BIOMASS AND BIOENERGY 35 (2011) 227–235

Available at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

Optimum stand density of *Leucaena leucocephala* for wood production in Andhra Pradesh, Southern India

J.V.N.S. Prasad [a,*], G.R. Korwar [a,1], K.V. Rao [a,1], U.K. Mandal [a,1], G.R.Rao [a,1], I. Srinivas [a,1], B. Venkateswarlu [a,1], S.N. Rao [b,2], H.D. Kulkarni [c,3]

[a] Central Research Institute for Dryland Agriculture, Santoshnagar, Hyderabad-500059, India
[b] Indian Tobacco Company (ITC), Paper Boards and Specialty Papers Division (PSPD), Secunderabad-500003, India
[c] Indian Tobacco Company (ITC), Paper Boards and Specialty Papers Division (PSPD), Sarapaka, Khammam (Dt), Andhra Pradesh-507 201, India

ARTICLE INFO

Article history:
Received 5 February 2009
Received in revised form
25 July 2010
Accepted 4 August 2010
Available online 15 September 2010

Keywords:
Biomass partitioning
Biomass production
Bole biomass
Pulpwood
Spacing tree density

ABSTRACT

Leucaena leucocephala is widely used as raw material for the manufacture of paper and packaging material and in biomass based power plants in the state of Andhra Pradesh, Southern India. Experiments were conducted to study the affect of tree density on the growth, biomass partitioning and wood productivity. Six treatments 1 × 1 m, 1.3 × 1.3 m, 3 × 0.75 m, 3 × 1 m, 5 × 0.8 m and 3 × 2 m corresponding to a tree density of 10,000, 6666, 4444, 3333, 2500 and 1666 were evaluated with leucaena variety K636. At 51 months after planting, spacings significantly influenced tree height, diameter at breast height (DBH), number of branches and biomass partitioning. Wider tree rows resulted in greater tree height and diameter growth resulting in higher per plant productivity. At harvest, 70% of trees in 3 × 2 m attained a diameter of more than 7.5 cm, while 35% of the trees attained the same DBH in 1 × 1 m spacing. Increased spacing levels decreased the relative amount of growth allocated to the bole of the tree. Marketable biomass yield was highest with 1 × 1 m spacing. Spacing of 3 × 0.75 m produced marketable biomass comparable to that of 1 × 1 m and greater proportion of stems with more than 5 cm diameter. Leucaena can be grown at 3 × 0.75 m spacing either for pulpwood or fuelwood depending on the prevailing market prices and demand.

1. Introduction

Leucaena leucocephala (Lam.) de Wit. is one of the most productive and versatile multi-purpose tree legumes suitable for tropical conditions. The genus has its origin in Central America and Mexico where it has been used as a source of edible pods, forage for domestic animals, poles for construction, firewood and shade in permanent plantations [1]. Leucaena has always primarily been used as high quality forage for ruminants, but it has also been valued for fuelwood, charcoal, timber and pulpwood [2]. Research information is available about its nutritive value, for enrichment of low protein animal diets and as forage for overcoming dry season fodder scarcity in various parts of the world [3–5]. In recent years, leucaena has gained prominence in improving the soil fertility and the physical conditions, arresting soil erosion and

* *Corresponding author*. Tel.: +91 40 24530161; fax: +91 40 24531802.
E-mail addresses: prasad_jasti@yahoo.com (J.V.N.S. Prasad), snraoifs@gmail.com (S.N. Rao), hd.kulkarni@itc.in (H.D. Kulkarni).
1 Tel.: +91 40 24530161; fax: +91 40 24531802.
2 Tel.: +91 9849496019.
3 Tel.: +91 8746 242331.
0961-9534/$ – see front matter
doi:10.1016/j.biombioe.2010.08.012

in reforestation and soil improvement programs [6,7]. The leaves, either as mulch or green leaf manuring is being studied for addressing the challenge of declining soil fertility in African situations [8,9].

Leucaena is one of the few trees from which wood is used for both the industrial and non industrial purposes. Wood of leucaena is generally described as being strong, light in weight, easy to work and able to give attractive finish [10]. These qualities make leucaena wood suitable to a wide range of uses, ranging from the traditional small scale use by farmers and small holders to the more recent utilization by large scale industries for pulp and energy generation [11]. *L. leucocephala* has porous wood structure, longer fiber than that of other hardwoods, high holocellulose, a-cellulose and low lignin content with xylan type hemicellulose making it a suitable raw material in pulp and paper industry [12].

Of the 660 paper mills in India, 26 are wood-based and face challenges with the supply of forest-based raw material. Many pulp mills are finding it difficult to gain access to land where they can establish plantations, and source wood from natural forests [13]. Of the annual pulp production of 1.9 million tonnes using 6.8 million tonnes of wood, nearly 20% of wood is procured from forests through government sources and remaining 80% is from private land holders through agroforestry systems [14]. In the state of Andhra Pradesh alone, 40 biomass based power projects with an installed capacity of 219.75 MW capacity are in operation [15] and one of the problems faced by these plants is availability and procurement of biomass raw materials. Development of specific biomass projects with co firing in existing coal fired power plants is increasing in India, due to the emphasis on reducing CO_2 emissions from the power plants and also the emerging opportunities under Clean Development Mechanism (CDM) of Kyoto protocol. There are many government sponsored schemes and incentives to set up biomass cogeneration and gasifier projects for the generation of thermal and electrical energy. Concern about global warming in recent decades has stimulated interest in using biomass energy which is close to carbon neutral. Production of energy from biomass crops is an important component in a portfolio of climate mitigation measures, as well as to provide a significant sustainable energy resource to displace fossil fuel resources. Though energy from biomass currently contribute a relatively small proportion to the total energy produced, the proportion is set to grow over the next few decades [16]. This will increase the demand for wood in coming years. It is estimated that by 2025, energy cropping could contribute green house gas mitigation equivalent to between 0.5% and 20% of the emission gap, between projected emissions and the emissions necessary for 550 μmol mol^{-1} CO_2 stabilisation [16].

