Growth, Biomass Productivity and Energy Characteristics of *Prosopis juliflora* (Sw.) DC. and *Leucaena leucocephala* (Lam.) De Wit in Afar Region, Ethiopia

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ABSTRACT

The performance of *Prosopis juliflora* and *Leucaena leucocephala* was investigated at plant spacings of 1 × 0.5, 1 × 1, 1 × 1.5, 1 × 2 and 1 × 2.5 m corresponding to a tree density of 20,000, 10,000, 6,666, 5,000 and 4,000 ha^{-1}, respectively, to identify the most suitable plant spacing for the optimum biomass harvest per unit area. The overall performance of *L. leucocephala* was superior to *P. juliflora* under most parameters measured, except for the calorific value. The performance of both species in terms of the plant height, stem diameter and number of trunks was affected by the population density at age 6 mths and there were significant increases at wider spacings (1 × 2 and 1 × 2.5 m) when the age advanced to 12 mth. There were significant differences in the biomass production per tree and better total above ground biomass results were obtained with plantings at wider spacings at both 6 and 12 mth of age. However, the total above ground biomass yield per hectare of both species increased markedly with increasing plant density at both 6 and 12 mth of age and this revealed that both species can be grown at closer spacing (1 × 0.5 m).

Keywords: *Prosopis juliflora*, *Leucaena leucocephala*, spacing, plant growth, biomass yield

INTRODUCTION

The majority of the Afar region of Ethiopia is characterized by arid environmental conditions and ecological degradation triggered by overgrazing (Abule *et al.*, 2005). The prevailing conditions in the region make the need for tree plantations a major priority. Although many native and exotic tree species were screened for other parts of Ethiopia during the last three decades, the most suitable tree species to be planted in the Afar region have still not been identified. Nevertheless, *Prosopis juliflora* (Sw.) DC. was introduced to the Afar region in the late 1970s and early 1980s by foreigners working in the Middle Awash irrigation project without prior research work about the nature of the plant. Since then, its invasion has escalated markedly from time to time and it has become one of the top three invasive species in Ethiopia and has been declared a noxious weed (Yibekal, 2012).

Although *P. juliflora* was successfully introduced to prevent soil erosion and desertification, its recent uncontrolled spread has

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Received date : 27/05/13 Accepted date : 18/07/13

created major concern. Afar pastoral and agro-pastoral communities are complaining about this tree species, citing problems associated with its invasiveness, thorniness, its effects on rangeland vegetation, invasion of water courses and its impact on the environment through loss of biodiversity (Berhanu and Tesfaye, 2006). In contrast to these claims, there is a growing demand for its products from the major cities for fuelwood, charcoal and other purposes (Berhanu and Tesfaye, 2006) and it is a fast-growing tree, tolerant to saline soils (Rim *et al.*, 2009) and grows well on heavy-metal-laden industrial sites (Usha *et al.*, 2009). Accordingly, the survival and performance of *P. juliflora* in the region require study with regard to its growth and wood production for proper management.

Besides studying the management of *P. juliflora*, identifying the most promising multipurpose tree that can be used to replace the plant is one of the intervention areas with high priority. It is believed that adopting a tree species to be planted over a large scale must take in consideration its ability to cope with the prevailing environmental conditions in terms of survival and growth, and to offer additional benefits to the community (Aref *et al.*, 1999). Among the potential legume species, *Leucaena leucocephala* (Lam.) de Wit is very attractive because of its adaptation to a wide range of soil and climatic conditions and its fast growth and ease of propagation (Brewbaker and Sorensson, 1993).

The genus *Leucaena* is reported to contain 16 species of which *L. leucocephala* is the most widely planted species as it is the most common leguminous tree for forage, fuel, stabilizing sloping soils, fixing atmospheric nitrogen and providing green manure (Brewbaker and Sorensson, 1993). However, information is lacking about the survival and growth of *L. leucocephala* under the prevailing conditions in the Afar region. Therefore, the growth and biomass production of *P. juliflora* and *L. leucocephala* in relation to plant density were investigated in the current study.

MATERIALS AND METHODS

Location of study area and site details

The study was conducted in the Dubti district of the Afar region of Ethiopia situated between 11° 46′N latitude and 41° 05′E longitude at an altitude of 375 m above sea level. The area is characterized by hot and dry climatic conditions (Yibekal, 2012) that include: an annual rainfall of 150–300 mm, 80% of which is concentrated in the months of July–September; a mean maximum temperature during the cropping period is 37.2 °C whereas the mean minimum temperature is 21.7 °C; and soils in the top 30 cm layer being slightly alkaline (pH 8.3), normal in electrical conductivity (1.42 $dS.m^{-1}$) and medium in organic carbon (1.88%), total nitrogen (0.44%), available forms of phosphorus (12.8 ppm) and potassium (383 ppm).

