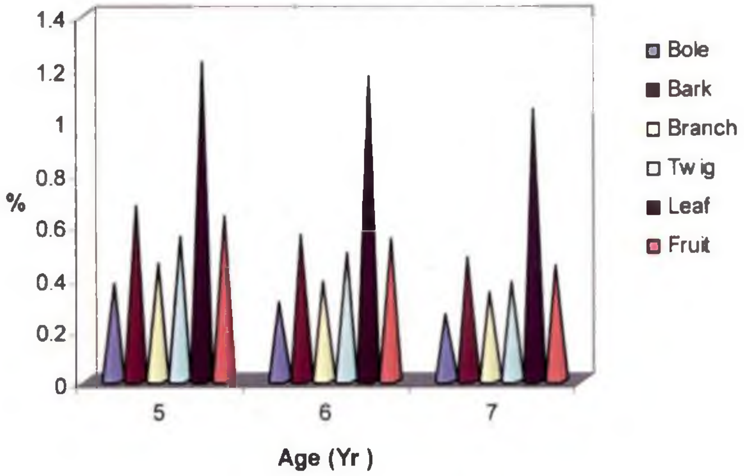

Fig. 17 Nitrogen percentage at different ages

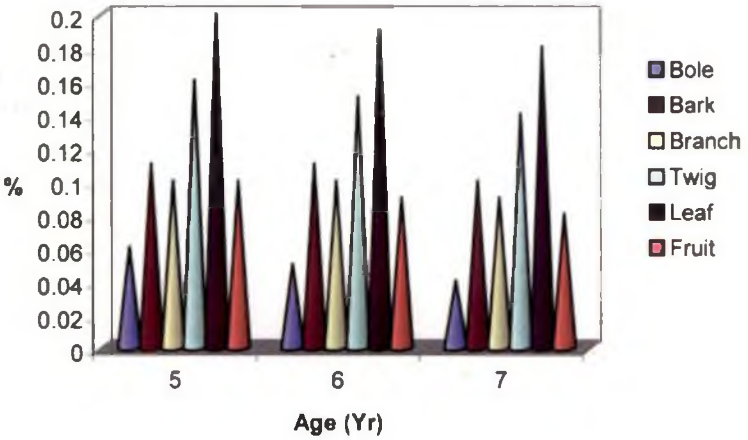

Fig. 18. Phosphorus percentage at different ages

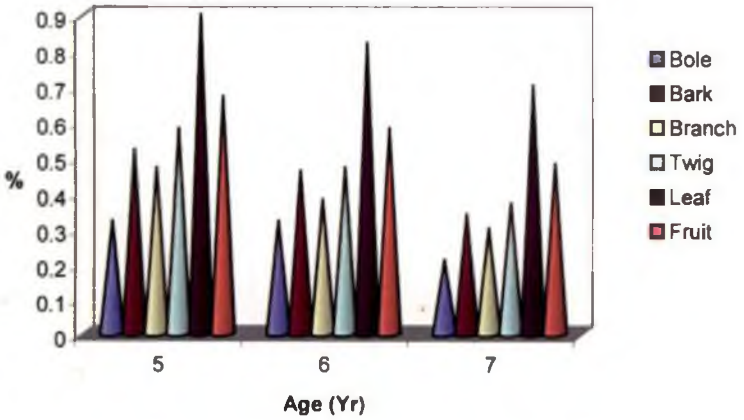

Fig. 19. Potassium percentage at different ages

4.7.2. Nutrient accumulation

Accumulation of N, P, and K in various components and total biomass at different ages has been given in Table (19) and Fig. (20-23). It was observed that there was no considerable variation in the accumulation of various elements between different ages. However, certain nutrients in some components significant variation between age groups studied. Accumulation of nitrogen in various components at different ages did not show significant difference whereas accumulation of phosphorus in twig showed significant variation between 5, 6 and 7 years. In fruits the difference was observed at 7 years to other ages, whereas, in other components did not show significant difference between all age groups studied. Potassium accumulation in fruit observed considerable variation between ages 5 and 7 years. However, accumulation in other components did not show significant difference between all age groups.

The accumulation of various nutrients showed an increasing trend with increasing age. The nitrogen in the total above ground biomass was recorded as 126.85 Kg ha^{-1} at 5 years and increased to 161.91 Kg ha^{-1} at 6 years. It is further increased to 182.23 Kg ha^{-1} at the age of 7 years. Potassium and phosphorus followed similar trend.

Among various components studied, bole accumulated maximum nutrients and minimum in bark except the phosphorus accumulation at age 6 and 7 years (Fig. 23). Where maximum was accumulated in branch. Nutrients accumulated in various components at different ages are varied. Nitrogen accumulation at age 5 year and age 7 year was in the order: bole > leaves > branches > fruit > twig > bark, whereas at age 6 years the sequence was bole > branches > leaves > fruit > twig > bark. The decreasing order of phosphorus accumulated in various components at age 5 years was bole > branch > leaves > twig >fruit > bark, whereas at age 6 and 7 years, the accumulation in branch become maximum and the decreasing order was as follows, branch > bole > leaf > twig > fruit > bark. Potassium accumulation at different components was showed same sequence in all ages, the decreasing order was bole > branch > leaves > fruit > twig > bark.

Among various elements, nitrogen contributed maximum accumulation in biomass followed by potassium and least by phosphorus except in fruits. In fruits potassium accumulated maximum followed by nitrogen and phosphorus. While at age 5 years, branch, twig and fruit accumulated maximum potassium rather than nitrogen.

Table 19. Nutrient accumulation at different ages (Kg ha $^{-1}$)

Nitrogen							
Age (Years)	**Bole**	**Bark**	**Branch**	**Twig**	**Leaves**	**Fruit**	**Total agb**
5	35.05^a	7.26^a	26.19^a	14.33^a	28.10^a	15.92^a	126.85^a
6	49.00^a	8.72^a	38.85^a	15.95^a	30.83^a	18.56^a	161.91^a
7	48.80^a	9.81^a	35.31^a	21.60^a	42.67^a	24.04^a	182.23^a
CD (0.05)	26.996	4.205	20.078	8.905	17.789	7.373	17.500
Phosphorus							
5	5.81^a	1.18^a	5.59^a	4.35^b	4.57^a	2.58^b	24.08^a
6	7.48^a	1.78^a	9.61^a	4.93^{ab}	5.09^a	3.00^b	31.89^a
7	7.19^a	2.14^a	9.55^a	7.33^a	7.34^a	4.41^a	37.96^a
CD (0.05)	3.987	0.923	4.912	2.30	2.945	0.52	15.240
Potassium							
5	31.24^a	5.76^a	28.88^a	14.63^a	20.74^a	17.77^b	119.02^a
6	50.96^a	7.14^a	37.67^a	15.58^a	21.90^a	20.39^{ab}	153.64^a
7	44.07^a	7.24^a	31.57^a	20.81^a	28.44^a	25.31^a	157.44^a
CD (0.05)	29.214	3.221	19.448	8.958	12.578	7.29	73.628

Values with same superscript do not differ significantly between themselves

The nutrient accumulation in g tree^{-1} also showed the same sequence as noticed in the kg ha^{-1} basis (Table 20). In both cases after six years, there was no considerable increase in nutrient accumulation. As noticed in biomass, nutrients also exhibited a levelling off in accumulation of nutrients at age 6 years.

Table 20. Nutrient accumulation in various biomass components at different ages (g tree^{-1})

Nitrogen							
Age (Years)	**Bole**	**Bark**	**Branch**	**Twig**	**Leaves**	**Fruit**	**Total agb**
5	31.14^{a}	6.26^{a}	22.74^{a}	13.47^{a}	25.03^{a}	14.72^{a}	113.36^{a}
6	44.10^{a}	7.84^{a}	34.97^{a}	14.35^{a}	27.75^{a}	16.70^{a}	145.71^{a}
7	43.92^{a}	8.83^{a}	31.78^{a}	19.44^{a}	38.41^{a}	21.63^{a}	164.01^{a}
CD (0.05)	24.296	3.785	18.070	8.014	16.010	6.636	70.650
Phosphorus							
5	5.13^{a}	1.09^{a}	5.31^{a}	3.67^{b}	4.19^{a}	2.35^{b}	21.74^{a}
6	7.46^{a}	1.61^{a}	8.65^{a}	4.43^{ab}	4.58^{a}	2.70^{b}	29.43^{a}
7	6.74^{a}	1.93^{a}	8.59^{a}	6.60^{a}	6.61^{a}	3.97^{a}	34.44^{a}
CD (0.05)	3.588	0.830	4.420	2.34	2.649	1.13	13.716
Potassium							
5	27.66^{a}	5.21^{a}	24.99^{a}	13.67^{a}	17.76^{a}	16.19^{b}	105.48^{a}
6	45.86^{a}	6.42^{a}	33.90^{a}	14.03^{a}	19.71^{a}	18.35^{ab}	138.26^{a}
7	39.66^{a}	6.52^{a}	28.41^{a}	18.73^{a}	25.60^{a}	22.78^{a}	141.70^{a}
CD (0.0s5)	26.213	2.900	17.503	8.062	11.320	6.58	66.266

