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Tree row spacing affected agronomic and economic performance of *Eucalyptus*-based agroforestry in Andhra Pradesh, Southern India

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Abstract The 3 × 2 m spacing currently used for eucalyptus plantations in the state of Andhra Pradesh, southern India does not permit intercropping from the second year. This discourages small landholders who need regular income from taking up eucalyptus plantations and benefiting from the expanding market for pulpwood. Therefore, on-farm experiments were conducted near Bhadrachalam, Khammam district (Andhra Pradesh) for over 4 years from August 2001 to November 2005 to examine whether wide-row planting and grouping of certain tree rows will facilitate extended intercropping without sacrificing wood yield. Eucalyptus planted in five-spatial arrangements in agroforestry [3 × 2 m (farmers' practice), 6 × 1 m, 7 × 1.5 m paired rows (7 × 1.5 PR), 11 × 1 m paired rows (11 × 1 PR) and 10 × 1.5 m triple rows (10 × 1.5 TR)] was compared with sole tree stands at a constant density of 1,666 trees ha^{-1}. Cowpea (*Vigna unguiculata*) was intercropped during the post-rainy seasons from 2001 to 2004, and fodder grasses (*Panicum maximum* and *Brachiaria ruziziensis*) were intercropped during both the seasons of 2005. At 51 months after planting, different spatial arrangements did not significantly affect height and diameter at breast height (dbh). Total dry biomass of eucalyptus in different spatial arrangements ranged between 59.5 and 52.9 Mg ha^{-1}, the highest being with 6 × 1 m and the lowest with 10 × 1.5 TR, but treatment differences were not significant. The widely spaced paired row (11 × 1 PR) and triple row (10 × 1.5 TR) arrangements produced 62–73% of sole cowpea yield in 2003, 59–66% of sole cowpea yield in 2004, and 79–94% of sole fodder in 2005. In contrast, the 3 × 2 m spacing allowed only 17–45% of sole crop yields in these years. The better performance of intercrops in widely spaced eucalyptus was likely because of limited competition from trees for light and water. Intercropping of eucalyptus in these wider rows gave 14% greater net returns compared with intercropping

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in eucalyptus spaced at 3 × 2 m, 19% greater returns compared with that from sole tree woodlot and 263% greater returns compared with that from sole crops. Therefore, in regions where annual rainfall is around 1,000 mm and soils are fairly good, eucalyptus at a density of 1,666 plants per ha can be planted in uniformly spaced wide-rows (6 m) or paired rows at an inter-pair spacing of 7–11 m for improving intercrop performance without sacrificing wood production.

Keywords Biomass · Tree–crop interactions · Tree spacing · Cowpea · Fodder grasses

Introduction

Rapid population increase and consequent increase in the requirement for different kinds of paper products and the emphasis on paper as an environmentally friendly packaging material have led to increased demand for wood. The imbalance between the supply and demand for forest products is growing. Many pulp mills are finding it difficult to source wood from natural forests and find land where they can establish plantations (Puri and Nair 2004). The majority of the mills are entering into contracts with local communities in the name of joint venture schemes for producing wood (Saxena 1995). The yields obtained from on-farm plantations of exotic species have often been many times greater than those from natural forests. The acreage under eucalyptus has increased rapidly in Andhra Pradesh during the last decade due to the assured market, high returns from trees and supportive government policies. Tree growing has 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.

