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Growth model for *Acacia auriculiformis* in relation to soil conditions in Kerala

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ABSTRACT

A growth model in relation to soil conditions was developed based on data generated from 50 semi- permanent sample plots laid out in *Acacia auriculiformis* plantations in Kerala. The study has also shed light on the optimum levels of soil attributes, which maximize the tree growth. The sample plots belonged to various age groups and site conditions. The plots were laid out during 2011 and growth measurements involving girth at breast- height (1.37 m above ground) and height were recorded for two successive years. In addition to this, measurements for miscellaneous tree species growing in these plots were also recorded. Diameter increment and volume (in terms of commercial, pulpwood, timber over-bark and timber under-bark) increment were computed for all the 50 plots. The soil samples collected from each plot were subjected to physical and chemical analyses to determine texture, pH, electrical conductivity (EC), organic carbon (OC), available N, P, K, exchange acidity (EA), exchangeable Al, Ca, Mg and available Fe, Cu, Zn and Mn using standard procedures.

In the growth model developed, K in 10- 20 cm depth level alone has turned out to be the foremost soil variable significantly influencing tree growth. The adjusted R^2 value for the diameter increment function was 0.70 and almost 0.90 for all the volume increment functions, which are reasonable values to expect under natural conditions. However, this implies that the remaining part of the variation in growth happens on account of factors not included in the model. The results also indicate a positive increase in the soil K in 10-20 cm layer with increase in diameter growth, keeping other factors constant.

It was observed that the empirical relationship between tree diameter/volume growth and soil characteristics varied with soil depth levels. In the 0-10 cm depth level, it was found that there was no significant relationship between soil properties and tree diameter growth. In the 10-20 cm depth level, the tree diameter growth was significantly influenced by soil K. The results indicated that with increase in soil K in sub surface layer, there was corresponding increase in the tree diameter growth. Almost 41 per cent of the variation in tree diameter growth was explained by soil K in 10-20 cm depth level.

In all the depth levels, it was found that there was no significant relationship between soil properties and tree volume growth (such as commercial, pulpwood and timber over-bark). However, the relationship between tree timber under-bark volume growth and soil properties differed with the different depth levels. Significant relationship was found between timber under-bark volume growth and sand in 0-10 cm layer. The results showed that with increase in the content of sand in the surface layer, there was corresponding increase in the tree timber under-bark volume growth.. About 48 per cent of the variation in tree under-bark volume growth was explained by the sand in surface layer. Significant relationship was also found between timber under-bark volume growth and soil pH in 10-20 cm depth level. The results revealed that with increase in soil pH in the subsurface layer, there was corresponding decrease in the tree timber under-bark volume growth. Approximately 49 per cent of the variation in tree under-bark volume growth was explained by the soil pH in subsurface layer.

The models obtained through stepwise regression were all linear in nature in all the depth levels, and no quadratic terms were present. As such, the optimum levels of soil attributes, which maximize the tree growth (diameter and volume), could not be determined through canonical analysis. This could be because of the shorter range of soil properties observed under natural conditions.

The relationship between the growth and soil properties obtained from the growth model developed in this study, which is based on unified approach, has greater reliability compared to the one arrived at from the empirical approach on account of its biological validity.

1. INTRODUCTION

The ever-increasing demand for paper combined with a decline in fiber supply from the forests is compelling the pulp and paper industry to go for technically and economically viable fiber resources. In several developing countries where the forest resources are limited, a large quantity of paper is produced from various annual plants. However, wood pulp is still needed for paper and rayon industries. Industrial plantations of fast growing tree species can produce 1.5- 2 times more wood per hectare per year, and reach maturity 2-3 times faster than long rotation softwood plantations (Cossalter and Smith, 2003).

Acacia is widely distributed in tropical and subtropical regions of Australia, South America, Asia and Africa. There are more than 1200 Acacia species, of which about 700 occur in Australia (Kokima, 2001). This species, which is ranked close to eucalyptus for applications in pulp industry, is a new introduction in the short-fiber pulp market (Paavilainen, 2000; Hillman, 2003) and are also extensively used as fuel wood, as construction and furniture timber, and as tannin for leather industry (Jahan *et al.*, 2006). Acacias are important in soil enrichment due to its nitrogen fixing attributes. This species, which adapts well to poor soils, plays an important role in preventing soil erosion. It is also a good species for plantation and Community Forestry Programmes.

Among the exotic species of acacias, *Acacia auriculiformis* is an important species that has been identified for plantation forestry in the wet-dry tropics. It is an evergreen tree that grows between 15 and 30 m tall, with the trunk attaining up to 12 m in length and 50 cm in diameter (World Agroforestry Centre, 2005). It is distributed from near sea level to 400 m, but is most common at elevations less than 80 m. It is predominantly found in the seasonally dry tropical lowlands in the humid and sub-humid zones. The mean annual rainfall in its natural range varies from 700-2000 mm, and the dry season may last for up to 7 months. However, it does not tolerate shade, and strong wind may easily break its branches. For newly emerged seedlings, about 50% shade is required and once the plants are established, 70% full sunlight is optimal. In general, 3-4 months are needed to raise transplantable seedlings that are 25 cm tall. Although the optimal planting density is not yet clearly established, most current plantings are spaced at 2 x 2 m to 4 x 4 m, the closer spacing being more suitable for firewood and pulp plantations.

Removal of lower branches of young plants has been suggested as a means of improving stem form and of reducing the incidence of multiple stems.

Acacia auriculiformis was introduced to India in 1950's through its cultivation in lateritic areas of West Bengal (Banerjee, 1973). It had been extensively used in various social forestry systems in West Bengal, Karnataka, Bihar, Orissa, Uttar Pradesh, Kerala and a few other States. It is planted as shelter plants, soil improver and ornamental trees. Besides, this is an economically important tree as a source for tannin, gum, pulp and timber (Kushalapa and Turnbull, 1991). About 50 % of the social forestry plantations raised in 1973 on lateritic land was of *Acacia auriculiformis*. It has also been planted as a mixed crop with *Eucalyptus tereticornis, Leucaena leucocephala, Casuarina equisetifolia, Acacia. nilotica* and *Dalbergia sissoo*. As more and more plantations of this species are coming up, wood is also used as timber for furniture, agricultural implements, turnery articles, toys, construction material etc. The species entered as a major component in Social Forestry Programmes in Kerala since 1980's. According to Jayaraman and Rajan (1991), the performance of *A. auriculiformis* (in terms of yield) in Kerala has been exceptionally good compared to many other tree species of the Indian subcontinent.

Currently, Kerala Forest Department has around 5936 ha under *Acacia auriculiformis* plantations (Sivaram, 2008) mainly raised under different schemes including the World Bank aided Kerala Forestry Project. A large quantity of Acacia seedlings are being used for replanting purpose every year. In the past, most of these plantations were allotted to industrial concerns like M/s HNL, Vellore and M/s Gwalior Rayons, Mavoor. In recent times, the supply of raw materials by industry is on decline for several reasons. Presently, Kerala Forest Department proposes to carry out thinning for timber production. Recognizing the high demand for Acacia timber, this plantation species is being included in many of the Kerala Forestry Schemes. Since the yield is highly dependent on the local soil and climatic conditions, there is a need to study the relation between soil properties and the growth of Acacia. Another area where scientific information is lacking is development of growth model for this species in relation to soil conditions.

Ecosystems by virtue of being multivariate in nature often exhibit intricate relationships between their components. The relationships being obscure and complex are many times difficult to be expressed through simplistic models. This investigation however, attempts to probe on the intricacies of such relationships by taking forest plantation ecosystem as a typical case. More specifically, the study is aimed at developing a model for characterizing and analyzing the interrelation between soil and growth of *Acacia auriculiformis* trees in a plantation environment. It also proposes to utilize spatial data on multiple variables relating to soil and growth of *Acacia auriculiformis* trees for the model building, to develop most suitable model structure for depicting the said relationships and to identify optimum soil conditions that maximize the current growth at any specific age level. This study would mainly consider the most advanced modelling approach called unified approach proposed by Zeide (2003) for the construction of the model but has been referred as process-based model.

2. REVIEW OF LITERATURE

Several studies have been made on the growth and behavior of *Acacia auriculiformis* under different soil and eco-climatic conditions. A summary of studies carried out under these parameters is given below.

Growth behavior of Acacia auriculiformis

A study conducted by Ali *et al*. (1997) in 6 year old *Acacia auriculiformis* and *Acacia mangium* revealed that diameter and height growth did not vary significantly in these species. According to them, *Acacia. auriculiformis* could be recommended for fuel wood production based on density whereas *Acacia. mangium* for transmission and building poles due to its good stem form.

According to Gopikumar *et al*. (1998), *Albizia falcataria* (*Paraserianthes falcataria*), *Trema orientalis, Cassia renigera, Acacia auriculiformis, Macaranga indica, Delonix regia, Acacia mangium and Bridelia retusa* were fast growing tree species in terms of height and girth and showed potential for intensive planting under agro/social forestry programmes in Kerala.

Anil and Siddiqui (2001a) reported that there was an increase in mean diameter and height with an increase in spacing in *Acacia auriculiformis* plantation. Biomass production rate of *Acacia auriculiformis* was maximum (16.94 t/ha/year) at close spacing indicating that *Acacia auriculiformis* behaved as a fast growing tree species on lateritic soils.

Murthy and Devar (2004) studied *Acacia auriculiformis* plantations of 4 different age groups (*viz*., 4, 6, 8 and 10 year old) under 4 different site conditions (*viz*., coastal zone, lower Ghat, upper Ghat and eastern plain) in Karnataka and reported that diameter at breast-height, total height, bole height, crown diameter, basal area, bole volume and total volume were superior under the coastal zone at 4 years, lower Ghat at 6 years and eastern plain both at 8 and 10 year old plantations.