Apart from this, in recent years, the paper industry has increased their installed capacities in view of the increased demand for paper due to the rapid population increase and consequent increase in requirement for different kinds of paper products and the emphasis on paper as an environmentally friendly packaging material. Majority of the mills are entering into contracts with local communities in the name of outgrower or joint venture schemes for producing wood [17]. The acreage under leucaena has increased rapidly in Andhra Pradesh due to the assured market, high returns from trees and supportive policies of the state government during the last decade. It is estimated that Prakasam district of Andhra Pradesh alone produces 0.7 million tonnes of wood worth of Rs. 560 million annually from private holdings of farmers [18]. Tree growing as a commercial short rotation coppice has increasingly become a profitable land use with the establishment of company/farmer relationships, trading of wood in the open market, competition among paper mills to meet their wood requirements and development of wood markets.

Plantation spacing affects management options and the final product through out the rotation. Production of saw logs, pulp or material for bio energy, for example, may be optimized with initial spacing. Although wood quality is clearly of fundamental importance to the utilization of leucaena, there is little published information on this aspect. Much of the reports are related to the alley cropping systems where the emphasis was on the use of the foliage either as fodder or as source of nutrients. Literature on silvicultural manipulation of tropical trees where in stand density levels are varied are scarce. Due to the relatively recent nature of wide spread planting of leucaena in the semi arid regions of Andhra Pradesh, little is known about the biomass production of various spacings on low to medium productivity sites under rainfed conditions. Few studies have evaluated in detail the growth patterns of leucaena at different spacings for wood production and about the biomass distribution in stemwood, stem bark, branches and foliage. The question of what is the appropriate stand density to maximize biomass productivity for both the pulpwood and fuelwood purpose is of practical significance to tree farmers, paper and fuelwood industry and planners. The present experiment was designed in this context. Our objective was to characterize leucaena growth, biomass partitioning and wood production under different densities.

2. Materials and methods

2.1. *Site description*

The study was conducted in the Khammam district of Andhra Pradesh, Southern India where the acreage under leucaena plantations is growing. Experiments were conducted on three farms in three villages within 50 km distance of the paper industry (Indian Tobacco Company-Paper Boards and Specialty Papers Limited, Sarapaka (82°52′05″E and 17°41′19″N). The field trials were conducted as Type II trials [19] with the purpose of involving farmers in technology development process and for quick adoption of the promising treatments by the surrounding farming community. While researchers were responsible for site selection, design of the experiment and data collection, farmers under the advice of researchers were responsible for all field operations such as land preparation, tree planting, fertilizer application, weeding, harvesting etc. The three locations selected for the study were within the alluvial belt of Godavari river with relatively flat landscape (about 3% slope). The soils were neutral to slightly alkaline (pH 7.0–8.3), normal in electrical conductivity (0.14–0.19 Ds m^{-1}), low in organic carbon (0.31–0.58%) and available forms of all the three major nutrients (nitrogen 63–100 kg ha^{-1}, phosphorus 9.6–12.5 kg P ha^{-1} and potassium 75–110 kg ha^{-1}) in the top 15 cm soil layer. The area receives an average annual precipitation of 1120 mm, distributed in about 60 rainy days. About 85–90% of the total rainfall is received in five months, from June to October. The annual rainfall during the study period was 1091, 784, 1486, 1058, 1526 mm in 2001, 2002, 2003, 2004 and 2005, respectively. Mean maximum temperature during the cropping period is 36.2 °C where as the mean minimum temperature is 17.1 °C.

2.2. Experimental design

Six spacing treatments, which give tree densities ranging from 1666 trees to 10,000 trees ha^{-1} were evaluated. Spacings studied were 1 × 1 m (10,000 trees ha^{-1}), 1.3 × 1.3 m (5917 trees ha^{-1}), 3 × 0.75 m (4444 trees ha^{-1}), 3 × 1 m (3333 trees ha^{-1}), 5 × 0.8 m (2500 trees ha^{-1}) and 3 × 2 m (1666 trees ha^{-1}). Except for the closer spacings of 1 × 1 m and 1.3 m × 1.3 m, remaining treatments were spaced at a minimum distance of 3 m so that cultivation between tree rows can be taken up with tractor/bullock drawn implements through out the period of rotation. At each location all the six spacings were evaluated, forming one complete replication. The experimental design was a complete randomized block design. In each treatment, the central rows were considered as net plot leaving outer 2 rows and sufficient number of trees at both the ends as border. The minimum width of a plot was 10 × 25 m where as the maximum size of the plot was 30 × 40 m depending on the availability of space at each location. The numbers of trees in the net plots were 232, 225, 119, 91, 37 and 138 in 1 × 1 m, 1.3 × 1.3 m, 3 × 0.75 m, 3 × 1 m, 3 × 2 m and 5 × 0.8 m treatments, respectively. Application of rhizobium was done as leucaena was grown for the first time in these farmers' fields. The rhizobium bacterium was isolated from the root nodules of seedlings in nursery. The rhizobium was cultured in the laboratory. The culture was mixed in water and applied to young seedlings few days after transplanting in the main field during the first year. Trees were fertilized annually from second year on-wards with 23 kg P, and 44 kg K ha^{-1}. Phosphorus was supplied through single super phosphate and potash through muriate of potash. A nitrogen dose of 20 kg N was applied in the form of urea during the first year. Fertilizers supplying the above nutrients were mixed and the material was applied in 30-cm deep holes made at a distance of 0.5 m away from the stem on either side of the row. The fertilizer was divided equally to all the trees in a plot.

2.3. Tree establishment

The experiment was conducted under rainfed conditions. The selected fields for this study were not under cultivation during the previous four seasons. The fields were plowed twice using a disc harrow and leveled. Pits of the size 0.6 × 0.6 × 0.6 m were dug manually and 100 g of single super phosphate was added to each pit and the soil was thoroughly mixed. *L. leucocephala* variety K636 was selected for the study because of its high biomass potential and uniformity in growth. The seeds of the variety were treated with hot water and sown in polythene bags filled with soil and manure mixture. Three month old 30-cm tall seedlings were transplanted in pits in August 2001. A small quantity of water was added to each pit immediately after transplanting to prevent any seedling mortality.