Intercropping of annuals in timber trees compared with sole tree woodlots offers the advantages of reduced tree establishment costs, income generation during the unproductive phase of the trees, efficient use of natural resources, and risk reduction from catastrophic fires (Garrity and Mercado 1994). Couto and Gomes (1995) reported higher intercrop yield and the existence of complementary interaction in eucalyptus–beans system. One intercrop row of maize did not affect the survival and growth of eucalyptus and reduced the plantation cost by 60% (Couto et al. 1994). However, these studies were taken up during the first 1 year of tree planting. Some of these advantages are offset by the increased competition for aboveground and belowground resources as tree canopies and root systems expand over years. Eucalyptus was reported to negatively affect the intercrops when it was grown for wood production (Nissen et al. 1999; Narain et al. 1998; Kumar and Nandal 2004). In Ethiopia, tef (*Eragrostis tef*) yield was significantly reduced up to a distance of 12 m from eucalyptus tree line (Kidanu et al. 2005), whereas in India wheat (*Triticum* sps.), chickpea (*Cicer arietinum*), lentil (*Lens esculentum*) yields were depressed between 2 and 12 m from the tree row (Saxena 1991; Singh and Kohli 1992) when trees were grown on field boundaries. The tree population in most studies where the emphasis was on the productivity of intercrops was less than 1,000 trees ha^{-1} (Kumar and Nandal 2004; Saroj et al. 1999; Nadagouda et al. 1997). The competition to intercrops from eucalyptus may start from early stages when the tree is grown at higher density (e.g.1,666 trees ha^{-1}) in short rotations for pulpwood (harvest cycle 4 or 5 years) and the intensity of competition could be much greater in later stages.

The clonal eucalyptus plantations grown in Andhra Pradesh are generally harvested at 4-year intervals. Intercrops are grown in eucalyptus only during the first year of planting. The commonly used 3 × 2 m spacing (i.e. a density of 1,666 trees per ha) by farmers for eucalyptus causes yield reduction in majority of intercrops from the second year onwards. For this reason much of the acreage under plantations is confined to large-landholders. Smallholders are not able to take advantage of these systems due to the absence of regular annual income, which is essential to their livelihood. Annual crops not only provide annual returns but also dry fodder for animals which are an integral part of the farming systems in this region and make substantial contribution to the smallholders' household income. Increasing the possibility of intercropping beyond second year and improving intercrop yields in eucalyptus-based systems will not only provide regular income for the sustenance of farmers before eucalyptus is harvested (4 years) but also fodder for livestock. A strategy that can be adopted is to divide the land into as many equal parts as the cycle of the rotation such that an area is available for fresh planting of agroforestry and an equal area is ready for tree harvest every year (Couto and Gomes 1995). This may not be workable under Indian conditions as the average holding is only 1.4 ha and the multiplicity of operations every year leads to escalation of costs.

Techniques such as canopy pruning, pollarding, thinning, root pruning by trenching and moving the first intercrop row farther from the tree-row were suggested for reducing the competition of trees and to improve yields of intercrops in agroforestry (Nair 1993; Nissen et al. 1999). Pruning the canopy of tall growing trees may not be practical and moving the crop row farther away from the tree is not feasible when eucalyptus is planted in narrow rows at 3 m. Other techniques also suffer from one or the other limitations and can be applicable only in certain specific situations. Our interaction with farmers revealed that they are not interested in reducing the tree density for the fear that it will reduce returns substantially. Altering the tree spacing without reducing the tree density is one of the options that can minimize tree–crop competition and give more space to intercrops. Wider-row spacing of trees can provide more space to intercrops and reduce the interface between trees and crops. The question, therefore, worth exploring is what spatial arrangements can give more space for intercrops without sacrificing tree population and production?

The present study was taken up with the following objectives: (1) to evaluate the effects of different spatial arrangements on growth and biomass production of eucalyptus at a constant density of 1,666 trees per ha, and identify an appropriate alternative spacing to the current farmers' practice of 3 × 2 m that would prolong intercropping and enhance intercrop yields without affecting tree growth, (2) to study the extent of tree – crop competition in various tree geometry treatments, and (3) to evaluate economic returns of eucalyptus-based systems in comparison with that of the arable system of the region. The hypothesis tested was that widening the inter-row spacing or grouping 2–3 eucalyptus rows increases intercrop yields without affecting the tree yield compared with the farmers' practice.