Newaz *et al*. (2005) developed growth and yield prediction models for hybrid acacia (*Acacia auriculiformis* x *Acacia mangium*), grown in the plantations of Bangladesh, using simultaneous equation method. Models were selected for the species to estimate the stand height, stand dominant height, stand diameter, stand basal area per hectare and total volume yield per hectare. The models derived were statistically and biologically acceptable and could be satisfactorily used for stands of Hybrid Acacia of ages 4-7 years based on a base age of 6 years in the central region of Bangladesh.

The natural resistance of timber from 8 year old plantation of *Acacia auriculiformis* received from Mysore paper mills, Bhadravathi was tested for their durability against wood rotting fungi as per IS 4873-1968 under laboratory conditions by Nagaveni *et al.*(2007). The results showed high resistance against all the test fungi and the timber could be grouped under class-I.

Sarkar *et al.* (2008) carried out study to ascertain the growth performance of akashmoni (*Acacia auriculiformis*) in the strip and block plantations of Bangladesh. Growth statistics like mean diameter at breast-height, total height, volume over-bark, basal area per hectare per year and mean annual increment were estimated using the data collected from 6 to 10 year old plantations. The results showed that the growth performance of the species was better in strip plantations compared to block plantations. A financial analysis also favoured strip plantations over block plantations.

Relation between growth and soil properties of *Acacia auriculiformis* plantations with different densities were studied by Xu *et al.* (2008). They found that for stands of different density, the net increments of ground diameter, tree height and crown width were 1.5 cm, 1.3 m and 0.9 m, respectively, greater than the control. The net increments of ground diameter, tree height and crown width of high-density stand were greater than those of medium-and low-density stands. Compared with the control, soil organic matter, available N, P and K in the high-density stand decreased, and its exchangeable Ca and Mg increased, whereas soil organic matter and all nutrients in the medium-density stand increased substantially, and available P in the low-density stand increased slightly and soil organic matter and other nutrients increased substantially.

Rugmini (2010) developed local tree volume equations based on diameter at breast-height for *Acacia mangium* and *Acacia auriculiformis* in southern Kerala, India. The equations were based on data from 51 trees of *Acacia mangium* and 52 trees of *Acacia auriculiformis.* Local volume tables in terms of commercial, pulpwood, saleable timber (both over-bark and under-bark) and firewood volumes were prepared for the two species based on developed equations.

Hulikatti and Madiwalar (2011) conducted a field experiment to study the influence of weed and nutrient management practices on the growth and nutrient uptake in *Acacia* *auriculiformis* during 2006-07 in Karnataka. The results revealed that chemical weed control resulted in significant improvement of plant growth parameters *viz*., plant height (197.33 cm), collar diameter (2.58 cm), main stem volume (10.54 cm3), number of branches (10.64), total dry biomass production (469.21 g/plant) and nutrient uptake compared to control. At 10 months of treatment imposition, significantly higher dry biomass production was recorded in branches (103.33 g/plant), leaves (185.26 g/plant) and total above ground parts (471.83 g/plant) due to the application of FYM+NPK. The uptake of N and P was significantly higher due to FYM+NPK (34.28 and 2.97 kg/ha, respectively); whereas, uptake of K was unaffected. The interaction between weed and nutrient management practices were significant for uptake of phosphorus only.

Soils under Acacia auriculiformis

Jose and Koshy (1972) reported that continuous cropping of the same species over long gestation periods made huge demands on the site and soil. They also reported that soil compaction increased and soil fertility declined in older plantations. According to them, maintaining monoculture plantations of *Tectona grandis* and *Acacia auriculiformis* over years, adversely affected the soil characteristics.

Several attempts have been made to improve productivity of *Acacia auriculiformis* plantation through addition of nutrients. Hansen *et al*. (1988) reported an efficient rhizobial symbiosis on the roots of *Acacia, auriculiformis*. He estimated that about 10 kg N per hectare per annum is fixed into the plantation soil over six years growth period. This nitrogen was found to increase the growth of vegetation by 25 per cent.

Physicochemical properties of soils under 2, 3 and 4 year old plantations of *Acacia. auriculiformis* (and with no plantation) in Sadar Forest Division, West Tripura were studied by Chakraborty and Chakraborty (1989). Progressive increases with age of plantation (from values on barren land) are reported for soil pH (5.9 to 7.6), electrical conductivity (27.2 to 48.4 mm hos/cm), water holding capacity (22.9 to 32.7%), organic carbon (0.81 to 2.70%), nitrogen (0.364 to 0.504%) and potassium (5.45 to 7.10 mg/kg). The soil color also exhibited a progressive change from light yellowish brown to brown.

Simpson (1992) investigated the relationship between productivity of *Acacia. mangium* and soil nutrient levels in Kalimantan. He found that productivity is related to soil K. This parameter was responsible for 50% of the variation in data, the more productive stands showing higher K levels.

Sankaran *et al.* (1993) conducted a study on the soil characteristics of acacia plantations and compared with those of adjacent fallow land to ascertain the effect of acacia on soil properties. Soil analysis revealed that there was no significant difference between acacia plantations and adjacent fallow land in physical and chemical properties of soil as well as soil nutrient contents except in the case of pH which was significantly lower in acacia plantations (pH 4.7). N, P, K, Ca and Mg contents of acacia leaf litter from the permanent plots were, on an average, 1.38, 0.085, 0.040, 0.035 and 0.0075 %, respectively.

Bemhard-Reversat (1995) conducted a study on nitrogen cycling in tree plantations grown on a poor sandy savanna soil in Congo. Nitrogen accumulation in vegetation and soil, together with N flows in the ecosystem, were estimated. Results revealed that 800-1000 kg N ha-' were accumulated during 7 years in acacia stands. Nitrogen fixation was higher in *Acacia. auriculiformis* than in *Acacia mangium.* Nitrogen cycling through litter fall was high in acacia stands, up to 170 kg ha-' per year, and low in eucalypt and pine stands. However, in eucalypt stands, slow litter decay and reduced N release from decaying litter resulted in a relative accumulation of organic N in the forest floor. Decrease in N content was observed in organo mineral fractions under the trees. In top-soil (0-10 cm) N mineralization was higher in tree stands than in savanna and total N decreased significantly under 7-year-old eucalypt. Under older eucalypt, decreasing N content of organic matter was shown by the increase in C/N ratio. Under acacia, soil N increase was significant in the older stands but not in the younger ones, and fixed N accumulated in trees and in the forest floor first.

The effect of establishing plantations of *Acacia auriculiformis* (in 1985 and 1987) and *Eucalyptus tereticornis* (in 1985) on soil properties was investigated on deforested land at Trichur in Kerala (Animon *et al*., 1999). The control plot included in the study was a cashew (*Anacardium occidentale*) plantation. Soil was sampled at different depths (0-10, 10-30 and 30-60 cm) at the end of the summer and the peak of the rainy season (June and July) in 1997. Acacia depleted the soil moisture in the surface layers, while eucalypt depleted it in the deeper layers; in cashew the soil moisture was more evenly distributed but was less in the surface and middle layers than in the deeper layer. The pH of the surface soil as well as the content of organic carbon got slightly reduced under acacia and eucalyptus while phosphorus and potassium contents were on the increasing level. The number of soil microorganisms were less under eucalypt than under cashew, but those under acacia were more.

Devevaranavadgi *et al.* (2000) studied the effect of *Acacia auriculiformis* on physical and chemical properties of soil in northern dry zone of Karnataka. They found that soil physical properties, namely infiltration rate, pore space and water-holding capacity improved with tree planting. Among the chemical properties, organic carbon and available nutrients increased, while soil pH decreased with tree planting.

Islam and Weil (2000) studied the effect of land use changes on soil quality properties in a tropical forest ecosystem of Bangladesh. Soil samples were collected from adjacent well-stocked *Shorea robusta* natural forest; land reforested with *Acacia. auriculiformis*, grassland and cultivated land. Land use/land cover changes resulted in surface compaction and significant decrease in silt, clay, porosity, aggregate stability, N, fulvic and labile C, and microbial biomass C. Use of soil deterioration index showed that soil quality deteriorated significantly (− 44%) under cultivation, while in sites re-vegetated with fast-growing acacia or grasses, it improved by 6–16%. According to them improvement in soil quality and enhanced biological activity at reforested and grassland sites demonstrated the inherent resilience of these soils once re-vegetated with highly adaptable and fast growing acacia and grass species.

Anil and Siddiqui (2001b) conducted a study on a 9-year old plantation of *Acacia auriculiformis* established in 1984 at Rarha Research Station, Ranchi, Bihar to evaluate the effect of *Acacia auriculiformis* cover at different planting densities (10 000, 4444, and 2500 trees per ha). The survival percentage had been significantly affected by the spacing treatments. The survival at close, intermediate and wide spacing was 73.5, 87.2 and 87.1%, respectively. Soil pH decreased in comparison to the measurements in 1984. Although the change in soil organic matter was not significant, it showed an increase compared to the initial level. The level of available P_2O_5 and K_2O ranged from 32.67 to 37.29 kg/ha and 293.76 to 304.71 kg/ha, respectively. The available N ranged from 196 kg/ ha to 223 kg/ha at different spacing.

Osman *et al.* (2001) compared the soil properties of forest (*Acacia auriculiformis* and *Eucalyptus camaldulensis*) plantations and adjacent unplanted areas at 14 sites within Chittagong campus. Results revealed that soils under the plantations had significantly higher organic carbon, total nitrogen, available potassium and magnesium. On the other hand, both pH and available calcium were lower in soils under plantations than in the adjacent unplanted plot. Soil pH generally increased and organic carbon, nitrogen, available phosphorus and available potassium decreased with depth in planted soils.