2.4. Tree growth and biomass production

Tree height and diameter at breast height (DBH) were measured on fifteen selected trees in each treatment at monthly intervals at all the locations. Trees were harvested after 51 months in November 2005. At harvest, tree height, collar diameter and DBH were recorded for all the trees in the net plot of every treatment. DBH of the trees was recoded at 1.37 m height from the ground level. The trees were categorized into diameter classes of 2.5 cm. Diameter classes ranged from 2.5 to 5 cm to 15–17.5 cm across all the treatments. Trees having diameter equivalent to the mid point of a particular class were harvested to study the effect of spacing on biomass partitioning. Each tree was partitioned into foliage, branches, bark and stem, and biomass of these components was quantified immediately using an electronic balance. A total of 108 trees (6 dbh classes × 6 spacings treatments × 3 locations) were harvested for recording biomass in all tree geometry treatments and at all locations. For each felled tree, bole diameter was measured at the base and top of the stump and at 3-m intervals above the base. The canopy length, canopy width and total height were also measured. A disc was sawn from approximately the middle length of every bole, and taken to the laboratory in a sealed plastic bag. Samples of leaves, bark and branches were also collected, dried at 65 °C to constant mass to determine the dry: fresh biomass ratio. Trees selected for biomass study were from the central rows and were from the net plot. All the trees in the net plot were enumerated. Based on the data, distribution of trees in the net plot was compiled and percentage of trees according to the DBH class was calculated. Based on the recorded biomass data of tree for each girth class in each treatment at each location, the tree biomass production per hectare was calculated.

2.5. Statistical analyses

The data on tree growth and biomass production of individual trees and stand productivity was analyzed following the one-way analysis as per randomized block design. Where 'F' test was significant, treatment differences were tested using LSD at 5% significance level.

3. Results and discussion

3.1. Effect of stand density on tree growth

Tree survival at harvest was significantly influenced by stand density ($p = 0.05$). Survival at harvest ranged from 93% (3 × 2 m) to 71% (1 × 1 m). Survival in 3 × 0.75 m is 88% and 83% in 5 × 0.8 m and 3 × 1 m. Significantly higher tree survival was recorded in 3 × 2 m (93%) over 1.3 × 1.3 m (79%) and 1 × 1 m spacing (71%). Though termite attack was observed during the first three months after seedling transplantation, gap filling was done and 100% of the population was maintained by the end of the first year. Strong competition between trees at

Table 1 – Height growth (m) of leucaena planted at different spacings over a 4-year period (2001–2005) in Andhra Pradesh, India (n = 15).

Treatments	2002		2003		2004		2005		
	January	July	January	July	January	July	January	July	December
1 × 1 m	2.2	3.1	5.7	6.6	8.5	9.7	11.7	12.5	13.5
1.3 × 1.3 m	2.2	3.6	6.7	7.4	9.9	11.3	13.3	14.2	15.1
3 × 0.75 m	1.7	3.2	6.1	6.7	10.6	11.8	13.1	14.4	15.8
3 × 1 m	1.8	3.2	6.4	6.7	10.4	11.3	12.9	14.2	15.7
5 × 0.8 m	1.1	2.7	6.0	6.5	10.8	11.9	13.6	14.4	15.8
3 × 2 m	2.6	3.5	6.8	7.4	10.9	12.0	13.2	14.3	16.1
SED	0.4	0.3	0.5	0.4	0.89	0.8	0.6	0.4	0.5
LSD (0.05)	NS	NS	NS	NS	NS	NS	NS	0.9	1.1

SED = Standard error of difference of means.

higher stocking levels leads to growth suppression and mortality in areas where water is limiting [20].

The mean annual height increment in leucaena ranged from 3.1 to 3.7 m yr^{-1} (Table 1). Tree height is relatively higher in 3 × 2 m spacing and lower in 1 × 1 m during the study period. Within any given year, tree height growth was almost double during July to December, coinciding with the rainy season than in January–July, which is the rain free period. Differences in tree height due to stand density treatments were significant (p = 0.05) during July 2005 and at harvest (December 2005). During these stages the highest density of 1 × 1 m recorded lower height (p = 0.05). Wider spacing resulted in higher tree height growth. At the time of harvest, 50% of trees in 1 × 1 m attained a height of 14–18 m where as 63% and 80% of trees attained that height in 3 × 2 m and 5 × 0.8 m density. Reducing tree spacing from 3 × 2 m to 3 × 1 m has found to increase tree height in *Eucalyptus grandis* and in *Eucalyptus saligna* [21]. Unlike some of the temperate trees where height growth is relatively unaffected by tree density [22], height in leucaena was significantly influenced by density and affected by competition which could be due to extremely high densities in the present study.

Spacing did have noticeable effect on diameter growth. Individual trees responded to wider spacing and lower competition with greater individual diameter growth. For example, the lower stand density at 3 × 2 m and 5 × 0.8 m recorded relatively higher DBH over higher stand density treatments through out the study period but differences were significant (p = 0.05) from the third year of tree growth (Table 2). Statistical comparison showed that highest diameter growth occurred at 3 × 2 m spacing. At harvest, individual trees in 3 × 2 m spacing recorded a DBH which was about 55% and 11% greater than that of trees in 1 × 1 m and 1.3 × 1.3 m density, respectively. Trees in 5 × 0.8 m recorded relatively higher DBH than those in 1 × 1 m. At harvest, 93% of trees in 1 × 1 m attained a DBH of 10 cm while 72%, 80% and 68% of trees attained similar DBH in 3 × 1 m, 3 × 2 m and 5 × 0.8 m treatments, respectively. About 28%, 20% and 32% of trees attained more than 10 cm DBH in 3 × 1 m, 3 × 2 m and 5 × 0.8 m treatments, respectively at harvest (Fig. 1). Decrease in diameter growth of trees with increase in density was reported in Cordia sps [23], in eucalyptus [20,21] and in 6 sub tropical rain forest tree species [24].