Materials and methods

Site description

The study was conducted on four farms spread over four villages within 50 km distance near Bhadrachalam town (82°52′05″E and 17°41′19″N) in Khammam district of Andhra Pradesh, Southern India. Substantial acreage is under eucalyptus plantations in Khammam district and the acreage is expanding every year. Farmers were involved in conducting the trials with the hope that they will facilitate 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, intercrop sowing, fertilizer application, weeding harvesting etc. The four 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 alkaline (pH 7.0–9.1, mean = 8.3 ± ,0.17, n = 20), they had normal to high electrical conductivity (0.14–0.69 Ds m^{-1}, mean = 0.19 ± 0.08, n = 20), were low in organic carbon (0.31–0.60%, mean = 0.36 ± 0.1, n = 20) and available forms of all the three major nutrients (nitrogen 63–130 kg ha^{-1}, mean = 89 ± 1.3, n = 20), (phosphorus 7.0–18.5 kg P ha^{-1}, mean = 12.2 ± 0.42, n = 20) and (potassium 75–120 kg ha^{-1} mean = 110 ± 1.53, n = 20) in the top 15-cm soil layer. The area receives an average annual precipitation of 1,120 mm, distributed in about 60 rainy days. About 85–90% of the total rainfall is received in 5 months, from June to October. The annual rainfall during the study period was 1,091, 784, 1,486, 1,058, 1,526 mm in 2001, 2002, 2003, 2004 and 2005, respectively. Mean maximum temperature during the cropping period was 36.2°C where as the mean minimum temperature was 17.1°C.

Experimental design

The spatial arrangements evaluated were 3 × 2 m (farmers' practice), 6 × 1 m (single wide rows), 7 × 1.5 m in paired rows (7 × 1.5 PR), 11 × 1 m paired rows (11 × 1 PR) and 10 × 1.5 m triple rows (10 × 1.5 TR). All the treatments had the same tree density of 1,666 trees ha^{-1}. In 7 × 1.5 m PR, distance between any two sets of paired rows was 7 m and distance between rows within a pair was 1 m and trees within the rows were spaced at 1.5 m apart. In 11 × 1 m PR, the paired rows were spaced at 11 m, rows in the pairs were spaced at 1 m and trees within the row were spaced 1 m apart. In 10 × 1.5 m TR, distance between any two sets of triple rows was 10 m, rows in the triple row set were at 1 m apart and trees within a row were at 1.5 m apart. At each location all the five spatial arrangements were evaluated, forming one complete replication. The experimental design was a split plot with tree spacings in the main plots and intercrops and no intercrop (i.e. sole tree stand) in the subplots. All the tree geometry treatments were randomized at each location. Tree rows at all the locations were in east–west direction. Each plot had at least three sets of paired rows or triple rows and the central set was considered as net plot leaving sufficient border at each end. The minimum width of a plot was 24 m and length 40 m depending on the availability of space.

Tree establishment

The fields selected for this study were not under cultivation during the previous four seasons. They were plowed twice using a disc harrow and leveled. Pits of 0.2 × 0.2 × 0.2 m size were dug manually and 100 g of single superphosphate was added to each pit and the soil thoroughly mixed. *Eucalyptus tereticornis* clones were selected for their high biomass potential and uniform growth, which is particularly important for comparing the effect of tree arrangements. 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 seedling mortality. Any seedlings that died were replanted within 30 days of planting. Trees were fertilized annually from the second year onwards with 46 kg N, 23 kg P, and 45 kg K ha^{-1}. The fertilizers selected to supply the major three nutrients (urea, single superphosphate and muriate of potash) were mixed and the material was placed 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 among all the trees in a plot.

Tree growth and biomass production

In each sub-plot, five trees were randomly marked and the same trees were measured at monthly intervals for height and diameter at breast height (dbh) at all the locations. However, only the data collected in July at the start of each rainy season were presented. Trees were harvested 51 months after planting in November 2005. At harvest, tree height and dbh were recorded for all the trees in the net plot of each treatment (which differed from 194 to 151 trees depending on the spatial arrangement). The dbh of trees was recoded at 1.37 m height from the ground level. Five trees from the central row in each treatment were partitioned into foliage, branches, bark and stem, and biomass of these components weighed immediately using an electronic balance. For each felled tree, bole diameter was measured at the base and top of the stump and at 3-m intervals above the base. A disc was sawn from approximately the middle of every bole, and taken to the laboratory in a sealed plastic bag. Samples of leaves, bark and branches were also collected and dried at 65°C to constant mass to determine the dry: fresh biomass ratio. Based on the recorded fresh biomass of trees and fresh to dry biomass ratio, dry biomass of each component and the total dry biomass per hectare were calculated.