In order to determine the changes in the chemical properties of soils under plantations compared to control sites, a study was conducted by Ramesh and Devar (2003) in Karnataka. Four different plantations were studied, *viz*., *Acacia auriculiformis*, *Acacia mangium*, *Casuarina equisetifolia* and *Tectona grandis*, including a control site for each tree species. Results showed that soil pH was low under all plantations at all depths except under *Acacia mangium*. Electrical conductivity was found to be very low under all plantations and their control sites. Organic carbon, on the other hand, was higher under all plantations compared to their respective controls at all depths.

Drechsel *et al.* (2004) studied the effects of *Cassia siamea, Albizia lebbek, Acacia auriculiformis*, and *Azadirachta indica* on soil fertility of five-year-old fallows on Ferric Acrisols in Central Togo. Under acacia, highest biomass production and low soil Ca and P were noted. In addition, topsoil pH under acacia was lower than grass or bush fallow or the other species. Pure A*cacia auriculiformis* stands seemed to be less favourable for improving soil fertility on planted fallows but more suited for firewood plantations and topsoil protection. All tree species tested were superior to natural grass/herb fallow in building up surface soil fertility. However, differences with natural bush fallow were not significant.

Doi and Ranamukhaarachchi (2009) reported that *Acacia auriculiformis* plantation raised on degraded soil had restored its original soil characteristics similar to that of dry evergreen forest soil with respect to bulk density, exchangeable acidity (Al, H), moisture content, pH, organic matter content, base nutrients (K, Ca, Mg) and available phosphorus.

Macedo *et al*. (2007) reported that in Rio de Janeiro, when forests were clear felled, the soil began to degrade almost immediately resulting with loss of organic matter, triggering a series of soil processes. The establishment of a leguminous (*Acacia auriculiformis*) plantation in the degraded land re-established the soil carbon and nitrogen stocks after 13 years. The carbon and nitrogen stocks indicated that the use of legume trees was efficient in re-establishing the nutrient cycling processes of the systems.

Jithendra Kumar (2008) conducted a study on nitrogen and phosphorus release from litter decomposition in an *Acacia auriculiformis* plantation. The three years old plantations of *Acacia auriculiformis* at Phulwaria-Shivpur Forest Division, at the out-skirt of Varanasi City, Uttar Pradesh, were studied for litter decomposition and release of N and P. The results revealed that the decomposition rate varied during the first three months. The annual release rate (g m^{-2}) of nitrogen was 5.79, 2.38, 3.06, and 4.00 and of phosphorus was 0.98, 0.73, 0.76, and 0.89 for phyllode, twig, root and fruit decomposing litter, respectively. The higher release rate was observed at the end of first month in all the litter components. Similarly, the higher decomposition and release rate of nitrogen and phosphorus impoverished the nutrient pool of the soil.

Ohta (2012) reported soil changes associated with afforestation in *Acacia auriculiformis* and *Pinus kesiya* on denuded grasslands of the Pantabangan area, Central Luzon, the Philippines. According to them, soil physical properties improved by afforestation were bulk density and porosity, though the effect was limited to the thin (0-5 cm) superficial soil layer. Hydraulic conductivity of the surface-soil increased in the acacia plantation, while that of the pinus plantation decreased slightly due to abundant mycelia. The values of CEC and concentration of exchangeable cations, especially of Ca^{2+}, were generally lower in the surface soils under tree growth than in the grasslands. The decrease of these values was assumed to be a transitory phenomenon occurring only during the early stage of tree growth in the plantations in areas with a pronounced dry season. Available nitrogen content and its proportion to total nitrogen content in the top soil increased significantly by plantation establishment.

There is hardly any published information on development of a model structure for growth in relation to soil conditions and also on optimum soil conditions at which the growth is maximum. The present study was undertaken to generate this information.

3. MATERIALS AND METHODS

3.1. Data

3.1.1. Tree growth

The study sites were distributed in the State of Kerala, which is located on the Malabar Coast of south-west India. The State has an area of 38,863 km^2 and is bordered by Karnataka to the north and north-east, Tamil Nadu to the east and south, and the Arabian Sea on the west. Laying between north latitudes 8°17'30" and 12°47'40" and east longitudes 74°27'47" and 77°37'12", Kerala experiences a humid equatorial tropical climate. The State has a coastal length of 590 km and the width varies between 11 and 121 km. The State enjoys both South-west and north-east monsoons receiving an average annual rainfall of 2000-3000 mm. The mean daily temperatures range from 19.8 °C to 36.7 °C. Mean annual temperatures range from 25.0–27.5 °C in the coastal lowlands to 20.0–22.5 °C in the eastern highlands. The region receives relatively short dry period stretching from December to March.

A set of 50 semi-permanent sample plots were laid out in *Acacia auriculiformis* plantations representing various age groups and site conditions in different parts of the State of Kerala (Figure 1) during August to November 2011. The plots were of size 30 m x 30 m. The plots belonged to various age groups (2 to 23 years), stocking levels and site conditions. The details of the sample plots are reported in Table 1. The trees in all the above sample plots were re-measured during August to November 2012.

Girth at breast-height (1.37 m above ground) was recorded on all the trees in the plots. Height was measured on a sub sample of less than ten trees covering the range of diameters in each plot. For miscellaneous tree species growing in the plots, girth at breast-height and species identity were also recorded. Geographical position in terms of latitude, longitude, and altitude were recorded along with other site features including the slope of the sample plots.

The data from the plots were first processed to generate plot level information related to various aspects of the plant growth. Plant diameter was calculated as the diameter corresponding to mean basal area of the trees in the plot. Plant height was computed as