Values with same superscript do not differ significantly between themselves

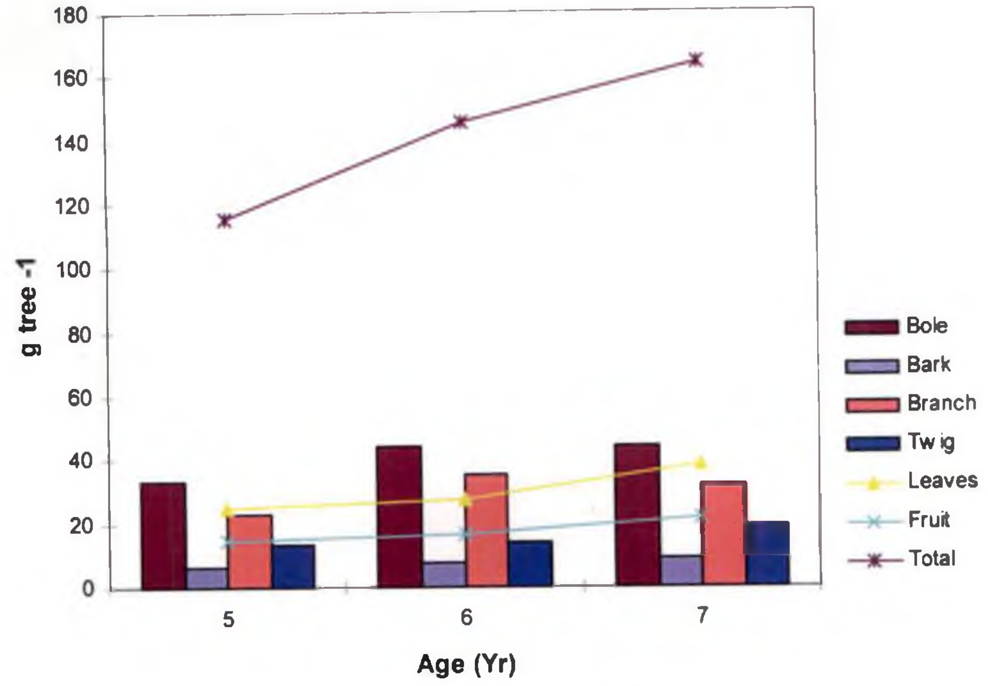

Fig 20 Nitrogen accumulation in different ages

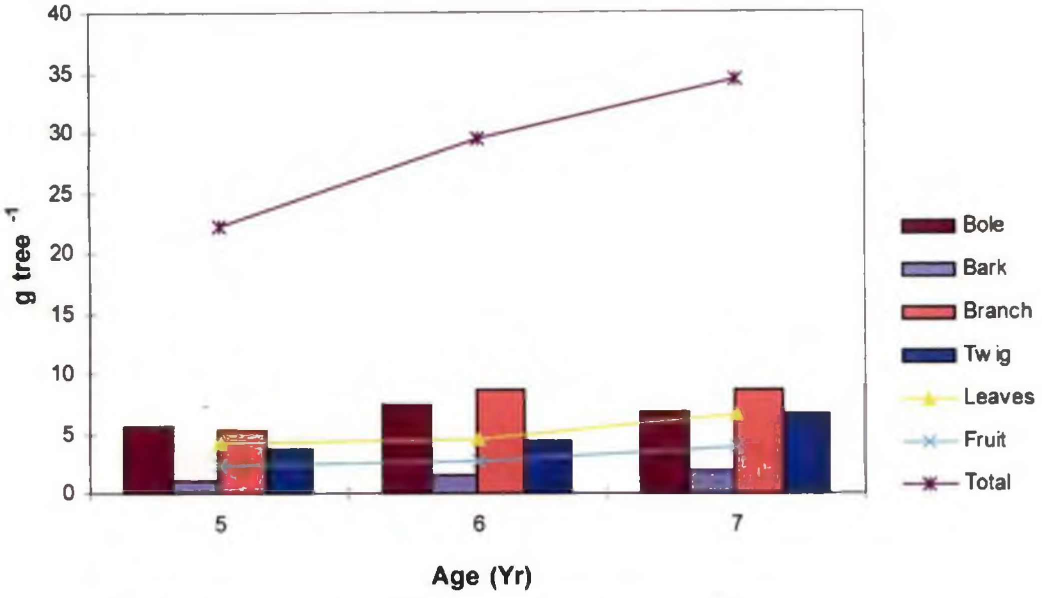

Fig. 21 Phosphorus accumulation in different ages

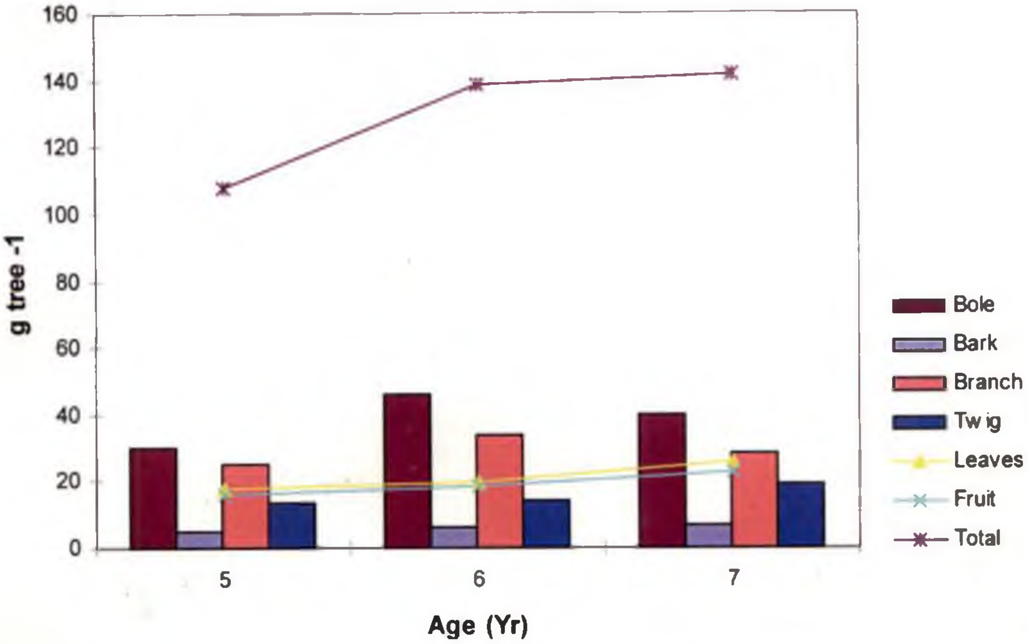

Fig. 22 Potassium accumulation in different ages

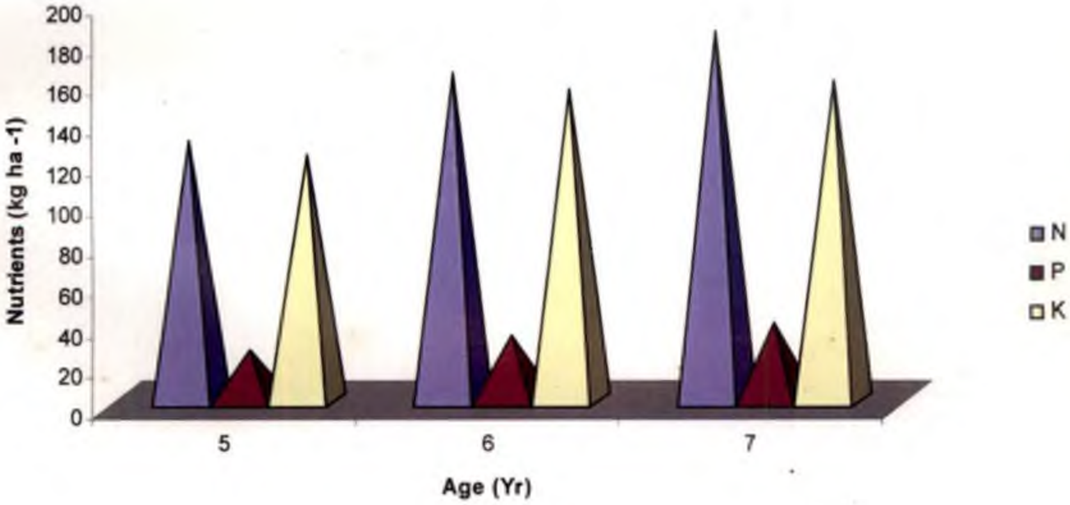

Fig. 23 Total nutrient accumulation in the AGB at different ages

4.8. Nutrient use efficiency

Nutrient use efficiency is expressed as a quotient of standing biomass divided by above ground nutrient pool. It is the total biomass synthesised per unit of nutrients utilised. The study of such nutrients for each component at different ages showed an increasing trend with increasing ages (Table 21). The quotient for nitrogen ranged as 190.41 at 5 year to 243.43 at 7 year; Phosphorus was 995.13 to 1168.60 at 5-7 years; Potassium ranged 202.74 to 281.76 at 5-7 years. Among the biomass components nutrient use efficiency was maximum recorded in bole (N, 275.99 to 369.67; P, 1601.88 to 2509.04; K, 304.73 to 409.35) and least by leaf (N, 81.14 to 93.04; P, 498.91 to 540.87; K, 109.93 to 139.59).