Canopy height and canopy width increased with the decrease in stand density but the magnitude of increase is small and non significant (P = 0.05). Canopy height ranged from 5.6 m in the case of 2.5–5 cm-diameter trees to 8.9 m in the case of 12.5–15 cm diameter trees (Table 3). Canopy width ranged from 1.5 m in 2.5–5 cm diameter trees to 3.7 m in case of 12.5–15 cm diameter trees (Table 4). At harvest, mean canopy width varied from 2.18 m in 1 × 1 m to 2.56 m in case of 3 × 2 m spacing. The ratio between crown diameter and stem diameter in leucaena did not vary significantly with density in this study. Foresters are interested in the relationship between the crown and stem diameters because a rigid ratio would limit the number of trees of a certain mean diameter in an area for any given species [25]. Dawkins [26] suggested that trees with a low ratio are suitable for pure even aged plantations than those with higher ratios, because those with lower

Table 2 – Diameter at breast height (cm) of leucaena trees planted at different spacings over a 4-year period (2001–2005) in Andhra Pradesh, India (n = 15).

Treatments	2002		2003		2004		2005		
	January	July	January	July	January	July	January	July	December
1 × 1 m	2.2	3.2	3.8	4.2	5.0	5.4	6.0	6.1	6.6
1.3 × 1.3 m	2.3	3.0	5.3	5.5	6.3	6.9	8.1	8.4	9.2
3 × 0.75 m	2.2	3.6	4.0	4.8	6.0	6.5	7.7	8.0	8.3
3 × 1 m	2.1	2.7	4.3	4.6	5.8	6.5	7.5	7.7	8.1
5 × 0.8 m	2.1	2.6	5.0	5.3	6.6	7.3	8.4	8.7	9.2
3 × 2 m	2.4	3.0	5.3	6.1	7.2	7.9	9.0	9.3	10.2
SED	0.2	0.3	0.6	0.4	0.8	0.9	0.9	1.0	1.1
LSD (0.05)	NS	NS	NS	0.93	1.86	2.09	2.10	2.33	2.5

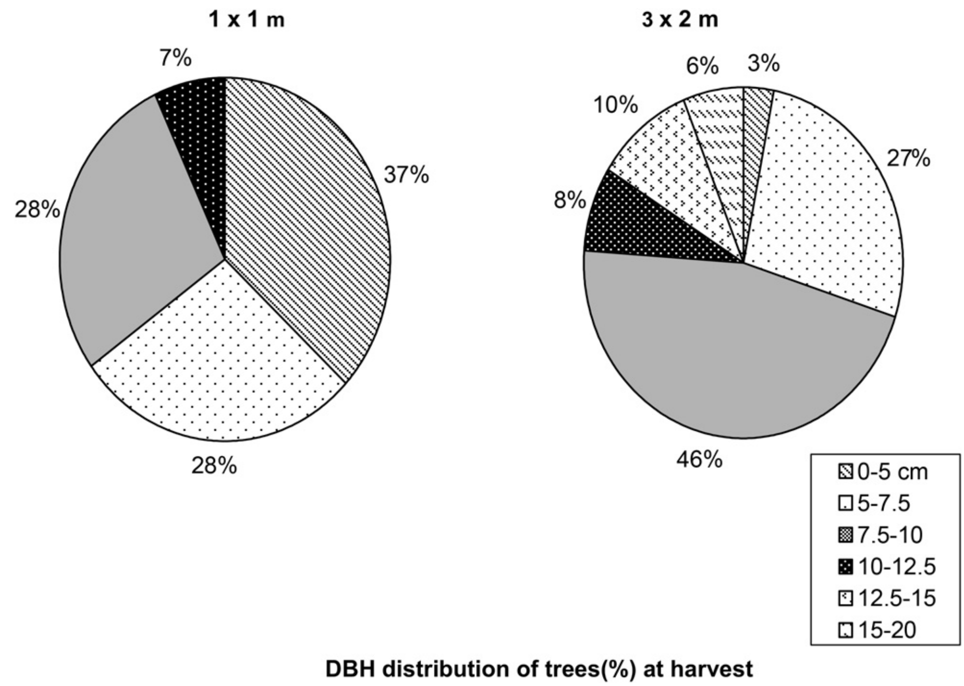

Fig. 1 – Diameter at breast height (DBH) distribution of leucaena trees (%) as influenced by different spacings at harvest (51 months after planting) in Andhra Pradesh, India (n = 232 in case of 1 × 1 m and n = 37 in case of 3 × 2 m).

ratio could support a greater basal area per unit land area. The mean ratio of leucaena in this study, 0.28, is relatively low [23], which suggest that it may be suited for monocultural stands.

Number of branches per tree increased with the reduction in stand density and differences were significant ($p = 0.05$) in large sized trees (DBH >12.5 cm). For example, in 12.5–15 cm DBH trees, 3 × 2 m density recorded on an average 11.33 branches where as 1 × 1 m density trees recorded only 5 branches. Canopy structure of trees was influenced by the stand density and trees at 3 × 2 m spacing produced large sized canopy with more width and with more number of branches in comparison to trees in 1 × 1 m and 1.3 × 1.3 m with the same DBH (Table 5).

3.2. *Effect of stand density on biomass partitioning*

Biomass accumulation in to bole increased with the increase in diameter of trees and differences were significant ($P = 0.01$) in trees with a diameter of more than 5–7.5 cm (Table 6). The mean dry weight of bole was 3.0 kg in the case of 2.5–5 cm DBH, 6.3 kg in the case of 5–7.5 cm diameter, 22.5 kg in the case of 7.5–10 cm diameter, 36.8 kg in the case of 10–12.5 cm diameter and 71.8 kg in the case of 12.5–15 cm DBH trees. With the increase in DBH, biomass of all the tree components also increased ($P = 0.01$). Relative biomass of bole to the total biomass of the tree ranged from 89.8% in the case of 2.5–5 cm DBH trees to 93% in the case of trees with 12.5–15 cm DBH. The biomass partitioning in to branches has declined from 6.6% to 3.29% where as in case of leaf it has increased from 3.6% to 4.2% with the increase in tree diameter.