Intercrops and their management

In the first 4 years after planting the trees, no intercrop was grown during the rainy season and only cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogea*) were intercropped during the post-rainy (October–February) season. However, as the tree effects were very similar on both the intercrops, results of only cowpea are reported here for simplicity. Cowpea was sown at a spacing of 30 × 10 cm. During 2005, three grasses, two varieties of guinea grass (*Panicum maximum* cv. Makueni and Riversdale) and Congo signal grass (*Brachiaria ruziziensis*) were sown as intercrops. Grass seeds were sown at a spacing of 40 × 20 cm with the recommended seed rate. These grasses were selected for their shade tolerance and high biomass production (Stur 1991). A sole tree treatment without intercrop was maintained throughout the study. The minimum gross area of the sole tree plot was 144 m^2. Sole stands of the test intercrops were grown each season in the same field away free from the effect of trees.

The experiment was conducted under rainfed conditions. Cowpea was sown using bullock-drawn implements and the grasses were sown manually in lines. Cowpea was fertilized with the recommended rate of 20 kg N ha^{-1} and 18 kg P ha^{-1} in the form of di-ammonium phosphate before sowing. In the case of grasses, 40 kg N ha^{-1}, 22 kg P ha^{-1} and 25 kg of K ha^{-1} was applied basally before sowing and top dressed later with 20 kg N ha^{-1}. While N and P were supplied through diammonium phosphate, K was supplied through muriate of potash; top dressing of N was through urea. Weeds were controlled by inter-row cultivation using bullock-drawn implements. Crop yields in each treatment were recorded by harvesting the rows separately starting from the first row adjacent to the tree to the centre of each plot on either side of the central tree row(s) in each treatment. The yields of all rows were then combined to get yield of that particular treatment. In the case of grasses, samples were collected at 1-m intervals from the first row to the center on either side of the tree row. The mean of both the sides of the tree row represents the yield of that row. When grasses were the intercrops during 2005, the minimum gross plot area for each grass was 108 m^2. Samples of green biomass were oven dried at 70°C till a constant weight is attained and the ratio of fresh to dry biomass was used to convert the fresh weights to dry weights on hectare basis.

Light measurements

Photosynthetically active radiation (PAR) was measured on three occasions during 2002–2003, and on five occasions during the 2005 cropping seasons at monthly intervals using a 1.2 m long line quantum sensor (ACCUPAR of Decagon). During 2002–2003, PAR was measured at 1 m away from the tree row in both the northern and southern directions and at the center between the tree rows of each treatment. Measurements were made above the crop canopy in four directions and the average values of the three observations over time were considered. During 2005, light data were recorded for all the three grasses and the average values were presented. Measurements were made at 0.5 m from the tree row and at every 1 m up to 5 m from the tree row and in the open conditions far away from the interference of trees. Light measurements were taken between 1100 and 1300 hours in all the fields. The average PAR transmitted to the crop through tree canopy during the season, which is the ratio of PAR below the canopy to PAR incident in the open was presented.

Soil water

Soil water was monitored during the 2002 and 2005 post-rainy seasons. Soil samples were collected at monthly intervals after sowing the intercrops. Soil water data for the year 2002–2003 and 2005 were presented. Samples were collected at four locations from two depths 0–20 cm and 20–40 cm in each treatment: in the tree row, 1 m away from tree row in both the northern and southern directions and in the center of tree row. The collected samples were weighed immediately, dried in an oven at 105°C for a constant weight and reweighed for determining the soil water content.

Economics

Financial analysis was conducted comparing different agroforestry systems with sole eucalyptus and sole annual crops covering one harvest cycle of eucalyptus. The parameters used for comparison of systems were net returns, net present value (NPV) and benefit/cost ratio. Net present value was computed using 6, 12 and 18% discount rates. The stream of costs incurred and the direct benefits derived from each system were worked out. In the case of agroforestry treatments, the costs included initial expenditure for planting trees plus cultivation costs for field crops such as land preparation, fertilizers, sowing, weeding, harvesting, and threshing. In the case of sole crops, the expenditure incurred for raising crops each season was considered. Farmers were consulted in arriving at the quantity of different inputs, particularly labour for different field operations. For financial analysis, cowpea yield and average yield of three grasses were considered. Products which do not have any economic value in the region such as cowpea haulms and eucalyptus branch wood were not considered in the analysis. Biomass of fresh debarked eucalyptus wood was used for calculation of returns. Costs of inputs and outputs prevailing at the time of harvest (November 2005) were used in the financial analysis.