Among the nutrients, phosphorous constituted maximum nutrient efficiency followed by potassium and least by nitrogen except in bole at 6 years, branch and twig at 5 years and fruit in all age groups, where nitrogen showed maximum nutrient use efficiency when compared to potassium (Table 21).

Nutrient use efficiency of total above ground biomass and biomass component increased in all nutrients with increasing age, whereas in phosphorus nutrient use efficiency it showed a decreasing order in bole between 5 and 6 years, agb and branch between 6 and 7 years (Table 21).

Table 21. Nutrient use efficiency at different ages

Nitrogen							
Age (Years)	**Bole**	**Bark**	**Branch**	**Twig**	**Leaves**	**Fruit**	**Total agb**
5	275.99	148.76	216.49	187.72	81.14	162.69	190.41
6	334.49	185.78	262.03	212.54	87.25	191.35	233.46
7	369.67	206.93	279.81	241.67	93.04	216.72	243.43
Phosphorus							
5	1601.88	915.25	1014.31	618.39	498.91	1003.88	995.13
6	2191.18	910.11	1059.31	687.63	528.49	1180.00	1185.32
7	2509.04	948.60	1034.55	712.14	540.87	1181.41	1168.60
Potassium							
5	304.73	187.50	196.33	183.87	109.93	145.75	202.74
6	321.62	226.89	270.24	217.59	122.83	173.61	246.02
7	409.35	280.39	312.96	250.84	139.59	205.85	281.76

Discussion

DISCUSSION

Biomass studies are important for forecasting the productivity, volume, nutrient accumulation and also for fixing rotation in tree stands. Biomass production and productivity of plant or ecosystem varies with the availability of resourses and characteristics of environment in which they grow (Booth and Macmutrie, 1988). So for the estimation of biomass under different climatic and geographical areas, we need to find out the range over which species can grow (Rawat and Negi, 2004).

With the increase in demand for the medicinal plants, it is important to ensure the conservation of natural resources. Due to indiscriminate utilisation of these resources from the forest, the availability of these plants has come down drastically. Cultivation of these plants outside the conventional forest is important in order to meet ever increasing demand of medicinal plants. *Caesalpinia sappan* is extensively used for medicinal properties and also to extract brazilin dye from the wood. Therefore wood biomass is the commercial part of the tree. Quantity of wood produced at different ages determines the potential of this tree for development of plantations. An attempt has been made here to study the biomass production, productivity and nutrient accumulation of *Caesalpinia sappan* plantation at different ages.

5.1. Growth parameters

Present study indicated that diameter and height varies between plantations of the particular age. At age 5 years diameter varied from 5.56 cm to 6.23 cm and height varied from 5.91 cm to 6.18 cm and at age 7 year, it showed an increase of diameter ranging from 7.12 cm to 7.99 cm whereas height varied from 6.37 m to 7.02 m. This variation may be due to the difference in edaphic and climatic variation between plantations. Similar observation was found in eight year old *Azadirachta indica* plantations in which diameter ranged between 8.5 cm to 17.5 cm (Roy *et al.*, 2005). The trend of variability in dbh has been reported in many fast growing tree species like *Casuarina equisetifolia* (Sugur, 1989), *Eucalyptus camaldulensis* (Prasad *et al.*, 1984), *Populus deltoides* (Puri *et* *al.*, 1994) and *Albizia lebbek* (Pathak *et al.*, 1992). There was a consistent trend of height increase with the diameter for this species at this site as also supported by other workers on matching sites in the case of *Albizia lebbek* (Debroy, 1988 and Pathak *et al.*, 1992).

Significant variation in diameter and height was noticed at different ages. At the age of 5 year diameter and height were 5.96 cm and 6.02 m respectively and at age 7 years, it substantially increased to 7.52 cm and height 6.68 m. Diameter and height of *Populus deltoides* clone D-121 ranged from 14.9 to 25.2 cm and height from 12.9 to 25 m at 4 to 8 years of age (Singh and Rana, 2004). Similarly significant variation in growth parameters at different ages was also reported in *Casuarina equisetifolia* (Lugo *et al.*, 1990).

5.2. Above ground biomass

Biomass accumulated per tree depends on factors like density, age of the tree and environmental condition in which it is grown (Landsberg, 1995). In the present study, it was observed that above ground biomass at age of 5, 6 and 7 years was 21.43 kg tree^{-1}, 34.02 kg tree^{-1} and 39.92 kg tree^{-1} respectively . Whereas agb of *Leucaena leucocephala* was 21.87 kg tree^{-1} at 5 year old plantation (George, 1993). Hence, the amount of agb at 5 year in case of *Caesalpinia sappan* is on par with *Leucaena leucocephala.* Vidyasagaran (2003) observed that agb produced at age of 7 years in *Casuarina equisetifolia* was 50.9 in kg tree^{-1}, which is higher than the present study. It may be due to slow growing nature of the *Caesalpinia sappan*. Higher age groups produce more dry matter, which was revealed by Negi and Tandon (1997) in *Eucalyptus hybrid* and Cromer *et al.* (1993) in *Eucalyptus grandis.*

Bole biomass accounted highest when compared to other components of the tree. In the present study it was observed that bole biomass was maximum in all age groups (Table 4). Bole biomass of 8.55 kg tree^{-1}, 14.75 and 16.24 kg tree^{-1} at ages 5, 6 and 7 years was observed. Similar observation was made in *Ailanthus triphysa* (7.35 kg $^{-1}$) and *Lucaena leucocephala* (6.70 kg tree^{-1}) at age 5 years (George, 1993). In case of *Casuarina equisetifolia* also, bole biomass (33.91 kg tree^{-1}) was maximum out of all other components at age 7 years (Vidyasagaran, 2003). The higher bole biomass may be due to the higher accumulation of nutrients in the bole compared to other components.

Above ground biomass increased with increasing age. In the present study, above ground biomass showed the increasing trend from age 5 year to age 7 year (21.43 kg tree^{-1} to 39.92 kg tree^{-1}). Similar increasing trend was observed in case of *Poulownia fortunei* (10.06 to18.0 kg tree^{-1}) from age 1 year to 4 year (Charansingh, 2003). This trend was also supported by Gurumurthy and Rawat (1989) in *Casuarina equisitifolia.* The increasing trend is due to the higher accumulation of photosynthates with advancing ages.

5.3. Percentage distribution

The percentage of bole biomass to their total above ground biomass was maximum in all age groups. In the present study, at 6 year, percentage of bole contribution (43.35 %) was maximum, whereas bole biomass percentage in case of *Senna siamea* was 54 percent (Harmand *et al.*, 2004) and 51.2 per cent in *Populus deltoides* (Singh and Rana, 2004) which is higher than the observation made in the present study. Percentage of bole biomass at age of 7 year was 40.08 percent (Table 5) which is lower than the percentage bole biomass of fast growing species. Percentage of bole biomass recorded in case of *Acacia mangium* at 7 year was 65 percent (Kunhamu 2006) and 74 per cent in case of *Eucalyptus camaldulensis* (Harmand *et al.*, 2004). In the present study, lower percentage of bole biomass may be due to the distribution of the photosynthates to other components like branch, leaves and fruits (Table.5). High percentage of bole biomass also reported in many species (Logo *et al.*, 1990; Grier *et al.*, 1992 and Karmacharya and Singh, 1992).