Experimental design and tree establishment

The experimental design was a split plot design with three replications, using the two tree species as a main plot and five plant spacings (1 × 0.5, 1 × 1, 1 × 1.5, 1 × 2 and 1 × 2.5 m corresponding to a tree density of 20,000, 10,000, 6,666, 5,000 and 4,000 ha^{-1}, respectively) as subplots. The area of each plot was 50 m^2 whereas each block was 250 m^2. The fields were plowed twice using a disc harrow and leveled. Pits (0.6 × 0.6 × 1 m, width by length by depth) were dug manually and the hole refilled with the original soil plus manure. Mechanical scarification of both *P. juliflora* and *L. leucocephala* cv K636 seeds was carried out by immersing in boiling water and allowing to cool for 24 hr. Seedlings were raised in polythene bags (15 × 25 cm), filled with a mixture of sand, soil and farmyard manure in a 1:1:1 ratio. Seedlings aged 2 mth (average height of 30 cm) were transplanted into the experimental plots on

20 August 2010. The seedlings were irrigated once a week for the first 2 mth after transplanting and twice a month until harvesting. The plantations were not subjected to pruning, thinning or any other silvicultural practices except weeding and hoeing. No fertilizer application was practiced.

Tree growth and biomass production

The tree height was measured on 15 selected trees in each treatment at monthly intervals. Sample trees were harvested after 6 mth and 12 mth in January 2011 and July 2011, respectively. At harvest, the tree height, root length, number of trunks and stem diameter were recorded on five randomly selected plants. The stem diameter was recorded at 1.3 m height from the ground level. Each tree was partitioned into leaves, branches and stem, and the biomass of these components was quantified immediately. Samples of the stem, leaves and branches were taken, dried at 65 °C until constant mass and then the dry biomass of each portion was determined. The total dry biomass and biomass allocation to each component of each tree were calculated. The tree above ground biomass (TAB) production per hectare was calculated based on the recorded biomass data of the trees in each treatment. The main root length of each sample tree was obtained through destructive methods.

Sampling and analysis

The thermochemical properties (specific gravity, moisture content, calorific value and ash) of the wood samples of both species were determined only for plants aged 12 mth. Parts of the oven-dried samples were ground to pass through a 30 mm sieve and were used for ash and calorific value analysis. A total of 10 discs (each 2.5 cm thick) were cut from along the length of each sample tree. These were oven dried at 103 ± 2°C, weighed and dipped into hot paraffin to give the samples a waterproof coating and re-weighed. The weight of an equal volume of water was determined by the water displacement method as described in the standard and suggested methods of Technical Association of the Pulp and Paper Industry (1972). The specific gravity of the stem was then calculated as the ratio of the oven-dry weight of the disc over the weight of an equal volume of water. For determination of the calorific value, powdered samples were again dried at 70 °C for 24 hr and pressed into pellets. A Parr oxygen bomb calorimeter, (Model 1341; Parr Instrument Company; Moline, IL, USA) was used for determination of the heat of combustion. The calorific value of the prepared sample capsule was determined using an adiabatic calorimeter at the Central Geological Laboratory, Hydrocarbon Division of the Ethiopian Geological Survey Authority.

Statistical analysis

Analyses of variance were applied to test for the existence of statistical differences in the plant height, stem diameter, biomass yield, ash composition, specific gravity and calorific values between the two species as well as between different plant spacings. Significantly different means were separated using the least significant difference at the 5% level of significance.

RESULTS AND DISCUSSION

The analysis of variance procedure showed that *L. leucocephala* and *P. juliflora* trees differed significantly across treatment in most of the growth characteristics measured in the present study (Table 1). *L. leucocephala* trees had a greater number of trunks ($P < 0.05$) and greater plant height ($P < 0.01$), stem diameter ($P < 0.01$), root length ($P < 0.05$), leaf biomass ($P < 0.01$), and total above ground biomass per tree ($P < 0.01$) than *P. juliflora* at age 6 mth. However, *P. juliflora* surpassed *L. leucocephala* only in the branch biomass yield per tree which was significantly higher. The growth nature of both species followed a similar trend and

L. leucocephala trees had a significantly higher ($P < 0.05$) height, stem diameter, number of tillers and root length than *P. juliflora* at age 12 mth.