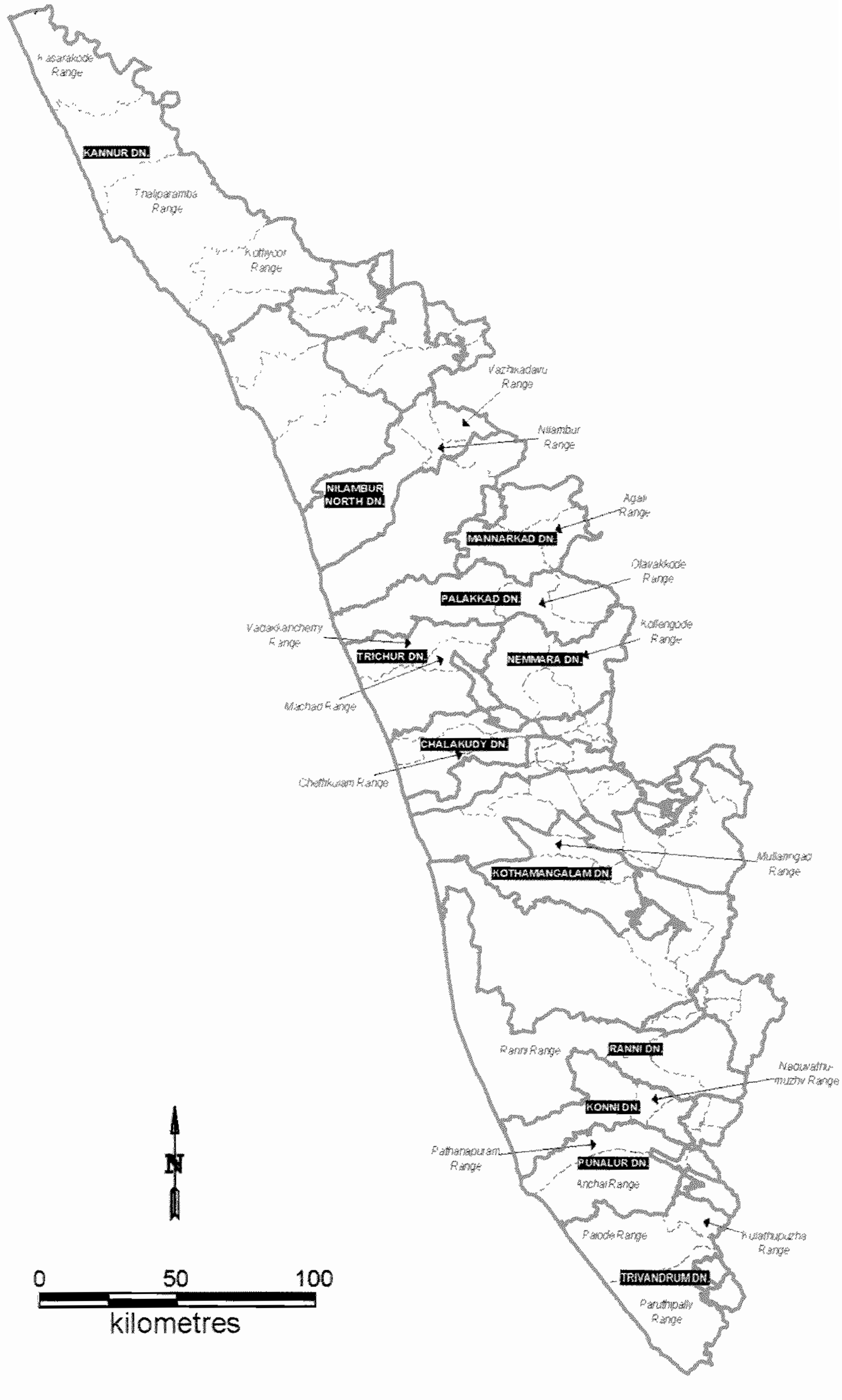

Figure 1. Map showing the locations of the study plots

Table 1. Details of the sample plots

Sl. No.	Plot No	Circle	Division	Range	Plantation	Area(ha)	Year of planting
1	1	Central	Thrissur	Peechi	Chennaipara	15.68	2000
2	2	Central	Thrissur	Machad	Chinganchira	35	2004
3	3	Central	Thrissur	Machad	Pattanikkadu	10	1989
4	4	Central	Thrissur	Machad	Chittanda	68.5	2004
5	5	Central	Thrissur	Machad	Cheerathra	30	2005
6	6	Central	Thrissur	Wadakkanchery	Chittanda	47.25	2005
7	7	Central	Thrissur	Wadakkanchery	Veettikunnu	15	2007
8	8	Central	Thrissur	Wadakkanchery	Mayannur	5	2007
9	9	Central	Thrissur	Wadakkanchery	Mayannur Bit II	5	2005
10	10	Central	Thrissur	Wadakkanchery	Kadagodu Bit II	45.75	2005
11	11	Central	Thrissur	Wadakkanchery	Wadakkenchery Hills Bit I	50	2005
12	12	Eastern	Nemmara	Kollangode	Chemanampathi Bit I	25	1999
13	13	Eastern	Nemmara	Kollangode	Chappakkadu Bit I	47	1999
14	14	Eastern	Nemmara	Kollangode	Chappakkadu Bit I	20	2004
15	15	Eastern	Nemmara	Kollangode	Chappakkadu Bit II	43	1999
16	16	Eastern	Nemmara	Kollangode	Chamanampathi	25	2005
17	17	Eastern	Pallakkad	Olavakkode	Vadasseri	17.5	2004
18	18	Central	Chalakkudy	Chettikulam	Central Nursery	2.7	1995
19	19	Eastern	Nilambur North	Nilambur	Mundapadam	12.75	2004
20	20	Eastern	Nilambur North	Vazhikkadavu	Othumunghalpotty	10	2004
21	21	Eastern	Nilambur North(R)	Nilambur	Poochakuthu Bit II	1.44	2006
22	22	Eastern	Nilambur North	Nilambur	Vadapuram	1.2	2005
23	23	Eastern	Mannarkkad	Agali	Cholakkadu	11.2	2004
24	24	Eastern	Mannarkkad	Agali	Kallamala East	20	1998
25	25	Eastern	Mannarkkad	Agali	Thuvva	12	2005
26	26	Eastern	Mannarkkad	Agali	Sholayur	6.25	2003
27	27	High Range	Kothamangalam	Mullaringadu	Chullikkandam	14	2002
28	30	Southern	Punalur	Pathanapuram	Poovolikkuzhi	91	2001
29	31	Southern	Punalur	Pathanapuram	Kundamkulam	85.2	2003
30	32	Southern	Punalur	Anchal	Panayam	16.75	2003
31	33	Southern	Punalur	Anchal	Kadamankode Bit II	20.64	2003
32	34	Southern	Punalur	Anchal	Kuthiraketty	15	2004
33	35	Southern	Punalur	Anchal	Kadamankode	31	2010
34	36	Southern	Trivandrum	Kulathupuzha	Ilavupalam	10	2005
35	37	Southern	Trivandrum	Kulathupuzha	Irachippara	10.4	2006
36	39	Southern	Trivandrum	Kulathupuzha	Kalayapuram	13	1995
37	41	Southern	Trivandrum	Kulathupuzha	Madathara	29	2006
38	42	Southern	Trivandrum	Palode	Pethala Idinjar	54	2006
39	43	Southern	Trivandrum	Palode	Kochadappupara	10.54	2010
40	44	Southern	Trivandrum	Palode	Pramala Bit 2	51	2007
41	45	Southern	Trivandrum	Paruthippalli	Sundarimukku	27.82	2008
42	48	Northern	Kannur	Thalipparamba	Kunnathur	10	1999
43	49	Northern	Kannur	Thalipparamba	Anara	25	1996
44	50	Northern	Kannur	Kottiyoor	Illam Moola	10	2003
45	51	Northern	Kannur	Kasarakode	Kanakamajjalu	24	1998
46	52	Northern	Kannur	Kasarakode	Mulleria	16	2003
47	53	Northern	Kannur	Kasarakode	Koovaduka	10	2004
48	54	Southern	Punalur	KFDC	Punnala Block 4	57.51	2008
49	56	Southern	Punalur	KFDC	Kadasseri Block 1	9.62	2010
50	57	Southern	Punalur	KFDC	Karavoor Block 5	9.8	2008

the mean predicted height of the trees in the plot. Height of each tree was predicted using a height-diameter relation developed (utilizing the data on diameter at breast-height and height of the trees pooled for each Forest Division) for each Forest Division. The height-diameter relation fitted was of the following form.

$$\ln h = a + b \ln D \qquad (1)$$

where,

h = Height of the tree (m)

D = Diameter at breast-height (cm)

a, b are parameters to be estimated

Top height was computed as the height corresponding to the quadratic mean diameter of the largest 250 trees (by diameter) per hectare as read from the height-diameter relation developed for each Division.

Site index curves were developed using Schumacher functions (Clutter *et al.*, 1983).

$$\ln H = a + b A^{-1} \qquad (2)$$

$$\ln S = \ln H - \hat{b}\left(\frac{1}{A} - \frac{1}{A_0}\right) \qquad (3)$$

where,

S = site index (top height at the base age of 8 years in m)

H = top height of the stand (m)

A = age of the stand (year)

A_0 = Base age, taken as 8 years

a, b are parameters

$\hat{b}$ = Estimate of b

Volume of each tree was predicted using the volume prediction equations developed by Rugmini (2010). Estimate of the current commercial volume, pulpwood volume, timber over-bark and timber under-bark in each plot were obtained by applying volume prediction functions on each tree and aggregating the values at the plot level. The prediction equations are given below.

$$\ln V_c = \underset{(0.171)}{-8.675} + \underset{(0.057)}{2.478} \ln D \qquad (4)$$

$$\ln V_{p} = -8.789 + 2.466 \ln D \qquad (5)$$
$$(0.175) \quad (0.058)$$

$$\ln V_{tob} = -12.120 + 3.221 \ln D \qquad (6)$$
$$(1.081) \quad (0.320)$$

$$\ln V_{tub} = -12.187 + 3.197 \ln D \qquad (7)$$
$$(1.099) \quad (0.325)$$

where,

V_c = Commercial (over-bark) volume of wood to a lower limit of 15 cm girth over bark (m^3).

V_p = Pulpwood (under-bark) volume of wood to a lower limit of 15 cm girth under bark (m^3).

V_{tob} = Saleable timber (over-bark) volume of wood to a lower limit of 70 cm girth under bark (m^3).

V_{tub} = Saleable timber (under-bark) volume of wood to a lower limit of 70 cm girth under bark (m^3).

D = Diameter at breast-height (cm)

ln = natural logarithms

The figures in parentheses are standard errors of the estimates. All the regression coefficients in the Equations (4) to (7) are significant at $P = 0.01$.

As the sample plots covered a wide range of site conditions and age levels, the data set was considered ideal for developing models. Mean tree characteristics at plot level was used for the model development.

The increments in mean diameter, height, volume (commercial and pulpwood and timber over-bark and under-bark) were obtained as the difference between means of diameter, height, volume (commercial, pulpwood and timber over-bark and under-bark) at the current measurement and that in the succeeding measurement. The increment thus obtained was divided by the interval between measurements to get the mean annual increment.

3.1.2. Soil

Three soil pits were dug in each plot and samples collected from 0-10 and 10-20 cm depths. The soil samples from each plot were made into a composite sample. Stones and plant debris in the samples were removed and brought to the laboratory. They were air dried under shade, powdered, sieved through 2 mm sieve and subjected to physical and chemical analyses to determine texture, pH, electrical conductivity (EC), organic carbon (OC), available N, P, K, exchange acidity (EA), exchangeable Al, Ca, Mg and available Fe, Cu, Zn and Mn using standard procedures (Black *et al.*, 1965 and Jackson, 1958).

3.2. Statistical analysis

Structurally, there are two sets of variables involved in the study, *viz*., that on growth of acacia trees and the corresponding status of soil properties observed in the sample plots. The types of analysis carried out for developing the growth model and studying the empirical relation between the two sets of variables are described below.

3.2.1. Growth model

Growth model based on unified (process-based) approach was used in this study for model development, which combines the merits and demerits of both top-down and bottom-up enquiry in scientific investigations (Zeide, 2003). The parameters of the model are biologically meaningful. Process-based or simply process model is a classical model, which aims not only at a description but also at understanding the underlying cause-and-effect relationships. Although the promise of process models is yet to be realized, they are considered as the major achievement of forest science in the twentieth century.

The growth model proposed by Zeide (2004) had two equations one describing the diameter growth and the other volume growth. The diameter growth function with appropriate modification is as follows:

$$y = a_2 H^{b_3} D^{p} e^{-qt} e^{-S_t/c_2} e^{-S_m/c_3} \quad (8)$$

where,

y = Growth increment in a mean tree diameter

H = Top height at the base age of 8 years (site index)

D = Initial value of the mean tree diameter

t = Age (years)

S_t = Stand density of acacia

S_m = Stand density of miscellaneous species

a_2, b_3, c_2, c_3, p and q are parameters

The model consisted of five modules: site index (H^{b_3}), unrestrained growth (D^p), aging (e^{-qt}), density of acacia (e^{-S_t/c_2}) and density of miscellaneous species (e^{-S_m/c_3}). Site index as measured by height of trees will have an increasing effect on growth. Diameter represents the size of the tree and growth is generally proportional to the initial size raised to a power. Increasing age acts as a diminishing factor on growth and thus has a negative index. Higher density level of acacia or miscellaneous species will have a negative effect on the growth of individual trees. However, higher density levels of acacia trees lead to increase in total volume but the effect of miscellaneous species is one-sided.