Statistical analyses

The crop data and tree data were subjected to one-way analysis as per randomized block design. When the intercrops were three grasses, the data were analyzed following 2-way analysis of variance for split plot taking the tree geometry treatments as main plots and intercrops as subplots. When '*F*' test was significant, treatment differences were tested using LSD at 5% significance level. Where pair-wise treatment comparisons were made, for example, average of agroforestry systems versus sole tree stand, '*t*' test was used at 0.05 probability.

Results and discussion

Effect of geometry on tree growth

The tree survival at harvest was not significantly affected by tree geometry and the survival was 85% in 7 × 1.5 PR, 88% in 3 × 2, 90% in 6 × 1, 92% in 10 × 1.5 TR and 95% in 11 × 1 PR. Closer within the row spacing either as a consequence of widening or grouping of rows did not induce any extra mortality.

As there was apparently no effect of intercrops on height and dbh growth of eucalyptus, results averaged over the intercrops were reported (Table 1). The tree growth was highest during the second year after planting. Within any given year, tree growth was highest during July to December, coinciding with the rainy season. The trees in 11 × 1 PR and 10 × 1.5 TR treatments grew slightly taller than in 6 × 1 m and 3 × 2 m until about 2 years after planting. However, the trees in 6 × 1 m and 3 × 2 m treatments also came up well to measure as tall as in other treatments during the later years. The mean annual height increment ranged from 3.36 to 3.62 m year^{-1}. Treatment differences on the basis of average height were not significant ($P = 0.05$).

During the second and third years after planting, trees in 3 × 2 m had similar dbh to those in 6 × 1 m spacing but they had greater dbh than those in paired-row spacings (Table 1). At harvest, the trees in 3 × 2 m attained the highest dbh, which was about 13% greater than the dbh of trees in 10 × 1.5 TR. Nevertheless, treatment differences for average dbh were not significant ($P = 0.05$) during the study period. Thus, we did not observe any major impact of tree geometry on eucalyptus growth during 4 years of this study. It appears that the effect of single and double row arrangements on the growth and size of trees evened out over time. Eucalyptus growth observed in our study was greater than that of the trees raised from seedlings at Bijnor (Rawat and Negi 2004), but was comparable to the growth of clonal saplings at Bhadrachalam, which has rainfall similar to our study sites (Lal et al. 1997).

Effect of tree geometry on biomass production

The debarked bole wood is the marketable product for eucalyptus grown for pulp production in this region. In the absence of any specification from industry on bole

Table 1 Growth of eucalyptus planted in different spatial arrangements in agroforestry measured at the beginning of each rainy season (July) over a 4-year period in Andhra Pradesh, India

Treatments	2002		2003		2004		2005	
	Height (m)	dbh (cm)	Height (m)	dbh (cm)	Height (m)	dbh (cm)	Height (m)	Dbh (cm)
10 × 1.5 m triple rows	3.23	1.57	7.68	4.96	10.57	7.15	12.58	8.32
11 × 1 m paired rows	3.95	1.24	8.71	5.36	9.49	7.08	13.44	9.12
7 × 1.5 m paired rows	3.10	1.12	7.72	5.23	9.45	7.14	12.26	8.62
6 × 1 m	2.98	1.23	7.13	5.36	10.23	7.83	13.18	8.43
3 × 2 m farmers' practice	3.05	1.78	8.26	5.50	11.03	8.86	13.13	9.58
SED	0.34	0.22	0.63	0.29	0.89	0.54	0.97	0.82

At sub-plot level, $N = 20$ in years 2002–2004 and the same in 2005 (at harvest) is 194–151, *SED* standard error of difference of means

Table 2 Marketable yield and total biomass of eucalyptus planted in agroforestry at different spatial arrangements at harvest (51 months after planting), at Bhadrachalam in Andhra Pradesh, India