The dry matter partitioning to tree parts also differed significantly between the two species (Table 1). At age 12 mth, *L. leucocephala* trees had significantly higher mean leaf, stem and total dry weights per tree than those of *P. juliflora* by 17, 43 and 24%, respectively. The significant differences in dry matter accumulation continued to age 12 mth when the mean leaf, stem and total dry weights per tree of *L. leucocephala* were significantly higher than *P. juliflora* by 9, 18 and 22%, respectively. Compared with *L. leucocephala*, the branches of *P. juliflora* comprised a better proportion of the total weight of the trees. This may reflect the growth nature of *P. juliflora* as it has a spreading, umbrella-shaped crown of thick branches (El-Keblawy and Al-Rawai, 2007).

The mean values of the stem biomass yield per hectare of *P. juliflora* were lower by 43 and 37% from that of *L. leucocephala* at age 6 and 12 mth, respectively. The estimated foliage production of *L. leucocephala* trees in the present study was 6.66 $t.ha^{-1}$ compared with 5.5 $t.ha^{-1}$ for *P. juliflora* trees at age 12 mth. This result was higher than the foliage production (2.26 $t.ha^{-1}$) of 2 yr-old *L. leucocephala* grown at 2 × 1 m spacing in Saudi Arabia. This discrepancy may have been the result of the variation in the site characteristics (soil fertility, row spacing, rainfall and temperature) where the trees were grown (Aref *et al*., 1999).

There was a difference in plant parts accumulation; *L. leucocephala* trees allocated 16, 19 and 65% to their stem, branches and leaves, respectively, whereas *P. juliflora* trees allocated 19, 28 and 53% to their stem, branches and

Table 1 Tree growth and wood traits of *P. juliflora* and *L. leucocephala* at 6 and 12 mth after planting in Afar Region, Ethiopia.

Parameter	6 Month mean			12 Month mean		
	PJ	*LL*	Significance	*PJ*	*LL*	Significance
Plant height (m)	1.84^b	2.03^a	**	5.11^b	5.22^a	*
Stem diameter (cm)	1.60^b	2.10^a	**	3.20^b	5.10^a	**
Number of trunk	2.70^b	11.10^a	***	4.31^b	12.76^a	***
Root length (m)	2.16^b	2.28^a	*	3.10^b	3.29^a	*
Stem biomass ($kg.tree^{-1}$)	0.96^b	1.69^a	***	2.09^b	2.68^a	***
Branch biomass ($kg.tree^{-1}$)	0.50^a	0.48^b	*	1.18^a	0.87^b	**
Leaf biomass ($kg.tree^{-1}$)	0.35^b	0.42^a	**	0.64^b	0.78^a	*
TAB ($kg.tree^{-1}$)	1.81^b	2.39^a	**	3.91^b	4.33^a	*
Stem biomass ($t.ha^{-1}$)	8.45^b	13.48^a	*	18.39^b	23.99^a	**
Branch biomass ($t.ha^{-1}$)	4.46^a	4.34^a	ns	7.54^b	10.35^a	ns
Leaf biomass ($t.ha^{-1}$)	3.13^a	3.78^a	*	5.50^b	6.66^a	*
TAB ($t.ha^{-1}$)	16.04^b	21.60^a	**	34.23^b	38.19^a	**
Calorific value ($kJ.kg^{-1}$)	–	–	–	20.91^a	19.60^b	***
Ash (%)	–	–	–	2.24^a	1.93^b	**
Specific gravity	–	–	–	0.72^a	0.52^b	**

Means followed by the same lowercase superscript letter within a row are not significant ($P < 0.05$) at 6 and 12 mth after planting; * = ($P < 0.05$); ** = ($P < 0.01$); *** = ($P < 0.001$); ns= Not significant; TAB = Total above ground biomass; PJ = *P. juliflora*; LL = *L. leucocephala*; Stem diameter = Stem diameter over bark measured at 1.3 m.

leaves, respectively. The branches of *P. juliflora* comprised a larger proportion (28% on average) and the stems a lower proportion (53%) of the total weight of tree compared to *L. leucochephala* whose stem parts were substantially larger than those of *P. juliflora* trees.