The percentage contribution of the bole and branches showed an increasing trend from 5 year to 6 year, correspondingly, there was a decrease in percentage of leaves and fruit biomass. But there was a decrease in bole and branch biomass from 6 year (43.35 to 26.93 per cent) to 7 year (40.68 and 22.28 per cent) and in leaves and fruits show an increasing trend (Table 5). Decrease in percentage of biomass in bole and branches are definitely due to more accumulation of photosynthates for leaf and fruit production. The increase of the bole biomass was also observed in *Populus deltoides* clone G3, in which showed that increase in biomass of bole from 48.1 per cent at 4 year to 60.6 per cent at 6 year, it was further decreased to 57.5 per cent at 8 years and in bole, similar observation was found in *Populus deltoides* D-21 clone, at age 4 year as 14.3 per cent, 17.9 per cent at 6 year and 11.7 per cent at 9 years (Singh and Rana, 2004). Similar observations were noticed in the case of *Leucaena leucocephala* (K-500) T Jhansi (Pathak and Gupta, 1987).

The other components had also showed variation with increasing age. In the case of bark, twig and fruit, percentage distribution of biomass decreased from 5 year to 6 year, further it increased at 7 years. The same trend was also found in bark of *Populus deltoides* D-121 clone. The bark at 4 year was 9 per cent, then decreased to 6.4 per cent at 6 years and further increased to 8.5 per cent at 9 years (Singh and Rana, 2004). In the present study, the leaf biomass was decreased from 9.28 per cent at 5 year to 7.12 per cent at 6 years and an increase to 8.94 per cent at 7 years. The similar trend was noticed in *Populus deltoides* clones D-121 and G3 (Singh and Rana, 2004). A significant difference in biomass components were reported by Toky *et al.* (1996) in *Albizia* provenances; Ginwal *et al.* (1995) in *Acacia nilotica*; Gurumurthy and Rawat, 1989 in *Casuarina equisetifolia*.

5.4. Dry matter production per unit area

In the present study, agb at age 5 year was produced 23.8 t ha^{-1}. In case of *Gmelina arborea,* it was 21.7 t ha^{-1} (Swami and Puri, 2004) and *Ailanthus tryphysa* produced 21.87 t ha^{-1}(George, 1993) which was on par with the agb produced in the present study. At the age of 6 year it was observed that *C. sappan* produced 37.8 t ha^{-1} of agb whereas *Populus deltoides* produced 60.4 t ha^{-1} (Mohsin, *et al.,* 1999) and *Eucalyptus hybrid* 74.38 t ha^{-1} of agb (Mohsin *et al.,* 2003). Lower production may be due to the slow growing nature of this species and variations in density. In the present study, agb produced at age 7 year was 44.36 t ha^{-1}. The biomass observed in the case of *Eucalyptus camaldulensis* in Camaroon was 34.85 t ha^{-1} (Harmand *et al*., 2004). The higher agb may be due to the variation in locality, whereas in case of *Populus deltoides* above ground biomass produced at 7 year was 95.98 t ha^{-1}(Mohsin *et al.,*1999) and in *Eucaliptus* *hybrid,* it was 91.66 t ha^{-1} (Mohsin *et al.,* 2003), which may be due to fast growing nature of *Populus deltoides* and *Eucalyptus grandis.* The higher bole biomass at age of 7 years also reported in *Acacia mangium* (Halende, 1989 and Kunhamu *et al.,* 2006).

Second highest biomass was produced in branches, which was observed to be 5.67 t ha^{-1}, 10.18 t ha^{-1} and 9.88 t ha^{-1}at three age groups (Table 6). At age 5 year, *Casuarina equisitifolia* branch biomass was recorded 3.75 t ha^{-1} (George, 1993). The wide canopy development nature of *C.sappan* trees may be reason to produce more branch biomass. The value obtained in *Populus deltoides* (11.44 t ha^{-1}) at age 6 years was in agreement with the value recorded in the present study (Mohsin *et al.,* 1999). The branch biomass produced at age 7 years was less than the branch biomass produced in *Eucalyptus hybrid* (11.09 t ha^{-1}) at age 7 years. In the present study more biomass was allocated to leaf and fruit which correlates the lesser production of branch biomass.

Leaf biomass is the important component in the tree for the photosynthesis and allocation of photosynthates to the other part of the tree. Leaf biomass produced at age 5, 6 and 7 was recorded 2.28 t ha^{-1}, 2.69 t $ha^{-1}$and 3.97 t ha^{-1}. The leaf biomass produced at age 5 years in *Casuarina equisitifolia* (2.79 t ha^{-1}) and in *Ailanthus tryphysa* (1.98 t ha^{-1}) was in agreement with the values recorded in the present study (George, 1993). The foliage biomass produced in *Eucalyptus hybrid* was 7.93 t ha^{-1} (Mohsin *et al.,* 2003) which is very high value compared to the value obtained in the present study. This variation may be because of the higher leaf biomass production of fast growing species compared to slow growing species. Where as the value obtained in the present study is evident the biomass produced (3.06 t ha^{-1}) in *Eucalyptus camaldulenisis* (Harmand *et al.,* 2004)

Biomass production in unit area showed an increasing trend from age 5 year to age 7 year (Table 6). The total agb observed was 23.81 t ha^{-1}, 37.80 t ha^{-1} and 44.36 t ha^{-1} at ages 5, 6 and 7 years. Similarly, the increase of biomass from 6 year to 7 year showed in *Eucalyptus hybrid* was 104.68 t ha^{-1} and 129.82 t ha^{-1} (Mohin *et al.,* 2003) and in *Dalbergia latifolia* ranging from 53.09 t ha^{-1} to 160.04 t ha^{-1} at the age 3 years to the age of 7 years (Das and Chaturvedi, 2003). The highest biomass accumulation occurs because of the combined effect of age and number of trees per hectare (Nwoboshi, 1985).

The biomass components also showed the trend as the total above ground biomass except in branches. In branches, the biomass decreased at of age 6 years to 7 years. This decrease in branch biomass may be due to the higher production of the leaf, and fruit biomass at age 7 years (Table 6).

5.5. Productivity

In the present study, productivity at age 5 year was recorded 4.77 t ha^{-1}yr^{-1}. This value is comparable with the productivity obtained in *Ailanthus triphysa* at age of 5 year (George 1993), which was recorded 4.31 t ha^{-1}yr^{-1}. The productivity was recorded in the present study at age 6 years was 6.30 t ha^{-1}, whereas in the fast growing species like *Eucalyptus hybrid* produced 13.36 t ha^{-1}yr^{-1} (Mohsin *et al.*, 2003) and *Populus detoides* recorded 12.39 t ha^{-1} yr^{-1}, (Mohsin *et al.*, 1999) was higher than the value obtained in this study. At the age of 7 years, *Eucalyptus camaludulensis* produced 6.16 t ha^{-1} yr^{-1} (Harmand *et al.*, 2004) which is in agreement with the productivity recorded in the present study (6.34 t ha^{-1} yr $^{-1}$).

The productivity also increased with increasing age. The increase of productivity at age 5 year to 6 year was 4.77 t ha^{-1} yr^{-1} to 6.30 t ha $^{-1}$ yr$^{-1.}$ It further increased to 6.34 t ha^{-1} yr^{-1}. The above finding is evident in the case of *Eucalyptus hybrid* at age 6 and 7 years, wherein productivity varied from 12.39 t ha^{-1} yr^{-1} and 13.09 t ha^{-1} yr^{-1}(Mohsin *et al.,* 2003). This value is higher than present study because *Eucalyptus hybrid* is a fast growing species.

Productivity at different ages indicated a leveling off at higher ages which was similar to the trend shown by biomass on unit area basis (6.30 and 6.34 t ha $^{-1}$ yr^{-1}) and per tree basis (5.67 kg tree $^{-1}$ yr^{-1} to 5.70 kg tree $^{-1}$ yr^{-1}). An increase of 0.04 tha^{-1} yr^{-1} was observed in unit area basis. Similarly a leveling off between 6 and 7 years in *Populus deltoides* was recorded, which showed that productivity was 13.36 and 13.71 t ha $^{-1}$ yr^{-1} at ages 6 and 7 years (Mohsin *et al.*, 1999).

Present investigation revealed that *Caesalpinia sappan* plantation growing in the study sites gave maximum biomass productivity at age 6 years. Beyond, no considerable increase in productivity was obtained. This declining trend in the productivity and nutrient accumulation with increasing stand age, elucidate possibility of fixing the age for final harvest.