Stand density influenced the biomass partitioning into bole, branches, leaf and the total dry biomass production in trees with DBH more than 7.5 cm ($p = 0.05$). Partitioning of biomass in to bole increased with the increase in tree density (Table 6). Trees in the highest stand density (1 × 1 m) partitioned 88% of the total biomass in to the stem where as the lowest stand density (3 × 2 m) partitioned only 82% in to stem in small sized trees (2.5–5 cm). However in large sized trees

Table 3 – Canopy height (m) of leucaena as influenced by different tree spacings as per different diameter classes at harvest (51 months after planting) in Andhra Pradesh, India.

Treatments	2.5–5 cm	5–7.5 cm	7.5–10 cm	10–12.5 cm	12.5–15 cm
1 × 1 m	5.3	6.8	6.7	7.9	7.9
1.3 × 1.3 m	6.2	7.5	6.4	8.5	8.0
3 × 0.75 m	5.4	6.4	7.5	8.3	9.6
3 × 1 m	5.6	6.5	7.8	8.7	9.9
5 × 0.8 m	5.4	5.7	6.8	8.7	8.0
3 × 2 m	5.9	6.6	8.1	9.0	10.3
SED	0.7	0.9	0.9	1.8	0.8
LSD (0.05)	NS	NS	NS	NS	NS

Table 4 – Canopy width (m) of leucaena as influenced by different tree spacings as per different diameter classes at harvest (51 months after planting) in Andhra Pradesh, India.

Treatments	2.5–5 cm	5–7.5 cm	7.5–10 cm	10–12.5 cm	12.5–15 cm
1 × 1 m	1.5	1.5	1.8	2.9	3.2
1.3 × 1.3 m	1.2	1.2	2.2	2.9	3.6
3 × 0.75 m	1.4	1.3	2.4	2.4	3.6
3 × 1 m	1.5	1.5	2.5	2.6	3.8
5 × 0.8 m	1.5	1.7	2.3	3.0	4.2
3 × 2 m	1.6	1.8	2.7	2.8	3.9
SED	0.2	0.1	0.4	0.6	0.5
LSD (0.05)	NS	NS	NS	NS	NS

(with DBH of 12.5–15 cm) partitioning in to bole and large sized branches gets increased to 87% in case of 3 × 2 m and 91% in case of 1 × 1 m (Fig. 2). There is a decrease in the proportion of material allocated to the bole wood with increasing spacing levels, which agrees with results of a similar study with eucalyptus [21]. In case of branches and leaf biomass, increase in spacing increased the biomass accumulation. In case of non-marketable branches the partitioning is to the extent of 9% in the lowest density (3 × 2 m) and 5% in case of the highest density (1 × 1 m) in small sized trees (2.5–5 cm). However it gets reduced to 5% in 3 × 2 m and 2% in 1 × 1 m density in large sized trees (DBH = 12.5–15). The wider spacings increased allocation to branches and leaves. Thus the net result is a decrease in allocation of available growth to the most merchantable portion of the stem, the bole wood at the widest spacing levels.

With increased competition between trees, stems will become more cylindrical [27], branch size and crown length gets reduced resulting in greater partitioning of biomass to the stem [28]. In the present study trees in the narrow spacing and higher stand density partitioned slightly more biomass in boles and less in branches and foliage than trees in lower stand densities (3 × 2 m). Similar results were also reported in loblolly pine silvopastoral stands [29] and in scots pine [30] and in *Eucalyptus europhylla* and *Eucalyptus camaldulensis* [21]. These changes in biomass partitioning can be explained by resource availability; i.e., the reduction in moisture and solar radiation available to crowns of trees at higher densities [31].

3.3. Effect of stand density on biomass production

Individual tree biomass productivity was significantly influenced by spacing. The mean total dry biomass production of a tree with DBH of 7.5–10 cm is 25.5 kg in case of 1 × 1 m and 30.4 kg/tree in 3 × 2 m. Similarly in 10–12.5 cm DBH trees, 5 × 0.8 m tree density produced 47 kg/tree where as 1 × 1 m produced a dry biomass of 38 kg/tree (data not presented). However, the per hectare biomass productivity is highest in 1 × 1 m spacing. The marketable biomass (fresh bole biomass) per hectare was highest with 1 × 1 m, which was significantly higher ($P = 0.05$) than that produced by 3 × 2 m, 3 × 1 m and 5 × 0.8 m However, differences between 1 × 1 m, 1.3 × 1.3 m and 3 × 0.75 m were not significant (Table 7). The total dry biomass has increased with the increase in the tree density. Differences in dry biomass accumulation in to bole, branch and bark were significant ($P = 0.05$). Biomass contributed by different tree parts to the total was as follows: bole > branch > bark > leaf. Leucaena in Andhra Pradesh is grown primarily for wood, which is used for manufacturing of various kinds of paper and packaging material and also as fuel for heating purpose in biomass based power industries. The entire stem and branches, which are big in size, is the marketable product when used for paper production. Specifications regarding the thickness of the stem are not being enforced and hence the total wood production is the primary criterion for evaluating the treatments for its use as pulpwood.

The sizes of stems are relatively bigger at the widest spacing levels, presumably due to higher availability of soil, moisture and light resources. However, since the density of planting ranged from 1666 stems ha^{-1} to 10,000 stems ha^{-1}, the overall productivity of a unit area of land can be quite different than the average stem size considered alone. Average trees at 3 × 2 m spacing would need to grow 6 times the weight of average trees at the 1 × 1 m spacing in order for total weights per hectare to be equal. This did not occur. At lower stand densities trees grow vigorously putting more height and diameter growth and produced large sized trees at harvest compared to higher stand densities. At harvest the

Table 5 – Number of branches in leucaena as influenced by various spacings as per different diameter classes at harvest (51 months after planting) in Andhra Pradesh, India.