Even though the performance of both species endured hot environmental conditions in terms of maintaining reasonable growth, the performance of *L. leucocephala* was better than that of *P. juliflora* based on most parameters. Although the superiority of *P. juliflora* over several other species has been reported in traits like growth and biomass production (Ashori and Nourbakhsh, 2008), *L. leucocephala* demonstrated its potential for biomass production in the Afar region. The higher biomass production from *L. leucocephala* in the current study was due to the alkalinity of the soil, optimum soil fertility and higher temperature (Nazarian *et al.*, 2004). MacDicken and Brewbaker (1982) reported that *L. leucocephala* cv Tarramba at a plant spacing of 1 ×1 m produced biomass of 26 $kg.tree^{-1}$ over a 2 yr period under the cool winter climate of Brisbane, Australia. Singh and Toky (1995) also reported a yield of 111.76 $t.ha^{-1}$ in above ground biomass at a plant spacing of 0.6 × 0.6 m over a 4 yr growing period in India. However, the yield obtained at age 12 mth in the current study showed the possibility of achieving higher biomass with an increased growing period.

The calorific value of the *P. juliflora* stem was significantly higher ($P < 0.01$) than that of *L. leucocephala* (20.91 and 19.60 $kJ.kg^{-1}$, respectively). Similarly, the specific gravity of *P. juliflora* was significantly higher ($P < 0.01$) than that of *L. leucocephala*. However, the ash content of *P. juliflora* was significantly lower ($P < 0.05$) than that of *L. leucocephala*. Since wood properties may also vary with position in the stem and crown (Kataki and Konwer, 2001; Lemenih and Bekele, 2004), further research is necessary to investigate variation within trees in order to provide recommendations for the most efficient use of the tree parts. Even though the calorific values of *P. juliflora* were higher than *L. leucocephala*, other bases of superiority in phenotypic characters such as thornlessness and manageability should be considered.

Plant spacing effect

P. juliflora

The mean plant height of *P. juliflora* ranged from 1.79 to 1.89 m and from 4.98 to 5.20 m at age 6 and 12 mth, respectively (Table 2). The differences in the plant height of *P. juliflora* due to stand density treatments were significant ($P < 0.05$). At age 6 mth, the plant height was significantly lower at the 1 × 0.5 m spacing than at any other spacing. The effect was more obvious when the *P. juliflora* was aged 12 mth. Accordingly, the tree height was relatively higher at the wider spacings (1 × 1.5, 1 × 2 and 1 × 2.5 m) and there was no significant difference between the closer plant spacings (1 × 0.5 and 1 × 1 m). A significantly higher ($P < 0.05$) plant height was recorded at the wider plant spacings (1 × 2.5 and 1 × 2 m) compared to the other densities. Both the height and diameter growth were significantly lower at the densest spacing compared to the wider-spaced stands. It has been reported that height growth responded to planting density earlier than did diameter growth and that the relative growth rates of trees were reduced at denser spacings (El-Keblawy and Al-Rawai, 2005).

A relatively higher stem diameter of *P. juliflora* was recorded at the lower stand densities (1 × 2 and 1 × 2.5 m) over the treatments involving closer plant spacing (Table 2). The significant influence of plant spacing on stem diameter was not observed in *P. juliflora* aged 6 mth. However, a significantly lower diameter was recorded at closer plant spacings (1 × 0.5 and 1 × 1 m) at age 12 mth. The increasing stem diameter and height of trees with the increasing distance between trees

Table 2 Spacing effect on growth performance and biomass production of *P. juliflora* in the Afar Region.