The volume growth model (Zeide, 2004) was of the following form, which included the effect of miscellaneous species on growth of acacia trees.

$$v = a_1 b_1 D^{b_1 - 1} y \, e^{S_t / c_1} e^{S_m / c_4} \qquad (9)$$

where,

v = Growth increment in tree volume such as V_c, V_p, V_{tob} and V_{tub}

y, D, S_t and S_m as defined earlier

a_1, b_1, c_1 and c_4 are parameters

The volume growth models were developed separately for commercial, pulpwood, timber over-bark and timber under-bark volume growth.

The density of acacia or miscellaneous growth was expressed in terms of modified Reineke's index (Zeide, 2005) given by the following equation

$$S = N\left(\frac{D}{25.4}\right)^{r} \qquad (10)$$

where,

N = Number of trees per ha

D = Quadratic mean diameter of trees in cm

r is a parameter which was taken as 1.6

For inclusion of soil variables in the above model (Equation.8), the site index was replaced by significant soil variables as determined through a regression of site index on soil variables. The significant soil variables were selected through stepwise regression analysis by considering site index as dependent variable and soil attributes as independent variables. For relating site index with soil attributes, the stepwise analyses (log linear regression analysis) were done separately for each depth level. An additional stepwise analysis was also done by combining the soil attributes from the two depth levels taken together. The site index was then replaced with the significant soil attributes retaining the same structural form as of site index in Equation (8) but one component for each soil variable like $S_1^{b_3}$, $S_2^{b_4}$ etc.

The parameters of the diameter and volume growth functions were estimated using PROC MODEL of SAS (SAS, 1993), assuming an additive error term. Simultaneous estimation procedure was used. The problem of auto correlation among the residuals arising on account of repeated measurements in the sample plots was taken care of by choosing an appropriate method of estimation. Hence parameters were estimated using iterated generalized method of moments (ITGMM option of SAS), which allows unstructured covariance matrix of residuals. The instrumental variables used were site index, plantation age, mean diameter of acacia and miscellaneous species and number of trees of acacia and miscellaneous species.

Relation between tree growth and stand features

Initially, linear regression analysis was done to relate the growth characteristics and the stand features like age of the stand, initial size, stand density of acacia and miscellaneous species, and site index. Equations were fitted separately for each growth characteristic such as quadratic mean annual increment in diameter, V_c, V_p, V_{tob} and V_{tub} by considering the growth characteristics as dependent variable and stand features as independent variables.

3.2.2. Empirical relation between tree growth and soil attributes

In order to find the empirical relation between tree growth and soil attributes, site index in the above equations was replaced by soil attributes as explained in Equation (11). The soil attributes were texture, pH, electrical conductivity (EC), organic carbon (OC), available N, P, K, exchange acidity (EA), exchangeable Al, Ca, Mg and available Fe, Cu, Zn and Mn.

The model relates the growth characteristics to the soil properties through a second order response function of the following form.

$$y = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \sum_{i=1}^{p} \beta_{ii} x_i^2 + \sum_{i<j}^{p} \beta_{ij} x_i x_j \qquad (11)$$

where,

y = growth increment in a mean tree characteristic (diameter/ V_c / V_p /V_{tob} / V_{tub})

x_i's are the set of soil attributes measured in the sample plot

β's are the regression coefficients

p = number of variables

The function represented in Equation (11) contained additionally age of the stand, mean diameter of trees and stand density as standardizing variables as the measurements on growth increment came from stands of varying age, initial size and density levels. In the regression function, the densities of Acacia and miscellaneous species were included separately. The density measures were computed as given in Equation (10).

Significant attributes from among the full set of attributes in the second order response function (Equation (11)) were identified through stepwise regression (Montgomery and Peck, 1982). The stepwise regression analysis was carried out after forcing in age, initial size and density in the above function (Equation (11)) other than soil variables. The stepwise procedure was executed using SPSS software package (Norusis, 1988). The stepwise analysis was done separately for each depth level and also for combining all soil attributes from the two depth levels as independent variables along with the forced in variables such as age, initial size and stand density in the function.

Generally, to characterise the nature of response surface and to find out the optimum levels of soil attributes, the resultant equations of stepwise regression are utilized and the levels of soil variables *e.g.*, x_1, x_2,... x_p which maximize the current growth are identified through canonical analysis (Montgomery, 1991). However, in the present study, no quadratic terms were found significant. As such the optimum levels of soil attributes in the two layers, which maximize the tree growth, could not be determined through canonical analysis. This could be because of the shorter range of soil properties observed under natural conditions. Hence no description on canonical analysis is made here.

4. RESULTS

The study plots were taken from sites of different site quality classes and age groups. The distribution of the plots over site quality/age classes is shown in Table 2.

Table 2. Distribution of sample plots in different age and site quality classes

Age classes (years)	Site quality classes				Total
	I	II	III	IV	
	Top height (m)				
	28-36	20-28	12 -20	4 -12	
0-4	-	2	5	3	10
5-9	6	15	7	-	28
10-14	5	2	1	-	8
15-19	2	-	1		3
≥ 20	1	-	-	-	1
Total	14	19	14	3	50

Plantations of site quality classes IV were generally not very frequent in the area sampled. Maximum representation was under site quality II corresponding to 5-9 age class. Maximum number of plots belonged to 5-9 age class. Minimum representation was in the ≥ 20 years age group. There were only four plots under the old age group (≥ 15 years).

Height of each tree was predicted using a height-diameter relation developed for each Forest Division. The estimates of parameters of the height-diameter relation obtained for the different Forest Divisions are given in Appendix 1. The adjusted R^2 varies from 0.490 to 0.949. A correction factor of (MSE/2) has to be added to $\ln h$ before transforming to the original height values while using equations with dependent variable $\ln h$. The estimates of height–diameter relation in respective Divisions were utilized in the computation of top height for the plots taken from each Division and in turn for obtaining the site index/ site quality of each plot.

The relation between top height and age was estimated as,

$$\ln H = 3.386 \; - 1.528\, A^{-1} \qquad (12)$$
$$\quad (0.040) \quad (0.132)$$

Adjusted R^2 of the above equation was 0.693 and Mean Square Error (MSE) was 0.052. The figures in parentheses are standard errors of the estimates.

Hence the site index equation with base age as 8 years is

$$\ln S = \ln H + 1.528\left(\frac{1}{A} - \frac{1}{8}\right) \qquad (13)$$

where S = Site index (top height at the base age of 8 years in m)

H = Top height of the stand (m)

A = Age of the stand (year)

Equations (12) and (13) were used to compute top height and site index for all the 50 plots. The ranges of different stand level attributes and soil properties observed in 50 plots are reported in Tables 3 and 4. Mean diameter at breast-height in 50 plots ranged from 5.75 cm to 22.64 cm. Age of sample plots varied from 2 to 23 years. The number of Acacia trees varied from 333 to 3022 trees ha^{-1} and number of miscellaneous trees ranged from 0 to 667 trees ha^{-1} and the range of site index was from 14.66 to 45.61 m.

Table 3. Range of plot level variables observed in selected study plots

Attribute	Minimum	Maximum	Mean	SD
Mean crop diameter (cm)	6.03	23.32	13.14	3.76
Mean crop height (m)	6.75	31.85	17.34	5.57
Mean basal area (m^2 ha^{-1})	28.59	426.98	146.66	83.30
Mean commercial volume (m^3 ha^{-1})	0.18	4.95	1.40	0.97
Mean pulpwood volume (m^3 ha^{-1})	0.15	4.26	1.21	0.84
Mean timber volume over- bark (m^3 ha^{-1})	0.03	1.85	0.40	0.35
Mean timber volume under- bark (m^3 ha^{-1})	0.02	1.72	0.38	0.33

SD – Standard deviation

Table 4. Range, mean and maximum values of soil properties of *Acacia auriculiformis* plantations in Kerala

Soil properties	Depth (cm)								Unit
	0-10				10-20				
	Mini.	Max.	Mean	SD	Min.	Max.	Mean	SD	
Sand	72	94	83.02	5.75	70	95	81.80	6.39	%
Silt	3	18	9.70	3.23	3	19	10.14	3.45	%
Clay	2	15	7.28	3.19	2	16	8.06	3.91	%
pH	4.08	6.02	4.94	0.45	4.17	5.99	5.00	0.44	
OC	0.12	2.93	2.04	0.82	0.08	2.80	1.60	0.74	%
EC	0.03	0.16	0.06	0.02	0.01	0.08	0.04	0.02	ds/m
N	0.01	0.03	0.02	0.01	0.01	0.03	0.02	0.00	%
P	0.25	41.35	12.52	10.77	0.45	68.75	8.88	11.69	kg/ha
K	23.85	257.40	88.89	55.77	1.14	214.70	69.68	48.86	ppm
Ca	41.11	2045.9	415.48	455.89	21.47	1660.82	289.79	361.66	ppm
Mg	16.33	570.61	126.42	129.13	11.05	492.94	102.52	115.63	ppm
Zn	0.45	800.73	250.31	179.05	0.56	886.95	237.48	233.36	ppm
Fe	15.07	362.72	57.51	53.13	13.12	679.53	69.90	98.05	ppm
Cu	0.09	3.11	1.04	0.70	0.05	4.33	1.14	0.82	ppm
Mn	4.62	417.96	86.10	102.88	2.75	564.81	69.61	98.87	ppm
Al	0	3	0.56	0.89	0	3	0.64	0.90	meq/100g
EA	0.20	6.30	1.73	1.69	0.30	6.10	2.36	1.73	meq/100g

n = 50

4.1. Growth model

SAS (Version 6) programme was used for estimation of parameters of diameter and volume equations. The estimate of the site index parameter was 0.338735 (±0.1421), indicating a less than proportionate increase in the diameter growth with increase in the site index, keeping other factors constant. The site index parameter and the parameter p were significant. The parameters c_2 and c_3 also turned out nonsignificant. These parameters were nonsignificant, indicating that either the Acacia density or the miscellaneous density had no direct effect on diameter growth. The parameter a_2 was

0.2091(±0.1641). The adjusted R^2 for the model was 0.6527. The residuals did not show any unsatisfactory pattern when plotted against predicted values of diameter increment.