5.6. Biomass prediction

Biomass prediction is considered to be a non destructive method in the estimation of biomass of trees in plantations. Since measurement of trees in a given plantation is usually impracticable, the biomass components and easily measurable variable of individual trees are commonly developed and used in prediction. The dry weight which is determined by regression equation to easily measurable dimensions such as dbh and combined effect of dbh and height (Anderson, 1971; Baker *et al.,* 1984; Dudley and Fowns, 1992; Rana *et al.*, 1993; Khan and Pathak, 1996 and Ajit *et al.*, 2003)

Prediction relationship attempted in the present study was linking the above ground biomass with dbh or total height of the trees. Among the ten equations tried, five are dbh alone as independent variable and five are dbh and height combined. All these equations are used for predicting total biomass, biomass components and volume. Out of these, best equations were selected on dbh alone and other for dbh and height combined. Linear models gave best fit total agb and biomass components. Linear equation was given higher values of coefficient of determination in many trees (Bradstock, 1981; Gurumurthy *et al.,* 1984 and Ajit *et al.,* 2003). Multiple regression models were also tried for developing best fit equation in many species. (Ghan *et al.,* 1993 and Kumaravelu, 1997). Regression equation for different biomass components like bole, bark, branches, twigs, leaves and fruits are developed for the best prediction (Stiell, 1957; Woessner 1973 and Rana *et al.*, 1993). Logarithmic transformation of the simple linear models was reported to give best prediction for biomass in many trees (Khan *et al.*, 1993; Kushalapa, 1993; Grewal, 1995 and Khan and Pathak, 1996).

Dry weight can be expressed as a function of dbh and height. Therefore in the present study the two parameters were taken as an independent variables and weight as a dependent variable for selecting best model. The selection of the independent variable dbh was occasioned by the ease and accuracy in making measurements. Dudely and Fowns (1992) observed that the time spent in field could not be greatly reduced by eliminating height measurement in stands that are relatively homogenous. The biomass estimation equation varies with species, age, stand density, genetic difference and environmental variability among sites (Campbell *et al.*, 1985).

Coefficient of determination is the criteria to select the best equation in many cases (Pande *et al.*, 1988; Halende, 1989 and Deans *et al.*, 1996). However, in allometric equation, these parameters may not be always suitable for comparing different models because the dependent variable varies from one model to another. Therefore it is possible to compare the different models by an index developed by Furnival (1961). In the present study, the best fitted equation selected based on high R^2 value and low Furnival index. Similar findings were reported by Gupta *et al.* (1990); Thakur and Kaushal (1991); Christine (1992); Kushalapa (1993) and Thapa (2005).

In the present study, suitable models for various components for agb were selected based on equations with high R^2 value and low Furnival index. For the prediction of total above ground biomass the best equation come as model 2 ($W = b_0 + b_1 d + b_2 D^2$). Model 2 come as best fit for predicting leaf biomass also. Similarly this equation was also suitable to predict agb of *Acacia mangium* which was $W = 34.63 - 3.515 (D) 0.09 (D)^2$ (Kunhamu *et al.* (2006). In other components like bole, bark, branch and fruit the best fitted equation was model 4 ($\ln W = b_0 + b_1 \ln D$). This model selected in fast growing species like *Ailanthus triphysa* was $\ln B = -7.895 + 2.623 \ln D$ (Geoge, 1993) and *Acacia auriculiformis* was $-1.298 + 2.307 \ln D$ (Jamaludheen, 1994). In twigs model 3 ($W = b_o + b_1 D^2$) was the best fit with high R^2 and low Furnival index. The same equation was selected with high R^2 value in *Melia azadirach* was $19.77 + 0.118 (D)^2$ (Roy *et al.*, 2005). In most of the components, the best fit equation observed was model 4. Number of reports revealed equations with dbh alone (Otieno *et al.*, (1991) in *Sesbania sesban*; Khan and Pathak (1996) in *Leucaena leucocephala* in Jhansi; Tandon *et al.*, (1998) in *Eucalyptus grandis*; Ajit *et al.* (2003) in *Acacia tortilis* and Xiao and Ceulemans (2004) in *Pinus sylvestris*). Equation with dbh and height as independable variable showed different models as best fit as indicated by their maximum R^2 and values and minimum Furnival index. Model 6 ($W = b_0 + b_1 D^2 H$) was proved best fit for agb and bole (Table. 10, 16). This equation was also selected for predicting the bole and agb in

Melia azadirach $W = 21.855 - 1\ (8.09 \times 10^{-5})\ D^2 H$ (Roy *et al.*, 2006). In branch and twigs Model 10 proved as best fit ($\ln W = b_0 + b_1 \ln D^2 H$). The same equation was also used to predict biomass of *Casuarina equisetifolia*, which is $W = -2.693 + 0.904 \ln D^2 H$ (Jamaludheen, 1994). But in bark best fit model was model 9 ($W = b_0 + b_1 \ln (D) + b_2 \ln H$) and in fruit best fit equation was model 7 ($W = b_0 + b_1 D2 + b_2 H + b_3 D^2 H$). Allometric equation with dbh and height have been developed in many tree species elsewhere (Whitesell *et al.*, 1988 in *Eucalyptus grandis*; Halenda, 1989 in *Acacia mangium*; Gurumurthy and Rawat, 1989 in *Casuarina equisetifolia;* Parrotta, 1989 in *Albizia lebbek;* Roy *et al.*, 1997 in *Leucaena leucocephala*; Karmacharya and Singh, 1992 in *Tectona grandis* and Kunhamu *et al.*, 2006 in *Acacia mangium)*

Among these selected models the most suited equation was model 4 ($\ln W = b_0 + b_1 \ln D$) with dbh alone. It is chosen because it is more suitable for the prediction of bole, bark, branch and fruits. Since this model is having one variable alone without derivatives and height combination, it was used to estimate the biomass of the *C.sappan* plantations in the study locations. Even though some other equations were proved more fit with combination of dbh and height and R^2 value and Furnival index were relatively similar to equations with dbh alone could not be selected it is difficult to measure height of the standing trees with definite accuracy. The time spent in field could be greatly reduced by eliminating height measurement in stands that are relatively homogenous. (Whittaker and Marks, 1975 and Dudely and Fowns, 1992).

The reliability of the observed and predicted values are plotted in graph with dependable variables total aboveground biomass and components like bole, bark, branch, leaves, twigs and fruits (Fig. 9-15). The graphs showed good relation between dbh and biomass with higher R^2 value in total agb (R^2 – 0.940), bole (R^2 –0.944), bark (R^2-0.658), and branch ((R^2-0.810) except in few cases at higher diameter. Roy *et al.* (2005) also reported the better fitness being in the lower diameter classes of total agb and biomass components. Similar trend of fitness in respect to aerial biomass in *Acacia nilotica* (Maguire *et al.,* 1990) and *Leucaena leucocephala* (Khan and Pathak, 1996) have been reported. In the case of twigs, leaves and fruits, comparatively low R^2 value (R^2 - 0.780, 0.676 and 0.750 respectively) observed which showed their weak correlation with the independent variable dbh (Fig.12- 14). This may be because of the shedding of the twigs, leaves and fruits in different proportion during the period of one year which altered the dry weight. Weak correlation dependent variable with twig leaves and fruits were reported (Tandon et al., 1993 in *Eucalyptus* hybrid; Deans *et al.,* 1996 in *Terminalia ivorensis* and Roy *et al.,* 1997 in *Leucaena leucocephala*;).

The weight table constructed for total above ground biomass and bole (ub) biomass based on the best fit models (model 2 and model 4) which can be utilised to estimate biomass for similar plantation directly by measuring the dbh alone. Biomass figures are obtained by substituting the values in regression equation and multiplied the number of trees per hectare.

5.7. Volume prediction

Prediction of volume of standing *C. sappan* trees on the basis of easily measurable parameters such as dbh and height has been attempted using different allometric regression models. The volume was estimated on the basis of frustrum of bole using Newton's formula (Chaturvedi and Khanna, 1982). Volume prediction had been estimated in many trees (Chaturvedi, 1974; Rao *et a*l., 1985 and Jain *et al.*, 1991).

In the present study, dbh alone as independent variable, best fitted equation with high R^2 value and low Furnival index was model 4 ($\ln W = b_0 + b_1 \ln D$) using the independent variable dbh. Similarly, the Model 4 was also used to predict the volume in *Populus hybrid* which was $V = 2.662 + 2.514 \ln D$ (Dogra and Sharma, 2003). The volume was also predicted in *Eucalyptus globulus* (Rana *et al*, 1993) and Roy *et al.,* 1997 in *Leucaena leucocephala* by using the dbh as independent variable.

The variables dbh and height as independent variables gave the best equation for volume was selected based on the high R^2 and low Furnival index was model 10 ($\ln W = b_0 + b_1 \ln D^2 H$). Model 10 was also tried in *Populus hybrid* and predicted as $0.0405 + 0.285 \ln D^2 H$ (Dogra and Sharma, 2003). The related studies with dbh and height were calculated in different species (Wagner, 1983; Singh and Dhanda, (1990) in *Eucalyptus* species and Wollmerstadtovon *et al.*, 1992).