Treatments	5–7.5 cm	7.5–10 cm	10–12.5 cm	12.5–15 cm
1 × 1 m	1.7	2.3	3.3	5.0
1.3 × 1.3 m	1.0	3.0	4.0	5.7
3 × 0.75 m	1.3	2.0	3.7	9.3
3 × 1 m	1.7	3.0	4.3	10.3
5 × 0.8 m	1.0	4.7	4.3	7.3
3 × 2 m	2.3	4.0	5.0	11.3
SED	0.5	0.7	1.2	2.2
LSD (0.05)	NS	NS	NS	4.9

Table 6 – Dry bole biomass production in leucaena (kg/tree) as influenced by various spacings as per different diameter classes at harvest (51 months after planting) in Andhra Pradesh, India.

Treatments	DBH classes				
	2.5–5 cm	5–7.5 cm	7.5–10 cm	10–12.5 cm	12.5–15 cm
1 × 1 m	3.5	7.1	21.8	35.6	66.4
1.3 × 1.3 m	3.0	7.1	22.9	39.3	68.4
3 × 0.75 m	2.6	5.0	18.8	31.0	70.2
3 × 1 m	2.8	5.6	20.3	34.2	75.1
5 × 0.8 m	2.8	6.1	27.7	43.4	72.0
3 × 2 m	3.2	6.7	23.6	37.1	78.7
Tree spacing	LSD (0.05)	4.8	Diameter	LSD (0.05)	4.5

number of trees attained a height of 14 m and with more than 10 cm DBH was highest with 3 × 2 stand density which resulted in highest per plant productivity. On the other hand trees in highest stand density had higher number of plants with less than 14 m height and highest number of trees with less than 10 cm diameter. However with increased stand density significant reduction in tree growth attributes were not observed resulting in highest biomass productivity per unit area. It is clear from the study that leucaena planted in wider rows result in lower per hectare yields due to decreased overall productivity and also decreased percent allocation of growth to merchantable parts. With modification of tree density the biomass yields of leucaena can exceed 15 Mg ha^{-1} year^{-1} when harvested at 4-year interval. The biomass productivity of the cultivar K636 of leucaena is comparable to that of eucalyptus clones under similar rainfall situations [32] and with relatively low inputs in to the system. Some of the *L. leucocephala* accessions like cv. Tarramba, produced biomass of 26 kg/tree over 2 year period under cool winter climate of Brisbane [33]. Mishra et al. [34] reported annual yields 23–43 Mg ha^{-1} year^{-1} for *L. leucocephala* in Uttar Pradesh, India. The high productivity could be due to coppicing which would result in 4–6 shoots with less girth used for firewood purpose. Allowing 4–6 shoots could be an advantage when total biomass yield was the main objective, but would be a disadvantage if poles or logs or pulpwood were the ultimate aim of the plantation.

L. leucocephala has excellent pulping qualities and it is one of the most valued tropical hardwoods for paper and rayon manufacture. The bark can be easily removed and low levels of extractives and lignin combined with holocellulose content produce a high pulp yield of 50%–52% [35]. The lignin content in leucaena wood ranges from 17 to 21% [36]. Paper industry during the periods of abundant supplies of wood imposes restrictions on the minimum diameter requirements of stem. In such cases the minimum diameter prescribed is about 5 cm. In the paper manufacturing process removal of lignin leads greater consumption of chemicals leading to the escalation of cost of production and also results in the pollution problems. Bark has relatively higher proportion of lignin than the wood.

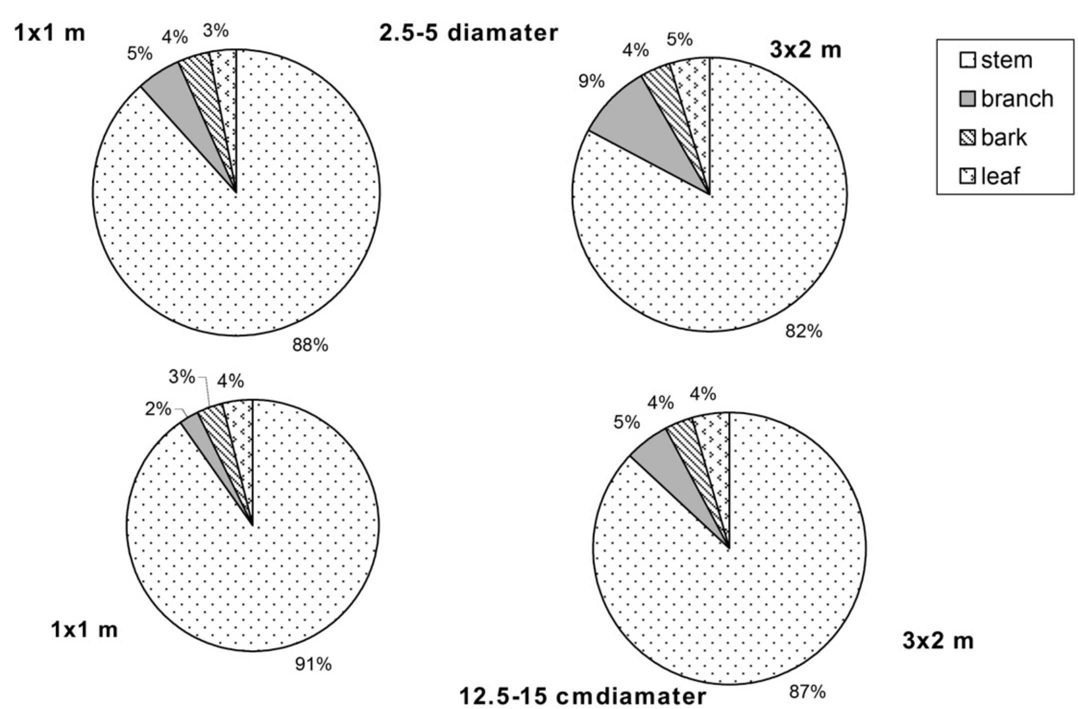

Fig. 2 – Biomass partitioning in to various components in different diameter sizes of leucaena trees influenced by spacings at the time of harvest (51 months after planting) in Andhra Pradesh, India.