Equation (9) when simultaneously estimated with Equation (8), produced the following estimates of a_1, b_1 and adjusted R^2 corresponding to V_c, V_p, V_{tob} and V_{tub} . The estimates were a_1= 0.2196(±0.0145), b_1= 2.6997 (±0.0462) and adjusted R^2 was 0.9558 for V_c ; a_1= 0.1856(±0.0121), b_1= 2.6885 (±0.0407) and adjusted R^2 was 0.9565 for V_p; a_1= 0.2053(±0.0256), b_1= 3.3189 (±0.0795) and adjusted R^2 was 0.9212 for V_{tob} ; a_1= 0.3736(±0.0751), b_1= 3.7107 (±0.1296) and adjusted R^2 was 0.8611 for V_{tub} . The estimates were highly significant. As the parameters c_1 and c_4 were nonsignificant, they were dropped from the model. These parameters were nonsignificant, indicating that either the Acacia density or the miscellaneous density had no direct effect on volume increment. Both of these variables had no influence on diameter growth (Z), which was already present in Equation (9) as a predictor variable. The value for a_1, the coefficient of proportionality and b_1, the power coefficient of tree volume equations were realistic. The adjusted R^2 for the fitted models were very high *i.e.*, more than 90 per cent. The residuals did not show any distortion when plotted against the predicted values of volume increment.

The resultant equations of the stepwise regression involving site index as dependent variable and soil variables as independent variables in the logarithmic scale, at two depth levels separately and also by taking soil variables from the two depth levels together (combined) are given in Table 5.

Table 5. Relation between site index and soil attributes in the log scale

Depth level (cm)	The resultant equation of the stepwise regression	Adjusted R^2 value
0-10	$\ln x_5 = 40.958 + 3.527 \ln x_6$ (3.936) (0.875)	0.225
10-20	$\ln x_5 = 31.276 - 6.930 \ln x_{26} + 3.980 \ln x_{37}$ (1.390) (1.189) (0.421)	0.305
Combined	$\ln x_5 = 29.064 + 0.933 \ln x_{31}$ (2.490) (0.012)	0.492

n = 50

All the regression coefficients are significant at P = 0.01.

where, x_5 = Site index

x_6 = Sand (%) in 0-10 cm depth level

x_{26} = pH in 10-20 cm depth level

x_{37} = Mn(ppm) in 10-20 cm depth level

x_{31} = K(ppm) in 10-20 cm depth level

The values in the parentheses are standard errors of the coefficients

For the first depth level (0-10 cm), the resultant model had a very low adjusted R^2 value of 0.225. The site index was significantly influenced by sand. The result showed that with the increase of sand in the soil there was corresponding increase in site index.

In the second depth level (10-20 cm), the resultant model had adjusted R^2 value of 0.305. The site index was significantly influenced by soil pH and Mn. The result showed that with the increase of Mn in the subsoil there was corresponding increase in site index. The result also revealed that with the increase of soil pH, site index decreased.

The equation fitted with respect to properties of soils from two layers (0-10 and 10-20 cm) taken together, had adjusted R^2 value of 0.492. The site index was significantly influenced by soil K in 10-20 cm layer alone. The result showed that with the increase of soil K in 10-20 cm layer, there was corresponding increase in site index

The results indicated that, of the 17 soil properties at each of the two depth levels, sand, pH, Mn and K had significant influence on site index. Consequently sand in the surface layer (0-10 cm) had positive influence on the site index. Mn and K in the sub surface layer (10-20 cm) had positive influence on the site index, whereas pH in the 10-20 cm layer had negative influence on site index. The model had an adjusted R^2 value of 0.492, which is greater than that of the other layers (0-10 cm and 10-20 cm) when taken separately. These significant soil attributes were considered for developing process-based models.

Process-based growth models (Equations 8 and 9) were developed for 0-10 cm depth level after replacing top height by significant soil attribute *viz.*, sand in 0-10 cm depth level in Equation (8). However, since the estimate of the sand in 0-10 cm depth level parameter was found nonsignificant within the process model setup, no model was developed for 0-10cm depth level.

With regard to 10-20 cm depth level, in Equation (8) top height was replaced by significant soil variables *viz.*, pH and Mn. Here also the estimates were turned out nonsignificant, hence no model was developed for 10-20 cm depth level also.

Regarding the combined set, process-based growth models (Equations 8 and 9) were developed after replacing top height by significant soil attribute *viz.*, K in 10-20 cm depth level. The estimate of the soil K in 10-20 cm depth level parameter was found significant within the process model setup. Thus the final diameter growth model was of the following form.

$$y = a_2\, x_{37}^{b4}\, Y^{p} e^{-qt} e^{-S_t/c_2} e^{-S_m/c_3} \qquad (14)$$

where, y = Growth increment in a mean tree characteristic

x_{37} = K(ppm) in 10-20 cm depth level

Y = Initial value of the mean tree diameter (m)

t = Age (years)

S_t = Stand density of Acacia

S_m = Stand density of miscellaneous species

a_2, b_4, c_2, c_3, p and q are parameters

The estimate of parameter p was 0.3268 (±0.1042). The estimate of q was 0.071 (±0.0031). The estimate of the soil K parameter, b_4, was 0.1367 (±0.0674), indicating a positive increase in the diameter growth with increase in the soil K in 10-20 cm depth level, keeping other factors constant. The estimates of the parameters *viz.*, soil K and p were highly significant.

The parameter c_2 was highly significant and c_3 was nonsignificant. The parameter a_2 was 0.9141 (±0.8102). The adjusted R^2 for the model was 0.7013. The residuals did not show any unsatisfactory pattern when plotted against predicted values of diameter increment.

The results showed that by replacing the site index with the soil parameter K in 10-20 cm depth level, the value of the adjusted R^2 had changed from 0.6527 to 0.7013.

Equation (14) when simultaneously estimated with Equation (9), produced the following estimates of a_1, b_1, which were highly significant. The adjusted R^2 for all the fitted models corresponding to V_c, V_p, V_{tob} and V_{tub} were very high *i.e.*, more than 90 %

Relation between tree growth and stand features

Linear regression equation relating quadratic mean annual increment in diameter, mean annual increment in V_c, V_p, V_{tob} and V_{tub} and the stand features like age of the stand, initial diameter, stand density of Acacia and miscellaneous species, and site index are reported in Table 6.

Table 6. Relation between tree growth characteristics and stand features

Tree growth characteristics (y)	The resultant equation of the stepwise regression	Adjusted R^2 value
Quadratic mean annual increment in diameter (cm)	$y = 1.493 - 0.026\,x_1 - 0.085\,x_2 - 0.000\,x_3 - 0.000\,x_4 + 0.040\,x_5$ (0.397) (0.028) (0.029) (0.001) (0.001) (0.015)	0.419
Mean annual increment in V_c (m^3)	$y = 0.005 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4 + 0.000\,x_5$ (0.005) (0.000) (0.000) (0.000) (0.000) (0.000)	0.206
Mean annual increment in V_p (m^3)	$y = 0.004 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4 + 0.000\,x_5$ (0.004) (0.000) (0.000) (0.000) (0.000) (0.000)	0.201
Mean annual increment in V_{tob} (m^3)	$y = -0.002 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4 + 0.001\,x_5$ (0.002) (0.000) (0.000) (0.000) (0.000) (0.001)	0.445
Mean annual increment in V_{tub} (m^3)	$y = -0.002 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4 + 0.000\,x_5$ (0.002) (0.000) (0.000) (0.000) (0.000) (0.000)	0.414

n = 50

All the regression coefficients are significant at P = 0.01.

where,

y = Growth increment in a mean tree characteristic (diameter/ V_c / V_p / V_{tob} / V_{tub})

x_1 = Age (years)

x_2 = Initial diameter (cm)

x_3 = Stand density of miscellaneous species

x_4 = Stand density of Acacia

x_5 = Site index

The values in the parentheses are standard errors of the coefficients. Zero values for regression coefficients and standard errors are only a consequence of number of digits displayed.

All the regression coefficients of the equation relating diameter growth and stand features, (adjusted $R^2 = 0.419$) except that of initial diameter and site index, all the other variables such as age, stand density of miscellaneous species and stand density of Acacia were found nonsignificant, indicating that initial diameter of the stand and site index had significant influence on the tree diameter growth. In contrast age of the stand, stand density of Acacia and miscellaneous species had no significant influence on the tree diameter growth.

Another linear regression equation relating mean annual increment in commercial volume and the stand features like age of the stand, initial diameter, stand density of Acacia and miscellaneous, and site index had adjusted R^2 0.206. The regression coefficients of age and initial diameter were found significant, indicating that age and initial diameter of the stand had significant influence on the tree volume growth. Site index, stand density of Acacia and miscellaneous species had no significant influence on the tree commercial volume growth.