Parameter	Tree age (mth)	Plant spacing (m)					Significance
		1×0.5	1×1	1×1.5	1×2	1×2.5	
Plant height (m)	6	1.79^{b}	1.80^{ab}	1.84^{ab}	1.89^{a}	1.87^{ab}	*
	12	4.98^{c}	5.07^{bc}	5.14^{ab}	5.17^{a}	5.20^{a}	**
Stem diameter (cm)	6	1.50^{a}	1.50^{a}	1.60^{a}	1.70^{a}	1.80^{a}	ns
	12	2.60^{c}	3.10^{b}	3.40^{a}	3.50^{a}	3.60^{a}	*
Number of trunk	6	2.50^{a}	2.64^{a}	2.70^{a}	2.88^{a}	2.80^{a}	ns
	12	3.36^{d}	4.10^{c}	4.36^{bc}	4.82^{ab}	4.92^{a}	***
Root length (m)	6	2.11^{a}	2.09^{a}	2.18^{a}	2.21^{a}	2.21^{a}	ns
	12	2.90^{d}	3.04^{c}	3.13^{b}	3.21^{a}	3.26^{a}	***
Stem (kg.tree^{-1})	6	0.87^{b}	0.91^{b}	0.98^{a}	1.02^{a}	1.03^{a}	*
	12	1.88^{c}	2.01^{b}	2.17^{a}	2.17^{a}	2.22^{a}	*
Branch (kg.tree^{-1})	6	0.47^{a}	0.48^{a}	0.50^{a}	0.52^{a}	0.52^{a}	ns
	12	1.03^{c}	1.17^{b}	1.23^{a}	1.23^{a}	1.24^{a}	*
Leaf (kg.tree^{-1})	6	0.33^{a}	0.34^{a}	0.35^{a}	0.37^{a}	0.37^{a}	ns
	12	0.54^{c}	0.61^{b}	0.68^{a}	0.68^{a}	0.69^{a}	*
TAB (kg.tree^{-1})	6	1.68^{c}	1.73^{bc}	1.83^{ab}	1.91^{a}	1.91^{a}	**
	12	3.45^{c}	3.79^{b}	4.08^{a}	4.09^{a}	4.15^{a}	**
Stem (t.ha^{-1})	6	17.48^{a}	9.06^{b}	6.52^{c}	5.10^{d}	4.10^{e}	***
	12	37.68^{a}	20.10^{b}	14.45^{c}	10.85^{d}	8.87^{e}	***
Branch (kg.ha^{-1})	6	9.44^{a}	4.80^{b}	3.36^{c}	2.61^{d}	2.07^{e}	***
	12	20.68^{a}	11.72^{b}	8.21^{c}	6.17^{d}	4.96^{e}	***
Leaf (kg.ha^{-1})	6	6.60^{a}	3.44^{b}	2.33^{c}	1.83^{d}	1.46^{e}	***
	12	10.72^{a}	6.06^{b}	4.56^{c}	3.41^{d}	2.75^{e}	***
TAB (t.ha^{-1})	6	33.52^{a}	17.30^{b}	12.21^{c}	9.54^{d}	7.64^{e}	***
	12	69.08^{a}	37.88^{b}	27.22^{c}	20.43^{d}	16.58^{e}	***
Calorific Value (kJ.kg^{-1})	12	20.88^{a}	20.90^{a}	20.93^{a}	20.83^{a}	21.00^{a}	ns
Ash (%)	12	2.24^{a}	2.24^{a}	2.26^{a}	2.26^{a}	2.19^{a}	ns
Specific gravity	12	0.70^{a}	0.74^{a}	0.73^{a}	0.72^{a}	0.74^{a}	ns

Means followed by the same lowercase superscript letter within a row are not significant ($P < 0.05$) at 6 and 12 mth after planting; * = ($P < 0.05$); ** = ($P < 0.01$); *** = ($P < 0.001$); ns= Not significant; TAB = Total above ground biomass.

might have been a result of the exploitation of the same available below-ground resources (water and nutrient) by fewer trees (Ong and Leakey, 1999).

There was no significant difference in the number of trunks of *P. juliflora* at age 6 mth. However, a significant difference ($P < 0.05$) was observed at age 12 mth and there was an increase in the number of trunks with a reduction in stand density. Trees planted at the 1 × 0.5 m spacing produced the lowest number of trunks compared to the other spacings.

The length of the main root of *P. juliflora* did not show a significant difference ($P < 0.05$)

among spacing treatments at age 6 mth, but wider spacings (1 × 2 and 1 × 2.5 m) produced longer roots than trees planted more closely at age 12 mth.

The biomass partitions and total above ground biomass per tree of *P. juliflora* at age 6 and 12 mth are presented in Table 2. The stem biomass yield of the plant was affected by spacing at age 6 mth and a significantly lower ($P < 0.05$) biomass yield per tree was recorded at the closer spacings (1 × 0.5 and 1 × 1 m). However, there were no significant differences among the 1 × 1.5, 1 × 2 and 1 × 2.5 m spacing treatments at age 6 mth. Similarly, there were no significant differences in both the branch and leaf biomass per tree of *P. juliflora* at age 6 mth, while a significantly lower above ground biomass yield per tree was recorded at the closer spacings (1 × 0.5 m and 1 × 1 m), but there was no significant difference between the 1 × 1.5, 1 × 2 and 1 × 2.5 m spacing treatments. Srivastava *et al.* (1999) also reported that *Terminalia arjuna* trees at wider spacings had higher individual biomass than those at closer spacings. Even though the biomass yield of *P. juliflora* per tree was higher at the wider spacing, its total above ground biomass yield per hectare increased with increasing plant density (Table 2).