The relation between dbh and volume were high and close to the predicted line due to the high R^2 value (0.964). The close relation between dbh and volume has been shown in *Eucalyptus* hybrid plantations (Dogra and Sharma, 2003) and in *Populus* species (Pandey *et al.,* 1998).

5.8. Nutrient accumulation

5.8.1. Nutrient concentration

The concentration of the nutrients N, P and K were highest in leaves (N, 1.04 to 1.22 per cent; P, 0.18 to 0.20 per cent; K, 0.70 to 0.90 per cent) followed by bark, fruit, twig, branch and least in bole in decreasing order. The higher leaf nutrient concentration also showed in 3 to 7 year *Populus deltoides*, in which nutrients ranged as N, 2.49 to 2.33 per cent; P, 0.21 to 0.19 per cent and K, 1.4 to 0.97 per cent (Mohsin *et a*l. 2005). The higher nutrient concentration in leaves was also reported in many species. (Veena *et al.,* 1981; Wang *et al.,* 1991 and Tandon, 1991). In the present study, bole constituted minimum concentration of all nutrients (N, 0.37 to 0.25; P, 0.06 to 0.04 and K, 0.32 to 0.21). *Populus deltoides* was also recorded minimum nutrient concentration in bole (Mohsin *et a*l. 2005). Similar findings were reported by George (1985) in *Eucalyptus* hybrid, Brohchilova, (1986) in *Pinus bachetieri* and Jamaludheen, (1994) in *Casuarina equisetifolia.* The highest concentration of the foliage is assumed to be good indicator for efficient nutrient return to the ecosystem. Foliar concentration is also form good indices of the nutritional status of the plant (Nowoboshi, 1985).

In the present study, it is observed that nutrient concentration of the biomass components decreased with increase in age. Similar trend was observed in *Pinus caribaea* (Kadeba, 1991), in which nitrogen in leaves decreased from 1.04 to 0.92 , branches from 0.33 to 0.28 and bole from 0.20 to 0.16 per cent with increase in age from 5 to 15 years. Similar observation was also reported in many species (Jokela *et al.,* 1981 in *Betula papyrifera*; Singh, 1984 in *Cryptomeria japonica* and Bargeli, 1995 in *Eucalyptus tereticornis* plantations).

Among the nutrients, nitrogen concentration was highest, followed by potassium and phosphorus among all components of the tree irrespective of the age. This trend is supported by many studies (Rawat and Singh, 1988 and Mohsin *et al.*, 2005). In the present study, at 5 years, nitrogen was recorded highest (0.37) followed by K (0.32) and P (0.06). Higher concentration of N was also reported in 5 year old *Acacia auriculiformis* N (2.319) followed by K (1.082) and P (0.081) (George, 1993). The K content in different components like bole, branch, twig and fruits showed more or less same compared to N concentration in different ages. It may be due to the more concentration of potassium needed for the fruiting. The similar observation has been observed in *Tectona grandis* and *Melia azadirach* in the sudan savanna (Adu-Aanning *et al*, 1995). *Bambusa bambos* (Shanmughavel 1996, 2001 and Kumar *et al.*, 2005).

5.8.2. Nutrient accumulation

Accumulation and export from the site have become an important consideration in short rotation plantations, where nutrient removed through frequent harvest may exceed the natural rate of nutrient input such as mineral weathering, atmospheric inputs and biological fixation (Kumar *et al.*, 1998).

Nutrient accumulation of the N, P, and K varied in various components of the plantations according to the concentration of the nutrients of the tree. It also observed that the standing state of nutrients in tree was increased with the agė of plantations due to the increased biomass accumulation (N, 126.85 to 182.23 Kg ha^{-1}; P, 24.65 to 37.96 Kg ha-1; K, 120.99 to 157.44 Kg ha^{-1}). Similarly an increase of nutrient with age was evident in 3 to 7 year old *Populus deltoides* (Mohsin *et al.*, 2005). The accumulation of nutrient ranged N (300.67 to 621.77 kg ha^{-1}), P (29.73 to 60.69 kg ha^{-1}) K (139.79 to 199.52 kg ha$^{-1)}$. In biomass components also showed the same trend except in bole and branches. It may be due to the low concentration of nutrient in the components like bole and branch. The increasing trend of nutrient accumulation in trees was observed in mature stands by Tandon *et al.* (1996) in *Eucalyptus* hybrid and Mohsin *et al.* (2005) in *Populus deltoids.*

The maximum accumulation of N, P, and K was found to be in the bole (N, 35.05 to 48.80 Kg ha^{-1}; P, 6.38 to 7.19 Kg ha^{-1}; K, 33.21 to 44.07 Kg ha^{-1}). It is also evident the accumulation of the nutrients at 7 year old *Eucalyptus camaldulensis,* in which nutrients were accumulated as N, 63.1 kg ha $^{-1}$ P, 9.92 kg ha $^{-1}$ and K, 45.5 Kg ha $^{-1}$(Harmand *et al.*, 2004). Similar observation was found in the *Casuarina equisetifolia* (Verma *et al.*, 1987) *Eucalyptus tereticornis* (Bargeli, 1995), *Populus deltoides* (Negi and Tandon, 1997), *Dalbergia sissoo* (Das and Chaturvedi, 2003) and *Gmelina arborea* (Swamy and Puri, 2005).

In bole and branch, the accumulation of the nutrients decreased from 6 to 7 years. The downward trend was also reported in *Eucalyptus globulus* and *Eucalyptus tereticornis* (Singh, 1984). The decreasing trend from ages 6 to 7 years is due to the lower biomass production in bole and branches at age 7 years.

Among nutrients maximum accumulation was observed for nitrogen and least by phosphorus in the total above ground biomass. Similar observation was reported in the *Eucalyptus camaldulensis* (Ranasinghe, 1992); *Alnus nepalensis* (Sharma, 1993); *Tectona grandis* (Negi *et al.*1995) and in *Acacia mearnsii* (Caldeira *et al.*, 2002). But in the components, it was true for nitrogen and potassium. The components like branch and twig in the initial years and fruit in all ages, K accumulated more, it may be due to the higher K accumulation required for the fruiting. The similar observation has been noticed in *Tectona grandis* and *Melia azadirach* (Adu-Anning, 1995).

Nutrient accumulation at 6 and 7 years did not show a definite increase in case of all nutrients (N, 161.91 to 182.23 Kg ha^{-1}; P, 31.89 to 37.96 kg ha^{-1} and K, 153.64 to157.44 kg ha^{-1}). So it showed a leveling off in accumulation beyond 6 year old plantation of *C. sappan*. Biomass production also indicated the similar trend (Table 6). This substantiates the probability of fixing final harvest of *C. sappan* may at age 6 years.

5.9. Nutrient use efficiency

Nutrient use efficiency is used to compare nutrient requirement of the species. In the present study, the nutrients for each component at different ages showed an increasing trend with increasing ages. An increasing trend of nutrient use efficiency with increasing age was reported by Bargeli (1995) in *Eucalyptus tereticornis* and Lodhiyal (1992) in *Populus deltoides*). In the present study, the quotient for nitrogen ranged from 190.41 to 243.43 at age 5-7 year; P was 995.13 to 1168.60 at 5-7 years and K 202.74 to 281.76 at 5-

7 years. However phosphorus nutrient use efficiency decreaed from age advancing 6 and 7 years (Table 21). It indicated that in *C. sappan*, the uptake of phosphorus after age 6 years had been decreased. Similar trend in efficiency of P noticed from 4 to 8 year old *Leucaena leucocephala* (1359 to 1027) plantations (Singh and Toky, 1993).

Nutrient use efficiency was highest at age 7 years and lowest at age 5 years. It proved that requirement of the nutrients at age 7 years was higher compared to other ages. The nutrient use efficiency in various components also showed an increasing trend with advancing ages. Among the nutrients P was utilised most efficiency followed by K and least by N. At age 8 years in *Acacia nilotica* observed that N, 67; P, 1534 and K, 177, which revealed that efficiency of P is highest (Singh and Toky, 1993). These observations are supported by many studies, Singh and Toky (1993) in *Eucalyptus tereticornis*, *Leucaena leucocephala* and *Acacia nilotica*; Gurumurthy *et al.* (1986) in *Casuarina equisetifolia.*

Summary

SUMMARY

The present study was conducted on biomass production and nutrient accumulation in an age series (5, 6 and 7) of *Caesalpinia sappan* plantations with respect of the objectives mentioned and the salient findings are summarised herein.