The regression equation relating stand features and pulpwood volume had obtained the adjusted R^2 value as 0.201. The regression coefficients of the equation site index and stand density of Acacia and miscellaneous were found nonsignificant, indicating that initial diameter and stand age had significant influence on the pulpwood volume.

Adjusted R^2 value of the equation relating stand features and timber over-bark volume was found 0.445. Here also regression coefficients of age and initial diameter were found significant, indicating that the timber over-bark volume was significantly influenced by age and initial diameter of the stand.

All the regression coefficients of the equation relating timber under- bark volume and stand features (adjusted $R^2 = 0.404$) except that of initial diameter, all the other variables such as age, stand density of Acacia and miscellaneous species and site index were found nonsignificant, indicating that initial diameter of the stand alone had significant influence on the tree timber under-bark volume.

Overall results of regression equations relating tree growth and stand features revealed that initial diameter of the stand had significant influence on quadratic mean increment in diameter, mean annual increment in commercial volume, pulpwood volume, timber over-bark volume and timber under-bark volume. Similarly, age of the stand had significant influence on mean annual increment in commercial volume, pulpwood volume and timber over-bark volume. Site index had significant influence only on quadratic mean annual increment in diameter. Stand density of Acacia and miscellaneous species had no significant effect on growth.

4.2. Empirical relation between tree growth and soil attributes

The relation between of soil properties on the growth of Acacia was investigated by fitting the regression equations on mean annual increment in tree diameter, commercial volume, pulpwood volume and timber under-bark and over-bark volume through stepwise regression. As measurements on growth increment come from stands of varying age, initial size and density, these variables were forced in the stepwise analysis along with the soil attributes. The resultant equations of the stepwise regression with respect to soil properties at two depth levels (0-10cm and 10-20 cm) separately and also by considering soil properties from two depth levels together (combined) are given in Table 7.

Quadratic mean annual increment in diameter

In the first depth level *viz.*, 0-10 cm layer, the resultant equation had an adjusted R^2 value of 0.334. No soil properties were found related to tree growth. The model is linear and no quadratic terms and interaction terms are present.

The equations fitted with respect to soil properties in 10-20 cm layer had the adjusted R^2 value of 0.411which is greater than that of the surface layer (0-10 cm). K in soils belonging to 10-20 cm layer had significant influence on tree diameter growth. Soil K had a linear positive effect on the tree diameter growth. The positive coefficient of K indicates that with increasing K in the soils in 10-20 cm layer, diameter growth also increased.

Table 7. Relation between tree growth and soil attributes

Tree growth characteristics (y)	Depth level (cm)	The resultant equation of the stepwise regression	Adjusted R^2 value
Quadratic mean annual increment in diameter (cm)	0 - 10	$y = 2.224 - 0.042\,x_1 - 0.058\,x_2 + 0.000\,x_3 + 0.000\,x_4$ (0.316) (0.029) (0.029) (0.001) (0.001)	0.334
	10-20	$y = 1.939 - 0.034\,x_1 - 0.073\,x_2 - 0.001\,x_3 - 0.000\,x_4 + 0.004\,x_{31}$ (0.316) (0.027) (0.028) (0.001) (0.001) (0.002)	0.411
	Combined	$y = 1.939 - 0.034\,x_1 - 0.073\,x_2 - 0.001\,x_3 - 0.000\,x_4 + 0.004\,x_{31}$ (0.316) (0.027) (0.028) (0.001) (0.001) (0.002)	0.411
Mean annual increment in V_c (m^3)	0 - 10	$y = 0.006 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4$ (0.004) (0.000) (0.000) (0.000) (0.000)	0.220
	10-20	$y = 0.006 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4$ (0.004) (0.000) (0.000) (0.000) (0.000)	0.220
	Combined	$y = 0.006 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4$ (0.004) (0.000) (0.000) (0.000) (0.000)	0.220
Mean annual increment in V_p (m^3)	0 - 10	$y = 0.006 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4$ (0.000) (0.000) (0.000) (0.000) (0.000)	0.215
	10-20	$y = 0.006 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4$ (0.000) (0.000) (0.000) (0.000) (0.000)	0.215
	Combined	$y = 0.006 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4$ (0.000) (0.000) (0.000) (0.000) (0.000)	0.215
Mean annual increment in V_{tob} (m^3)	0 - 10	$y = -0.001 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4$ (0.001) (0.000) (0.000) (0.000) (0.000)	0.457
	10-20	$y = -0.001 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4$ (0.001) (0.000) (0.000) (0.000) (0.000)	0.457
	Combined	$y = -0.001 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 + 0.000\,x_4$ (0.001) (0.000) (0.000) (0.000) (0.000)	0.457
Mean annual increment in V_{tub} (m^3)	0 - 10	$y = 0.013 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 - 0.000\,x_4 + 0.000\,x_6$ (0.006) (0.000) (0.000) (0.000) (0.000) (0.000)	0.491
	10-20	$y = 0.010 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 - 0.000\,x_4 - 0.002\,x_{26}$ (0.005) (0.000) (0.000) (0.000) (0.000) (0.001)	0.480
	Combined	$y = 0.013 + 0.000\,x_1 + 0.001\,x_2 - 0.000\,x_3 - 0.000\,x_4 + 0.000\,x_6$ (0.006) (0.000) (0.000) (0.000) (0.000) (0.000)	0.491

n = 50

The equation fitted with respect to soil properties from all layers (0-10 and 10-20 cm) taken together, had the same form and adjusted R^2 value (0 .411) as obtained in the case of 10-20 cm depth level.

The results indicated that, of the 17 soil properties studied at each of the two depth levels, the increment in diameter is related to subsoil K content. The results showed that by replacing the site index with the soil properties *viz.*, soil K in the 10-20 cm depth level, the value of the adjusted R^2 does not change drastically.

In all the above equations, no quadratic terms were present. As such, the optimum levels of soil attributes in the two layers, which maximise the tree diameter growth, could not be determined.

All the regression coefficients are significant at P = 0.01.

where, x_{31} = K(ppm) in 10-20 cm depth level

x_6 = Sand (%) in 0-10 cm depth level

x_{26} = pH in 10- 20 cm depth level

y, x_1, x_2, x_3 and x_4 are defined earlier

The values in the parentheses are standard errors of the coefficients. Zero values for regression coefficients and standard errors are only a consequence of number of digits displayed.

Mean annual increment in commercial volume (V_c)

In the first (0-10 cm), second (10-20 cm) and combined depth level (0-10 and 10-20 cm), the resultant equation had an adjusted R^2 value of 0.220. No soil properties were found significantly related to tree commercial volume growth.

In all the above equations, no quadratic terms were present. As such, the optimum levels of soil attributes in the two layers, which maximise the tree diameter growth, could not be determined.

Mean annual increment in pulpwood volume (V_p)

In the first (0-10 cm), second (10-20 cm) and combined depths (0-10 and 10-20 cm), the resultant equation had the same adjusted R^2 value (0.215). No soil properties were found significantly related to tree pulpwood volume growth.

In all the above equations, no quadratic terms were present. As such, the optimum levels of soil attributes in the two layers, which maximise the tree pulp wood volume growth, could not be determined.

Mean annual increment in timber over-bark volume (V_{tob})

In the first (0-10 cm), second (10-20 cm) and combined level depth level (0-10 and 10-20 cm), the resultant equation had the same adjusted R^2 value (0.457). No soil properties were found significantly related to tree timber over-bark volume growth.

In all the above equations, no quadratic terms were present. As such, the optimum levels of soil attributes in the two layers, which maximise the tree timber over-bark volume growth, could not be determined.

Mean annual increment in timber under-bark volume (V_{tub})

In the first depth level *viz.*, 0-10 cm, the resultant equation had an adjusted R^2 value of 0.491. Sand in soils had significant influence on tree timber under-bark volume growth. The positive coefficient of sand indicates that with increasing sand content in the soil, timber under-bark volume growth increased. The model was linear and no quadratic terms and interaction terms were present.

The equation fitted with respect to soil properties in 10-20 cm, had an adjusted R^2 value of 0.480. Soil pH had significant influence on tree timber under-bark volume growth. Soil pH had a linear negative effect on the tree timber under-bark volume growth. The negative coefficient of pH indicates that with the increase in soil pH, timber under-bark volume growth also decreased.

The equation fitted with respect to properties of soils in combined layers (0-10 and 10-20 cm) had the same structure and adjusted R^2 value (0.491) as obtained in 0-10 cm depth level equation. Sand in soils belonging to 0-10 cm layer had significant influence on tree timber under-bark volume growth. However, the absence of quadratic terms in the model indicates a linear surface. Sand belonging to 0-10 cm depth level had a linear positive effect on the timber under-bark volume growth.

In all the above equations, no quadratic terms were present. As such, the optimum levels of soil attributes, which maximize the tree timber under-bark volume growth, could not be determined. However, the absence of quadratic terms in the model indicates a linear surface.

The equations fitted, which relates between soil properties and tree timber under-bark volume growth, had the higher adjusted R^2 values when compared to that of the other growth characteristics (Table 6). The results showed that by replacing the site index with the soil parameter such as sand in 0-10 cm layer and soil pH in 10-20 cm layer, the value of the adjusted R^2 value was also changed.

Increment in tree diameter growth was not related to many soil properties except for K in the 10-20 cm layer and the increment in timber under-bark volume growth is influenced by surface sand and subsoil phosphorus content other than the forced in variables *viz.*, initial diameter, age, stand density of Acacia and miscellaneous species.