The stem, branch, leaf and total above ground biomass of *P. juliflora* did not show significant differences among the wider spacing treatments (1 × 1.5, 1 × 2 and 1 × 2.5 m) at age 12 mth (Table 2) but differences in the stem, branch and leaf dry biomass accumulation were significant ($P < 0.05$) for the closer spacing treatments (1 × 0.5 and 1 × 1m). Thus, the biomass yields per tree for all partitions of *P. juliflora* showed a significant ($P < 0.05$) increase with increasing plant spacing. As a result, the total above ground biomass yield per tree was significantly lower ($P < 0.05$) at plant spacings of 1 × 0.5 and 1 × 1 m (plant density of 20,000 and 10,000 ha^{-1}, respectively). These changes in biomass partitioning can be explained by resource availability due to the reduction in moisture and solar radiation available to the crowns of trees at higher densities (Nilsson and Hällgren, 1993). There was an increase in the proportion of material allocated to the stem wood with increasing spacing, which agreed with the results of a similar study in eucalypts (Bernando *et al.*, 1998). However, since the density of planting ranged from 4,000 to 20,000 trees.ha^{-1}, the overall biomass productivity per unit land area can be quite different to that of the average stem size considered alone.

In contrast to the above results, the per hectare biomass productivity was highest in the 1 × 0.5 m spacing which was significantly higher ($P < 0.05$) than those produced by other treatments. The total dry biomass per hectare increased with an increase in the tree density. Similar to this result, significantly higher stem biomass yields were reported from trees planted at a narrow spacing in loblolly pine silvopastoral stands (Ares and Brauer, 2005) and in *Eucalyptus camaldulensis* (Bernando *et al.*, 1998). The stem, branch, leaf and total above ground biomass yield per hectare of *P. juliflora* did show significant differences at all spacing treatments and at both 6 and 12 mth of age (Table 2) and differences in the dry biomass accumulation were significantly ($P < 0.05$) higher in the closest spacing (1 × 0.5 m) than in the others.

The total above ground biomass yield per hectare of *P. juliflora* at 1 × 1, 1 × 1.5, 1 × 2 and 1 × 2.5 m planting treatments reduced by 48, 62, 72 and 77% , respectively, from that of 1 × 0.5 m spacing at age 6 mth. When the plant spacing widened from 1 × 1 to 1 × 1.5 m, the total above ground biomass yield reduced by 29% and furthermore when the spacing further expanded from 1 × 1.5 to 1 × 2.5 m, the yield dropped by 20%. The yield reduction followed similar trends at age 12 mth and the total above ground biomass yields per hectare obtained at 1 × 1, 1 × 1.5, 1 × 2 and 1 × 2.5 m planting treatments were lower than the yield of 1 × 0.5 m spacing by 45, 61, 70 and 76%, respectively. The total above ground biomass per hectare obtained at the closest spacing (1 × 0.5 m) was more than four-fold that of the 1 × 2.5 m spacing treatment at both 6 and 12 mth age. The total above ground biomass per hectare obtained at 1 × 0.5 m at age 12 mth (69.08 $t.ha^{-1}$) was comparable with the result (68.7 $t.ha^{-1}$) reported by Goel and Behl (2001) for an 8 yr-old stand planted at 1.5 × 1.5 m spacing.

The specific gravity of *P. juliflora* at age 12 mth ranged from 0.70 to 74 (Table 2), which compared favorably with other commonly grown fuelwood species such as *Acacia auriculiformis*, *Acacia nilotica* and *Terminalia arjuna*. There was no significant difference in specific gravity. The results of the present study are comparable with similar studies (Goel and Behl, 2001), but lower than the result of 0.85 reported by (Sherif *et al.*, 2012). A steady increase in specific gravity is expected up to approximately age 5 yr (Mani and Parthasarathy, 2007).

L. leucocephala

Increasing the tree spacing showed a significant increase in tree height in *L. leucocephala* (Table 3). At age 6 mth, *L. leucocephala* trees attained a height of 2 m, except with the 1 × 0.5 m spacing. A greater influence of plant spacing on tree height was observed at age 12 mth. Similar results to the current findings (increased tree height with wider spacing) were reported by Effendi and Bachtiar (1994).

The plant spacing did have a noticeable effect on the stem diameter of *L. leucocephala* (Table 3). The lower stand densities at 1 × 2 and 1 × 2.5 m recorded relatively higher stem diameters in the higher stand density treatments throughout the study period. There are similar reports of trees in dense stands having slower growth than those in more open stands because of competition (Prasad *et al.*, 2011). The stem diameter of *L. leucocephala* recorded at 1 × 2.5 m spacing at age 12 mth was about 24% greater than that of trees planted at 1 × 0.5 m spacing. Increased diameter growth rates with increased distance between trees was reported for *L. leucocephala* by Effendi and Bachtiar (1994). A decrease in the diameter growth of trees with an increase in density was reported in *Cordia spp.* (Hummel, 2000), in eucalypts (Pinkard and Neilsen, 2003) and in six sub-tropical rainforest tree species (Grant *et al.*, 2006).