Table 7 – Fresh and dry biomass (Mg ha^{-1}) of different parts of leucaena planted in different spacings at harvest (51 months) at Bhadrachalam in Andhra Pradesh, India.

Treatments	Marketable bole biomass (bole) Fresh wt (Mg ha^{-1})	Dry biomass production				
		Bole	Branch	Leaf	Bark	Total
1 × 1 m	144.9	81.0	4.9	2.2	4.3	92.4
1.3 × 1.3 m	124.6	70.6	3.4	1.9	3.2	79.2
3 × 0.75 m	136.6	78.1	3.8	1.5	3.7	87.1
3 × 1 m	113.9	65.9	3.0	1.2	2.9	73.0
5 × 0.8 m	117.4	68.6	3.7	2.1	2.7	76.9
3 × 2 m	94.8	52.1	2.6	1.4	2.4	58.5
SED	10.7	6.3	0.9	0.5	0.6	7.1
LSD (0.05)	23.8	14.1	2.1	NS	1.4	15.7

Low lignin content results in low pulping time, reduced energy and chemical use during pulping [37]. In the present study the bark content was found to be about 4.2% on dry weight basis in 5 cm diameter stems where as it has got reduced to 2% in case of 10–15 cm diameter stems. Growing leucaena at closer spacings gives more shoots of smaller diameter, more bark leading to the increase in the cost of paper manufacture for the removal of lignin. Small diameter stems are difficult to store in the open due to the attack from wood eating beetles, resulting in greater losses in storage. The percentage of stems with less than 5 cm diameter are highest in case of 1 × 1 m spacing (37%) closely followed by 1.3 × 1.3 m (23%) and 3 × 0.75 m (22%) and 3 × 1 m (14%). The corresponding bole biomass production of stems with less than 5 cm diameter is about 12.5, 4.5 and 4.1 Mg ha^{-1} in 1 × 1 m, 1.3 × 1.3 m and 3 × 0.75 m, respectively. The marketable bole biomass production (with >5 cm dbh) in such situations is highest in case of 1 × 1 m (132 Mg ha^{-1}) followed by 3 × 0.75 m (122 Mg ha^{-1}) followed by 1.3 × 1.3 m (120 Mg ha^{-1}). In case of wider spacings such as 3 × 2 and 5 × 0.8 m the biomass contribution from stems with less than 5 cm diameter is negligible.

The value of wood as a fuel is determined principally by its specific gravity. Van Den Beldt and Brewbaker [38] reported *L. leucocephala* variety K636 as being of medium in density and specific gravity ranges from 0.45 to 0.59, a value that compared favorably with other commonly grown fuelwood species such as *Gliricidia sepium*, *Albizia* spp. *Calliandra calothyrsus* and *Prosopis juliflora* [11]. With a calorific value of between 4200 and 4670 kcal/kg [30], leucaena is comparable to other fast growing non resinous hardwoods. Due to this there has been recent interest in using leucaena to produce industrial energy. Panshin and de Zeeuw [39] observed little variation among tree species of leucaena in the heat produced by a unit of dry weight of oven dry wood. Non significant differences were also observed in calorific value between the heartwood and sap wood, between the heartwood and sap wood with age and wood samples from different tree positions in eucalyptus of a similar age [40]. Considering this it is the total biomass which is important for fuelwood production irrespective of diameter of stems.

4. Conclusions

In view of the uncertainties associated with market and prices associated with the end use, either as pulp or for fuel, it is wise to adopt a spacing which can take advantage of both the situations keeping in view the long term nature of the plantations. Hence a spacing of 3 × 0.75 m not only produces biomass comparable to 1 × 1 m, but also contains large sized trees. Inter row spacing of 3 m provides an opportunity for the performance of intercultural operations, tillage, and impositions of soil and water conservation practices in tree based systems which are essential to reduce runoff and infiltration particularly in the early stages of tree growth as these systems are grown under rainfed situations. The spacing of 3 × 0.75 m also facilitates intercropping during the first year of tree growth and provides additional income. Hence 3 × 0.75 m is advisable rather than 1 × 1 m and 1.3 × 1.3 m spacing in leucaena for wood production.

Acknowledgements

We would like to thank the Indian Council of Agricultural Research for funding this project through Cess fund and National Agricultural Technology Project (NATP-RNPS 26).

REFERENCES

[1] Argel PJ, Lascano CE, Ramirez L. Leucaena in Latin American farming systems: challenges for development. Paper presented at the workshop: leucaena – adaptation, quality and farming systems, held in Hanoi (Vietnam) from 9-14 February, 1998. Available on line, http://webapp.ciat.cgiar.org/tropileche/articulos.pdf/leucaen.pdf.

[2] Shelton HM, Jones RJ. Opportunities and limitations in Leucaena. In: Shelton HM, Piggin CM, Brewbaker JL, Editors. Leucaena opportunities and limitations: proceedings of a workshop held in Bangor, Indonesia. Canberra: ACIAR Proceedings; 1995. p. 16–23.

[3] Huxley PA. Tropical agroforestry. Malden, Massachusetts, USA.: Blackwell Science; 1999. 389.

[4] Dagang BKA, Nair PKR. Silvopastoral research and adoption in Central America: recent findings and recommendations for future directions. Agrofor Syst 2003;59:149–55.

[5] Shelton HM, Piggin CM, Brewbaker JL, Editors. Leucaena opportunities and limitations: proceedings of a workshop held in Bangor, Indonesia. Canberra: ACIAR Proceedings; 1995. p. 136–219.

[6] Meelu OP, Morris RA. Green manuring research in the Philippines – a review. Philipp J Crop Sci 1986;111:53–9.