1. The plantations did not show substantial variability in growth between plantations of the same age. whereas, between ages, there was significant difference. The diameter ranged from 5.96 cm to 7.52 cm and height ranged from to 6.02 m to 6.69 m at 5 and 7 years. The diameter and height increased with increasing age. Diameter at age 5 year was significantly different from ages 6 as well as 7 years and whereas height, the difference was confined to 5 and 7 years.
2. The observation on above ground biomass of sample trees and biomass components showed an increase with increasing age. The total above ground biomass ranged from 21.43 kg to 39.92 kg at 5 to 7 years. No significant variation between 6 and 7 year was observed. This indicated a levelling off in biomass production beyond 6 years. Biomass components also showed the same trend.
3. The percentage contribution of various components to above ground biomass was in the order: bole > branch > twig > fruit > leaves> bark. The biomass components expressed variation in growth with increasing ages. The bole and branch biomass decreased from 5 to 6 year and increased from 6 to 7 year. The twig, bark and fruits biomass decreased from 5 year to 6 year and increased at 7 year. But in leaves decreased with increasing age.
4. Biomass production on unit area (t/ha) found to be increasing with an increasing age. Generally, the biomass is more influenced by diameter and height. The increase of biomass ranged from 23.81 t ha^{-1} to 44.36 t ha^{-1}. The significant difference between 5 with 7 year has been noticed, but no variation between 5 to 6 year and 6 to 7 year as indicated by homogenous mean values. It was seen that increment pronounced more at age 5 and 6 years. There was no considerable difference in increment when age increased from 6 to 7 years.

5. All biomass components showed an increasing trend with increasing age except in branches. Where in branch biomass, decrease was noticed when age increased from 6 to 7 years.
6. The productivity of the agb increased with increase in age ranging from 4.77 t ha^{-1} yr^{-1} to 6.34 t $ha^{-1}yr^{-1}$. But the increase at ages 6 and 7 years was very low, (0.04 t $ha^{-1}yr^{-1}$) which indicated that no further increase in the productivity of the trees. It highlights that a levelling off the productivity beyond 6 year.
7. The productivity of the above ground biomass and biomass components (Kg $tree^{-1}$ yr^{-1}) showed no significant variation between ages. It indicated that there was culmination of the productivity at age 6 year. This reveals 6 year may be considered as optimum age for the final harvest of *C. sappan.*
8. Different prediction models estimated with respect to dbh and height for above ground biomass and biomass components. Accordingly the best fit equations were selected. The selection was based on equation with maximum R^2 and minimum furnival index.
9. With respect to dbh, as independent variable, the total above ground biomass, the best fit equation was model 2 ($W = b_0 + b_1 D + b_2 D^2$). For leaves also this model proved as best fitted. The components like bole, bark, branch and fruit, the best fit was model 4 ($\ln W = b_0 + b_1 \ln D$). But in twig best equation was model 3 ($W = b_0 + b_1 D^2$).
10. With respect to dbh and height the best equation fitted to agb was model 6 ($W = b_0 + b_1 D^2 H$). This model was best fitted to bole also. Whereas the branches and fruits were more fit with model 10 ($\ln W = b_0 + b_1 \ln D^2 H$). But in twigs best fit equation was model 7 ($W = bo + b_1 D^2 + b_2 H + b_3 D^2 H$) and in bark model 9 $\ln W = b_0 + b_1 \ln (D) + b_2 \ln (H)$ was selected.
11. Even though some equations were proved more fit with combination of dbh and height, R^2 value and Furnival index were relatively similar to equations with dbh alone could not be selected, it is difficult to measure height of the standing trees with definite accuracy. Hence, equations with dbh alone were selected for predicting the biomass.
12. The present investigation also revealed that in the case of agb, bole, bark and branch the observed values were very close to the predicted values, except for a few deviations at higher diameter. But in twigs, leaves and fruits

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noticed a weak correlation between biomass and dbh. The best equation with coefficient of determination and Furnival index was given highest statistical precision in prediction estimation.

13. Weight table is prepared for bole (UB) and total above ground biomass based on the best equations, the values of the similar plantation can be ascertained directly once the dbh known.
14. The volume was also estimated which ranged as 0.0156 to 0.0317 m^3 at 5 to 7 years. The model developed for volume with respect to dbh was model 4 ($\ln W= b_0 +b_1 \ln D$) and model 10 for dbh and height ($\ln W = b_0+ b_1 \ln D^2 H$).
15. Investigation on nutrient concentration at 5 to 7 year old plantations showed that there was no significant difference between trees of a particular age. However, significant variation in nutrient concentration observed among components between plantations of different ages. Leaves had the maximum concentration of the nutrients and bole had the lowest. It was also observed that nutrient concentration decreased with increasing age.
16. Among the nutrients nitrogen was highest followed by potassium and phosphorus was minimum among all components irrespective of age.
17. The nutrient accumulation in the agb as well as biomass components increased with the age of plantation except in bole and branches. The maximum accumulation was found to be in bole and minimum in bark. The accumulation of the nutrients between age 6 and 7 years did not show a significant difference. The productivity also did not significantly increased with age increased from 6 to 7 years. This reveled that age 6 year is the optimum age for final harvest of *Caesalpinia sappan.*
18. Among the nutrients, nitrogen accumulated maximum followed by potassium and phosphorus.
19. Nutrient use efficiency increased with increasing ages. It was found to be maximum in bole and minimum in leaf. Efficiency of phosphorus was maximum followed by potassium and nitrogen.

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Appendices

APPENDICES

Appendix 1.Anova for comparing between age classes

	Source	df	Mean Square
DBH	Between Age	2	20.356
	Error	96	2.253
	Total	98	
Height	Between Age	2	10.093
	Error	96	1.015
	Total	98	

Appendix II. Anova for comparing between plots of each age group

AGE	Parameter	Source	df	Mean Square
5	DBH	Between plot	2	1.393
		Error	30	1.295
		Total	32	
	HT	Between plot	2	.229
		Error	30	.718
		Total	32	
6	DBH	Between plot	2	6.329
		Error	30	2.566
		Total	32	
	HT	Between plot	2	3.978
		Error	30	1.037
		Total	32	
7	DBH	Between plot	2	2.114
		Error	30	2.693
		Total	32	
	HT	Between plot	2	2.113
		Error	30	1.070
		Total	32	

Appendix III. Anova for comparing biomass production of each component

Kg/tree				t/ha			
	Source	**df**	**Mean Square**		**Source**	**df**	**Mean Square**
Stem(UB)	Between Groups	2	205.70	Bole	Between age	2	253.90
S	Within Groups	18	45.98		Error	18	56.75
	Total	20			Total	20	
Bark	Between Groups	2	1.39	Bark	Between age	2	1.72
	Within Groups	18	0.42		Error	18	0.52
	Total	20			Total	20	
Branch	Between Groups	2	71.46	Branch	Between age	2	88.21
	Within Groups	18	16.03		Error	18	19.78
	Total	20			Total	20	
TWIG	Between Groups	2	13.63	Twig	Between age	2	16.82
	Within Groups	18	1.93		Error	18	2.38
	Total	20			Total	20	
LEAVES	Between Groups	2	4.67	Leaves	Between age	2	5.76
	Within Groups	18	1.53		Error	18	1.89
	Total	20			Total	20	
FRUITS	Between Groups	2	11.64	Fruits	Between age	2	14.36
	Within Groups	18	1.10		Error	18	1.36
	Total	20			Total	20	
Total_drwt	Between Groups	2	1022.33	Total Dryweight	Between age	2	1261.88
	Within Groups	18	198.22		Error	18	244.66
	Total	20			Total	20	

Appendix IV. Anova for comparing productivity (t/ha/yr)

	Source	df	Mean Square
Bole	Between age	2	3.852
	Error	18	1.438
	Total	20	
Bark	Between age	2	0.012
	Error	18	0.013
	Total	20	
Branch	Between age	2	1.550
	Error	18	0.530
	Total	20	
Twig	Between age	2	0.179
	Error	18	0.065
	Total	20	
Leaves	Between age	2	0.034
	Error	18	0.053
	Total	20	
Fruits	Between age	2	0.130
	Error	18	0.033
	Total	20	
Total Dryweight	Between age	2	15.937
	Error	18	6.289
	Total	20	

Appendix V. Anova for predicting the bole biomass

DBH			DBH and height		
Source	df	Mean Square	Source	df	Mean Square
Regression	1	8.048	Regression	1	1170.294
Residual	19	0.02531	Residual	19	3.616
Total	20		Total	20	

Appendix VI. Anova for predicting the bark biomass

DBH			DBH and height		
Source	df	Mean Square	Source	df	Mean Square
Regression	1	3.229	Regression	1	1.743
Residual	19	0.0848	Residual	19	0.07919
Total	20		Total	20	

Appendix VII. Anova for predicting the branch biomass

DBH			DBH and height		
Source	df	Mean Square	Source	df	Mean Square
Regression	1	7.782	Regression	1	7.901
Residual	19	9.597E-02	Residual	19	0.0897
Total	20		Total	20	