The number of trunks of *L. leucocephala* increased significantly ($P < 0.05$) with a reduction in stand density at both 6 and 12 mth plant age (Table 3). The trees planted at 1 × 2 and 1 × 2.5 m spacings produced more trunks compared to the other spacings. On the other hand, there was no significant difference in the number of trunks at the closer spacings (1 × 0.5, 1 × 1 and 1 × 1.5 m). The *L. leucocephala* trees at wider spacings produced large canopy sizes with a greater number of trunks compared with trees at higher planting densities at age 12 mth.

There were significant differences among spacing treatments in the main root length of *L. leucocephala* trees; wider spacings (1 × 2 and 1 × 2.5m) produced longer roots than trees planted more closely at age 6 mth. At age 12 mth, increased plant spacing produced a significant increase in the root length and the highest root length was obtained from *L. leucocephala* at 1 × 2.5m spacing. There were no significant differences in the main root length between 1 × 0.5, 1 × 1, 1 × 1.5 and 1 × 2 m spacings at age 6 mth. Similarly, there were no significant differences in the main root length between 1 × 0.5 and 1 × 1 as well as between 1 × 1.5 and 1 × 2 m spacings at age 12 mth. These results showed that the main root length of *L. leucocephala* was significantly influenced by planting density.

The biomass partitions and total above ground biomass per tree of *L. leucocephala* at age 6 and 12 mth are presented in Table 3. The stem and leaf biomass of *L. leucocephala* were affected by spacing at age 6 mth and a significantly lower biomass per tree was recorded at the closer spacings (1 × 0.5 and 1 × 1 m). Similarly, the

Table 3 Spacing effects on growth performance, biomass and energy value of *L. leucocephala* in the Afar Region.

Parameter	Tree age (mth)	Plant spacing (m)					Significance
		1×0.5	1×1	1×1.5	1×2	1×2.5	
Plant height (m)	6	1.95[a]	2.00[a]	2.04[a]	2.06[a]	2.10[a]	ns
	12	4.99[d]	5.15[c]	5.24[b]	5.34[a]	5.37[a]	***
Stem diameter (cm)	6	1.88[b]	1.96[b]	2.20[ab]	2.20[ab]	2.50[a]	*
	12	4.26[d]	5.00[c]	5.26[bc]	5.56[ab]	5.58[a]	***
Number of trunk	6	9.00[c]	10.00[bc]	10.40[bc]	12.60[ab]	13.40[a]	**
	12	9.20[b]	11.00[b]	11.60[b]	15.00[a]	17.00[a]	**
Root length (m)	6	2.19[b]	2.23[b]	2.26[b]	2.32[ab]	2.42[a]	*
	12	3.06[c]	3.16[c]	3.33[b]	3.38[b]	3.49[a]	**
Stem (kg.tree^{-1})	6	1.46[b]	1.46[b]	1.51[a]	1.52[a]	1.51[a]	*
	12	2.53[d]	2.65[c]	2.71[b]	2.76[a]	2.77[a]	***
Branch (kg.tree^{-1})	6	0.47[a]	0.48[a]	0.48[a]	0.49[a]	0.49[a]	ns
	12	0.74[d]	0.85[c]	0.90[b]	0.92[ab]	0.94[a]	***
Leaf (kg.tree^{-1})	6	0.406[b]	0.410[ab]	0.420[ab]	0.424[ab]	0.440[a]	*
	12	0.64[d]	0.75[c]	0.80[b]	0.85[ab]	0.86[a]	**
TAB (kg.tree^{-1})	6	2.33[c]	2.35[bc]	2.42[ab]	2.42[ab]	2.45[a]	**
	12	3.91[d]	4.26[c]	4.40[b]	4.53[ab]	4.56[a]	***
Stem (t.ha^{-1})	6	29.12[a]	14.60[b]	10.05[c]	7.57[d]	6.08[e]	***
	12	50.52[a]	26.54[b]	18.05[c]	13.79[d]	11.06[e]	***
Branch (kg.ha^{-1})	6	9.30[a]	4.78[b]	3.24[c]	2.42[d]	1.94[e]	***
	12	14.84[a]	8.54[b]	5.97[c]	4.60[d]	3.74[e]	***
Leaf (kg.ha^{-1})	6	8.12[a]	4.10[b]	2.83[c]	2.10[d]	1.76[e]	***
	12	12.80[a]	7.48[b]	5.33[c]	4.24[d]	3.42[e]	***
TAB (t.ha^{-1})	6	46.54[a]	23.48[b]	16.12[c]	12.09[d]	9.78[e]	***
	12	78.16[a]	42.56[b]	29.36[c]	22.63[d]	18.23[e]	***
Calorific Value (kJ. g^{-1})	12	19.63[a]	19.61[a]	19.54[a]	19.63[a]	19.59[a]	ns
Ash (%)	12	1.78[a]	1.77 [a]	1.81[a]	1.80[a]	1.81[a]	ns
Specific gravity	12	0.53[a]	0.54[a]	0.53[a]	0.55[a]	0.56[a]	ns