[7] Savale SR, Sanglikar RV, Sthool VA. Effect of Leucaena leucocephala barriers and bund on erosion losses and yield of pearlmillet + mothbean. Asian J Soil Sci 2007;2:142–5.
[8] Mugwe J, Mucheru-Muna M, Mugendi D, Kung'u J, Bationo A, Mairura F. Adoption potential of selected organic resources for improving soil fertility in the central highlands of Kenya. Agrofor Syst 2009;76:467–85.
[9] Kang BT, Caveness FE, Tian G, Kolawole GO. Long term alley cropping with four hedgerow species on an Alfisol in southwestern Nigeria – effect on crop performance, soil chemical properties and nematode population. Nutr cycl in Agroekosyst 1999;54:145–55.
[10] Rao YV. Leucaena plantations – a farming experience. Leucaena Res Rep 1984;5:48–9.
[11] Pottinger AJ, Hughes CE. A review of wood quality in Leucaena. In: Shelton HM, Piggin CM, Brewbaker JL, Editors. Leucaena opportunities and limitations: proceedings of a workshop held in Bangor, Indonesia, 1995. ACIAR Proceedings, Canberra. P. 98–102.
[12] Malik RS, Dutt D, Tyagi CH, Jindal AK, Lakharia LK. Morphological, anatomical and chemical characteristics of Leucaena leucocephala and its impact on pulp and paper making properties. J Sci Ind Res 2004;63:125.
[13] Puri S, Nair PKR. Agroforestry research for development in India: 25 years of experiences of a national program. Agrofor Syst 2004;61:437–52.
[14] Kulkarni HD. Private farmer and private industry partnerships for industrial wood production: a case study. Int For Rev 2008;10:147–55.
[15] Nedcap. Non conventional energy development corporation of Andhra Pradesh limited. Available at, http://www.nedcap.gov.in/biomassenergy.html; 2008.
[16] Sims RH, Hastings A, Schlamadinger B, Tailor G, Smith P. Energy crops: current status and future prospects. Global Change Biol 2006;12:2054–76.
[17] Saxena NC. Wood markets for farm eucalyptus in northwest India. In: Saxena NC, Ballabh V, Editors. Farm Forestry in South Asia. New Delhi, India: Sage Publications; 1995.
[18] Saigal S, Kashyap D. The second green revolution: analysis of farm forestry experience in western tarai region of Uttar Pradesh and coastal Andhra Pradesh. New Delhi: Ecotech Services Private Limited; 2002. 180.
[19] Franzel S, Sherr SJ. Trees on the farm: assessing the adoption potential of agroforestry practices in Africa. CABI; 2002.
[20] Pinkard EA, Neilsen WA. Crown and stand characteristics of *Eucalyptus nitens* in response to initial spacing: implications for thinning. For Ecol Management 2003;172:215–27.
[21] Bernando A, Maria Reis L, Geraldo Reis GF, Robert Harrison G, Deuseles Firme BJ. Effect of spacing on growth and biomass distribution in *Eucalyptus camaldulensis, E. pellita, E. europhylla* plantations in southeastern Brazil. For Ecol Management 1998;104:1–13.
[22] Daniel T, Helms J, Baker FS. Principles of silviculture. 2nd ed. New York: McGraw-Hill; 1979. 500.
[23] Hummel S. Height, diameter and crown dimensions of Cordia alliodora associated with tree density. For Ecol Manage 2000;127:31–40.
[24] Grant JC, Nichols D, Pelletier MC, Glencross K, Bell R. Five year results from a mixed-species spacing trial with six sub tropical rainforest tree species. For Ecol Manage 2006;233:309–14.
[25] Philip MS. Measuring trees and forests. Wallngford, UK: CAB International; 1994.
[26] Dawkins HC. Crown diameters: their relation to bole diameter in tropical forest trees. commonw For Rev 1963;42: 318–33.
[27] Muhairwe CK. Tree form and taper variation over time for interior lodgeole pine. Can J For Res 1994;24:1904–13.
[28] Neilsen WA, Gerrand AM. Growth and branching habit of *Eucalyptus nitens* at different spacings and the effect on final crop selection. For Ecol Management 1999;123:217–29.
[29] Ares A, Brauer D. Above ground biomass partitioning in loblolly pine silvopasture stands: spatial configuration and pruning effects. For Ecol Management 2005;219:176–84.
[30] Kellomaki S, Oker-Blom P, Valtonen E, Vaisanen H. Structural development of scots pine stands with varying initial density: effect of pruning on branchiness of wood. For Ecol Management 1989;1989(27):219–33.
[31] Nilsson U, Hallgren JE. Changes in growth allocation owing to competition for light in young fertilized Norway spruce trees. For Ecol Management 1993;62:157–72.
[32] Lal P, Kulkarni HD, Srinivas K, Venkatesh KR, Santa kumar P. Genetically improved clonal planting stock of Eucalyptus-a success story from India. Indian Forester 1997;123:1117–38.
[33] Mullen BF, Gutteridge RC. Wood and biomass production of Leucaena in sub tropical Australia. Agrofor Syst 2002;55: 195–205.
[34] Mishra PN, Tewari SK, Dheer S, Katiyar RS, Singh D. Effect of coppicing height on the regeneration and productivity of certain firewood shrubs in alkaline soils of North Indian plains. Biomass Bioenergy; 1995:459–63.
[35] MacDicken KG, Brewbaker JL. Descriptive summaries of economically important nitrogen fixing trees. Nitrogen Fixing Tree Reports 1982;2:46–54.
[36] Lopez F, Garcia MM, Yanez R, Tapias R, Fernandez MJ, Diaz MJ. Leucaena species valoration for biomass and paper production in 1 and 2 year harvest. Bioresour Technol 2008; 99:4846–53.
[37] Diaz MJ, Garcia MM, Eugenio ME, Tapias R, Fernandez M, Lopez F. Variations in fiber length and some pulp chemical properties of Leucaena varieties. Ind Crops Prod 2007;26: 142–50.
[38] Van Den Beldt RJ, Brewbaker JL. Leucaena wood production and use. Hawaii: Nitrogen Fixing Tress Association; 1985. 50.
[39] Panshin AJ, de Zeeuw C. Textbook of wood technology, vol. 1. McGraw-Hill; 1970. 705.
[40] Lemenih M, Bekele T. Effect of age on calorific value and some mechanical properties of three Eucalyptus species grown in Ethiopia. Biomass Bioenergy 2004;27:223–32.