Appendix VIII. Anova for predicting the twig biomass

DBH			DBH and height		
Source	df	Mean Square	Source	df	Mean Square
Regression	1	48.318	Regression	1	45.729
Residual	19	0.717	Residual	19	0.853
Total	20		Total	20	

Appendix IX. Anova for predicting the leaves biomass with dbh alone

Source	df	Mean Square
Regression	1	12.482
Residual	19	0.665
Total	20	

Appendix X. Anova for predicting the fruits biomass

DBH			DBH and height		
Source	df	Mean Square	Source	df	Mean Square
Regression	1	2.816	Regression	1	2.828
Residual	19	0.049	Residual	19	0.04876
Total	20		Total	20	

Appendix XI. Anova for predicting the total biomass

DBH			DBH and height		
Source	df	Mean Square	Source	df	Mean Square
Regression	1	2636.519	Regression	1	5349.322
Residual	19	18.861	Residual	19	13.853
Total	20		Total	20	

Appendix XII. Anova for predicting the volume

DBH			DBH and height		
Source	df	Mean Square	Source	df	Mean Square
Regression	1	2.816	Regression	1	9.775
Residual	19	0.049	Residual	19	0.009
Total	20		Total	20	

Appendix XIII. Anova for comparing the nutrient Percentage

Nitrogen				Phosphorus				Potassium			
	Source	**df**	**Mean Square**		**Source**	**df**	**Mean Square**		**Source**	**df**	**Mean Square**
BOLE	Between age	2	0.0247	BOLE	Between age	2	0.00054	BOLE	Between age	2	0.030
	Error	18	0.0016		Error	18	0.00003		Error	18	0.001
	Total	20			Total	20			Total	20	
BARK	Between age	2	0.0703	BARK	Between age	2	0.00017	BARK	Between age	2	0.057
	Error	18	0.0021		Error	18	0.00047		Error	18	0.001
	Total	20			Total	20			Total	20	
BRANCH	Between age	2	0.0216	BRANCH	Between age	2	0.00019	BRANCH	Between age	2	0.055
	Error	18	0.0016		Error	18	0.00004		Error	18	0.001
	Total	20			Total	20			Total	20	
TWIG	Between age	2	0.0500	TWIG	Between age	2	0.00069	TWIG	Between age	2	0.078
	Error	18	0.0027		Error	18	0.00002		Error	18	0.001
	Total	20			Total	20			Total	20	
LEAF	Between age	2	0.0608	LEAF	Between age	2	0.00045	LEAVES	Between age	2	0.077
	Error	18	0.0049		Error	18	0.00007		Error	18	0.003
	Total	20			Total	20			Total	20	
FRUIT	Between age	2	0.0604	FRUIT	Between age	2	0.00105	FRUIT	Between age	2	0.061
	Error	18	0.0024		Error	18	0.00004		Error	18	0.002
	Total	20			Total	20			Total	20	

Appendix XIV. Anova of nutrient accumulation (kg/ha)

Nitrogen				Phosphorus				Potassium			
	Source	**Df**	**Mean Square**		**Source**	**df**	**Mean Square**		**Source**	**df**	**Mean Square**
Bole	Between age	2	1220.50	Bole	Between age	2	27.59	Bole	Between age	2	1576.97
	Error	18	581.33		Error	18	12.68		Error	18	680.79
	Total	20			Total	20			Total	20	
Bark	Between age	2	14.57	Bark	Between age	2	1.87	Bark	Between age	2	7.01
	Error	18	14.11		Error	18	0.68		Error	18	8.28
	Total	20			Total	20			Total	20	
Branch	Between age	2	917.57	Branch	Between age	2	71.19	Branch	Between age	2	643.27
	Error	18	321.56		Error	18	19.25		Error	18	301.70
	Total	20			Total	20			Total	20	
Twig	Between age	2	174.91	Twig	Between age	2	28.12	Twig	Between age	2	128.03
	Error	18	63.26		Error	18	5.43		Error	18	64.01
	Total	20			Total	20			Total	20	
Leaf	Between age	2	481.11	Leaf	Between age	2	16.83	Leaf	Between age	2	143.85
	Error	18	252.42		Error	18	6.92		Error	18	126.20
	Total	20			Total	20			Total	20	
Fruit	Between age	2	147.58	Fruit	Between age	2	6.82	Fruit	Between age	2	159.25
	Error	18	43.37		Error	18	1.24		Error	18	42.37
	Total	20			Total	20			Total	20	
Total	Between Age	2	11622.736	Total	Between Age	2	646.593	Total	Between Age	2	8750.332
	Error	18	4915.358		Error	18	185.280		Error	18	4324.183
	Total	20			Total	20			Total	20	

Table XV. Weight table of *Caesalpinia sappan*

Girth at breast height (cm)	Dry weight (kg)		
	Stem Over Bark	Stem Under bark	Total
12	3.12	2.62	9.51
13	3.75	3.17	10.34
14	4.43	3.77	11.37
15	5.18	4.44	12.61
16	6.00	5.17	14.05
17	6.88	5.96	15.70
18	7.84	6.82	17.55
19	8.86	7.75	19.61
20	9.95	8.75	21.87
21	11.12	9.82	24.34
22	12.36	10.96	27.01
23	13.67	12.17	29.88
24	15.05	13.46	32.96
25	16.52	14.82	36.24
26	18.05	16.26	39.73
27	19.67	17.78	43.42
28	21.36	19.37	47.32
29	23.13	21.04	51.42
30	24.98	22.80	55.73
31	26.91	24.63	60.24
32	28.92	26.55	64.95
33	31.01	28.55	69.87

Table XVI. Marketable heartwood obtained from different ages

Tree No.	Diameter (cm)	Height (m)	Heartwood (Kg)
1	5.1	5.8	3.5
2	5.74	6.65	4
3	6.36	6.3	5
4	6.69	7	5.5
5	7	6.7	6.5
6	7.64	8.0	7.5
7	7.96	7.2	9.5
8	8.6	7.2	9
9	8.92	7.8	11
10	9.56	7.5	14

BIOMASS PRODUCTION AND NUTRIENT ACCUMULATION IN AN AGE SERIES OF *Caesalpinia sappan* Linn. PLANTATIONS

By

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ABSTRACT OF THE THESIS

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ABSTRACT

The present study was conducted at College of Forestry, Kerala Agricultural University, Vellanikkara on biomass production and nutrient accumulation in an age series (5, 6 and 7) of *Caesalpinia sappan* plantations in three districts of Kerala. The study reveals that diameter, height, biomass, productivity and volume increased with increasing age. The above ground biomass and biomass components also increased with increasing ages. The above ground biomass produced was 23.81 t ha^{-1} at 5 year, 37.80 t ha^{-1} at 6 year and 44.36 t ha^{-1} at 7 year. The productivity at age 5 year was 4.77 t $ha^{-1}yr^{-1}$, at age 6 year 6.30 t ha^{-1} yr^{-1} and at age 7 year was 6.34 t ha^{-1} yr^{-1}. The increase of the productivity between 6 and 7 years were very low (0.04 t $ha^{-1}yr^{-1}$), which indicated that no further increase in the productivity of the trees. It highlights that a levelling off the productivity beyond 6 year. This consideration suggests 6 year as the optimum harvesting period of *C. sappan.* The percentage contribution of various components to above ground biomass was in the order: bole > branch > twig > fruit > leaves> bark. The biomass components were also showed an increasing trend.

The prediction equations were prepared for above ground biomass as well as biomass components with respect to dbh and height. Even though some equations were proved more fit with combination of dbh and height, R^2 value and Furnival index were relatively similar to equations with dbh alone could not be selected, it is difficult to measure height of the standing trees with definite accuracy. Hence, equations with dbh alone were selected for predicting the biomass. With respect to the dbh alone as independent variable, the total above ground biomass, the best fit equation was $W = b_0 + b_1 D + b_2 D^2$. In leaves also this model proves as best fit. The components like bole, bark, branch and fruit, the best fitted equation was $\ln W = b_0 + b_1 \ln D$. But in twig, it was $W = b_0 + b_1 D^2$. Weight table prepared for bole (UB) and total above ground biomass based on the best fit equation using diameter at breast height

The nutrient concentration was increased with increasing age except in bole and branches. Concentration in bole and branches increased from 5 to 6 year and decreased from 6 to 7 year. Leaves had the maximum concentration of the nutrients and bole the lowest. The nutrient accumulation of the above ground biomass as well as biomass components increased with the increasing age of plantation. The maximum nutrients accumulated in bole and minimum in bark. Among the nutrients, N accumulated maximum followed by K and P. Nutrient use efficiency increased with increasing ages. The maximum nutrient use efficiency observed for P followed by K and N. It was found to be maximum in bole and minimum in leaf.