Means followed by the same lowercase superscript letter within a row are not significant ($P < 0.05$) at 6 and 12 mth after planting; * = ($P < 0.05$); ** = ($P < 0.01$); *** = ($P < 0.001$); ns= Not significant; TAB = Total above ground biomass.

biomass yield per tree of all plant parts of *L. leucocephala* showed a significant reduction particularly at closer spacings (1 × 0.5 and 1 × 1 m) at age 12 mth. The total above ground biomass per tree followed a similar trend with different plant parts as *L. leucocephala* showed a significant reduction with increasing tree density. However, the branch biomass was not affected by plant spacing at age 6 mth, but did show a significant difference at age 12 mth. The total above ground biomass per tree was significantly higher at wider spacings (1 × 2 and 1 × 2.5 m) for both 6 and 12 mth age.

The total above ground biomass yield per hectare of *L. leucocephala* at 1 × 1, 1 × 1.5, 1 × 2 and 1 × 2.5 m plant spacing reduced by 50, 65, 74 and 79% , respectively, from that of 1 × 0.5 m spacing at age 6 mth. When the plant spacing widened from 1 × 1 to 1 × 1.5 m, the biomass yield reduced by 31% while when the spacing was further expanded from 1 × 1.5 to 1 × 2.5 m, the yield dropped by 19%. The yield reduction followed similar trends at 12 mth age and the total above ground biomass yields per hectare obtained at 1 × 1, 1 × 1.5, 1 × 2 and 1 × 2.5 m planting treatments were lower than that at 1 × 0.5 m spacing by 46, 62, 71 and 77%, respectively. The total above ground biomass obtained at the closest spacing (1 × 0.5 m) was four times more than that of the 1 × 2.5 m spacing treatment at both 6 and 12 mth age (Table 3).

The specific gravity of *L. leucocephala* at 12 mth age ranged from 0.53 to 0.56 (Table 3) and the values were comparable with other commonly grown fuelwood species such as *Gliricidia sepium*, *Albizia spp*. and *Calliandra calothyrsus* (Pottinger and Hughes, 1995). Even though there was no significant difference in the specific gravity, the results were comparable with a similar study in *L. leucocephala* (Pottinger and Hughes, 1995).

CONCLUSION

The results of the study indicated that the overall performance of *L. leucocephala* was superior and it can be recommended as one of the plant species to be planted in the Afar region to provide viable options to the Afar communities affected by the invasion of *P. juliflora*. However, the performance of *L. leucocephala* under rainfed conditions should be evaluated before recommending it for use in large scale plantations. The findings of this research revealed that the growth and biomass production of *P. juliflora* and *L. leucocephala* were significantly influenced by plant spacing. Both tree species showed excellent performance and progressive increases in height and biomass yield per plant under the arid environment of the Afar region. The total biomass yield per hectare increased with increasing tree densities for both species. Accordingly, planting of both *P. juliflora* and *L. leucocephala* at higher plant densities can be recommended for short rotation wood production unless inter row spacing is required to provide an opportunity for other intra-row operations and the imposition of soil and water conservation practices in tree-based systems.

ACKNOWLEDGEMENTS

The authors would like to thank the Ethiopian Ministry of Agriculture for financing this research project through the Rural Capacity Building Project. The authors are also grateful to the Central Geological Laboratory, Hydrocarbon Division of Ethiopian Geological Survey Authority for providing laboratory facilities for wood properties analysis. The authors are pleased to acknowledge the assistance of the Staff of the Dubti Pastoral and Agro-Pastoral Research Center who took part in this study and shared their experience.

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