5. DISCUSSION

Growth model

Two most relevant points regarding the choice of the growth model used for the study were that the selected model had its base on the unified approach proposed by Zeide (2003) and that it was a whole stand model requiring only stand level information as input variables like mean diameter, number of trees per unit area and site index. Moreover, the model used modified Reineke's index as a predictor variable, which is a function of both mean diameter and number of trees, and is the most effective measure of the extent of denseness in a stand, so far proposed. This model is based on well-structured biologically valid functions and parameters, although some variable selection procedure was required for such models in the present case. Site index in this model was replaced by significant soil variables identified through stepwise regression analysis relating to site index and soil attributes. The growth models (Zeide, 2004), one describing the diameter growth and the other volume growth, were used for the present study.

In the 0-10 cm layer, site index was significantly influenced by sand. The model had an adjusted R^2 value of 0.225. The results were such that with the increase in sand, site index also increased. The findings agree with those of Alexander *et al.* (1987), where they had reported that, in teak as sand increases the site quality of teak also improved.

In the 10-20 cm layer, site index was significantly influenced by soil pH and Mn. The model had an adjusted R^2 value of 0.305. The results showed that site index was elevated with the increase in Mn and decrease in soil pH.

For the combined set *i.e.*, when properties of soils in all layers (0-10 and 10-20 cm layer) were taken together, soil K in 10-20 cm layer influenced the site index. The model had an adjusted R^2 value of 0.492. The results were such that with the increase in K in 10-20 cm layer site index also increased.

In the process-based model, soil K in 10- 20 cm depth level alone was turned out to be significant. The adjusted R^2 value for the diameter increment function was 0.70 and greater than 0.90 for all the volume increment functions, reasonable values to expect under uncontrolled conditions. The results also indicated a positive increase in the soil K in 10-20 cm layer with increase in diameter growth, keeping other factors constant. The results are corroborating with those of Simpson (1992). He found that in *Acacia mangium*, the more productive stands showed higher K levels. Moreover, increase in soil K with increase in the growth of acacia might be from the enhanced litter fall and consequent decomposition and release with the improvement of growth.

By replacing the site index with the soil parameter *viz.*, K in the 10-20 cm depth level in the diameter growth model, the value of the adjusted R^2 obtained was 0.70, leaving still a portion of the variation in diameter growth unexplained by the model. This indicates that the growth attained during any time interval is affected by extraneous factors other than soil or stand variables and also such factors could either mask or vitiate the effect of soil variables on growth.

Empirical relation between tree growth and soil attributes

The relation between the tree growth and soil attributes was studied through linear regression analysis. Reduction in the number of predictor variables was achieved through stepwise procedure.

For the first depth level (0-10 cm), it was found that there was no significant relationship between soil properties and tree growth such as diameter and volume (V_c, V_p and V_{tob}). This may be due to plantation activities and the soils in the surface layer would have been eroded and the soils in the sub surface layer exposed. The penetration of roots and the availability of nutrients in the sub surface layer would not be similar to those in the surface layer. This shows the necessity of soil amendments in the exposed subsurface layer. However, significant relationship was found between timber under-bark volume growth (V_{tub}) and sand. The results showed that with increase in the content of sand in the surface layer, there was corresponding increase in the tree timber under-bark volume growth. Furthermore, coarse textured soil with higher content of sand generally facilitates easy penetration and proliferation of roots deep into the soil. Even though, *A. auriculiformis* can adapt to wide range of soils with textural make up from clayey to sandy, relatively higher content of sand in the soil will definitely improve its growth presumably due to enhanced nutrient absorption brought out by the healthy and vigorous root system. In the present study range of sand is from 72 to 94 %, which reflected in increase in the volume growth.

In 10-20 cm depth levels, the tree diameter growth was significantly influenced by K. The results showed that with increase in K in sub surface layer, there was corresponding increase in the tree diameter growth. This clearly indicates that the growth of acacia might be from the enhanced litter fall and consequent decomposition and release with the improvement of growth. The similar result was obtained by Simpson (1992). Significant relationship was found between timber under-bark volume growth and soil pH. The results showed that with increase in soil pH in the sub surface layer there was corresponding decrease in the tree timber under-bark volume growth. The results also agree with the findings of Sankaran *et al.*(1993). This clearly indicates that soil acidity (K) and soil reaction (pH) in the sub surface layer affects the tree timber under-bark volume growth and diameter growth respectively.

For the combined set *i.e.*, when properties of soils in all layers (0-10 and 10-20 cm) were taken together, soil K in the 10-20 cm layer and sand in the 0-10 cm layer showed significant influence on tree diameter growth and tree timber under-bark volume growth respectively. The results agree with those of Simpson (1992).

Since the sample plots selected for the present study represent various age groups, stocking levels and site conditions, a wide variation in soil properties do occur naturally during the study period.

In all the depth levels, no quadratic terms showed up in the model. As such, the optimum levels of soil attributes, which maximize the tree diameter and volume growth, could not be determined through canonical analysis. This could be because of the restricted range of soil properties and also intercorrelation among the soil variables.

The study on the relationship between soil attributes and growth had showed the contribution of soil K in 10-20 cm layer in tree diameter growth; sand (0-10 cm) and soil pH (10-20 cm) in tree timber under-bark volume growth. Whereas through the process-based modelling approach soil K in 10-20 cm as the major soil variable significantly influencing tree diameter and volume growth. Admittedly, although other soil variables had relation with site index, these need not be shown up in the model for diameter growth. From the above findings, the study revealed that K (10-20 cm layer) in the soils has much to do with tree diameter growth; sand (0-10 cm layer), pH and K (10-20 cm layer) in soils significantly influencing volume growth.

The present study was conducted in selected *A. auriculiformis* plantations in the State. The ground vegetation and soil conditions were left as such and no attempts were made to change the soil status in order to avoid possible interference in the ecosystem which in turn may affect the performance of the plantation. In fact, the range of variation observed in the values of each of these characteristics in a particular soil depth is an important factor to be considered for judging the significance of their effect on tree growth although, in many instances, the range of variation was found to be small. Even when microclimatic and edaphic characteristics have a significant effect on growth and performance of plantations, the effects may not become apparent in a study like this and also the selection of specific variables could also be easily affected by the modeling approach. However, in spite of these limitations, certain broad indications were arrived at suggesting that the models derived in this study are statistically and biologically acceptable and could be satisfactorily used for stands of *A. auriculiformis*.

In this context, it may also be pointed out that tree growth, which is a manifestation of several years of complex interactions with soils and climate, need not show fine relationship with current soil fertility attributes. This is one of the limitations of this study.

The relationship between the growth and soil properties obtained from the growth model developed in this study, which is based on unified approach, has greater reliability compared to the one arrived at from the empirical approach on account of its biological validity.

However, the observation that the tree growth is significantly related with soil property K belonging to 10-20 cm depth level; 70 per cent of variation in diameter growth and 90 per cent variation in volume growth could be attributed by K in 10-20cm layer, are quite important.

6. CONCLUSIONS

The study conducted on modelling the growth of *A. auriculiformis* in relation to soil conditions from 50 semi permanent sample plots distributed in different parts of Kerala led to the following conclusions:

1. Growth models were developed through unified approach for tree diameter and volume growth. The adjusted R^2 value for the tree diameter growth model was 0.70 and that of volume growth in terms of commercial, pulpwood, timber over-bark and timber under- bark were found to be almost 90 per cent. Soil K in the subsurface layer was identified as the major soil variable significantly influencing tree growth. The results also indicated a positive increase in the soil K in 10-20 cm layer with corresponding increase in diameter growth, keeping other factors constant.

2. Almost 49 per cent of variation in the site index could be explained by soil K in 10-20 cm layer.

3. The empirical relation between tree diameter growth and soil characteristics varied with the soil depth levels. Diameter growth of *A. auriculiformis* does not seem to be significantly related to many of the soil properties except for K in subsurface layer. This clearly indicates that the K in subsurface layer affects the diameter growth of trees significantly.

4. The empirical relation between tree timber under-bark volume growth and soil characteristics varied with the soil depth levels. However, tree timber under-bark volume growth was significantly related to the soil attributes *viz*., sand in the surface layer and soil pH in the sub surface layer. This clearly indicates that the soil texture (sand) and soil reaction (pH) affect the tree timber under-bark volume growth.

5. In all the depth levels, the models obtained through stepwise regression were all linear in nature and no quadratic terms were present. As such, the optimum levels of soil attributes, which maximize the tree growth, were not attained within the range of the data.

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APPENDIX 1

Parameters of the height-diameter relation for *A. auriculiformis* in different Divisions

Circle/Division	a	SE(a)	b	SE(b)	Adj. R^2	MSE
Central						
Chalakkudy	2.002	0.384	0.471	0.123	0.734	0.007
Thrissur	1.211	0.166	0.7213	0.063	0.700	0.030
Eastern						
Nemmara	0.649	0.209	0.909	0.079	0.836	0.033
Palakkad	-1.009	1.258	1.430	0.468	0.625	0.036
Nilambur (North)	0.541	0.913	0.258	0.109	0.710	0.052
Mannarkkad	0.737	0.253	0.796	0.102	0.704	0.073
High Range						
Kothamangalam	2.062	0.489	0.427	0.177	0.490	0.017
Southern						
Ranni	1.207	0.406	0.690	0.145	0.784	0.027
Konni	0.820	0.231	0.799	0.082	0.949	0.006
Punalur	1.050	0.223	0.755	0.082	0.711	0.046
Thiruvananthapuram	-0.197	0.155	1.217	0.067	0.771	0.089
Thenmala	0.963	0.148	0.727	0.054	0.924	0.007
Northern						
Kannur	1.264	0.083	0.578	0.032	0.828	0.012
KFDC						
Punalur	0.106	0.141	1.007	0.064	0.898	0.026

Note: SE (t) indicates standard error of t

a, b refers to the parameters of Equation (1)

MSE indicates mean square error