Treatments	Marketable biomass (bole), fresh weight (Mg ha^{-1})	Total biomass, dry weight (Mg ha^{-1})
10 × 1.5 m triple rows	79.7	52.9
11 × 1 m paired rows	81.4	54.0
7 × 1.5 m paired rows	85.4	57.4
6 × 1 m	87.9	59.5
3 × 2 m farmers' practice	86.7	54.2
SED	6.9	5.9

size for pricing, total bole wood produced is the primary criterion for evaluating the treatments. The 6 × 1 m spacing produced the greatest fresh bole biomass of 88 Mg ha^{-1}, which was about 8 Mg more than that produced by 10 × 1.5 TR (Table 2). The total dry biomass was also greatest with 6 × 1 m treatment (59.5 Mg ha^{-1}) and lowest in the case of 10 × 1.5 TR treatment (52.9 Mg ha^{-1}). However, treatment differences were not significant ($P = 0.05$) either in terms of fresh or dry biomass of bole wood or other tree components. The relative contribution by different tree parts to the total biomass was: bole—81%, bark—8%, branches—8% and leaves—3%. The study demonstrated that clonal eucalyptus developed from elite trees in a 4-year rotation has the potential to produce on farms up to 135 t ha^{-1} of total fresh biomass. The results of this study are of great interest for discussions on future fibre and wood supply and carbon sequestration. It is clear that the productivity of clonal plantations can greatly exceed that of native forests.

Crop yields

During the first cropping season after planting the trees (i.e. 2001 post-rainy season), intercrop yields were not affected by the trees in any spatial arrangements. The adverse effect of trees on intercrops was significant from the second year onwards (i.e. 2002), which increased substantially in the subsequent seasons. Cowpea intercropped in closely spaced eucalyptus (3 × 2 m) during 2002 yielded only 45% of sole crop. The intercrop yields improved with increase in row spacing. However, only the triple rows at 10 m apart and paired rows at 11 m apart produced cowpea yields close to that of sole crop.

Table 3 Yields of cowpea grown in the post-rainy seasons of 2001–2004 and fodder grasses in both rainy and post-rainy seasons of 2005 in sole and eucalyptus-based agroforestry systems in Andhra Pradesh, India

Treatments	Cowpea (kg ha^{-1})				Fodder (Mg ha^{-1})[a]
	2001	2002	2003	2004	2005
10 × 1.5 m TR	1,062	655	518	387	1.53
11 × 1 m PR	965	594	441	342	1.83
7 × 1.5 m PR	926	485	405	229	1.36
6 × 1 m	865	408	353	285	1.58
3 × 2 m	879	296	121	134	0.88
Sole crop	968	650	706	584	1.94
LSD (0.05)	NS	118	102	57	0.56

[a] Average yield of three fodder grasses

During the 2003 and 2004 post-rainy seasons, intercropped cowpea in all the tree row arrangements produced significantly lower yields than sole crop. In these seasons, cowpea in 3 × 2 m tree spacing gave only 121 kg ha^{-1} (17% of the sole crop) and 134 kg ha^{-1} (23% of sole crop yield), respectively. The intercrop yields increased with increase in tree row spacing (or alley width), but only the triple row arrangement produced 73 and 66% of the sole cowpea in 2003 and 2004, respectively. Cowpea yields in other wider-row arrangements varied from 50 to 62% of the sole crop in 2003 and 39–59% of the sole crop in 2004. In 2005, all the three grasses showed similar yield potential in sole system with an average yield of 1.94 Mg ha^{-1} and system × grass species interaction was not significant. Hence average yields of three grasses in different systems were given (Table 3). The narrow tree spacing allowed significantly lower grass yield at 0.88 Mg ha^{-1} compared with all other agroforestry systems with wider row spacing for trees. Although the widest inter-row treatment (11 × 1 m PR) produced the highest yield at 1.83 Mg ha^{-1}, it did not differ from other wider-row arrangements which produced yields in the range of 1.36–1.53 Mg ha^{-1}.

The magnitude of crop yield losses in agroforestry systems increased with age of the trees. Compared with no yield loss in 2001, cowpea experienced an average loss of 25% (i.e. compared with sole crop yield) in 2002, which further increased to 48% in 2003 and 53% in 2004 (Table 3). Increased competition with age was due to the increased size of the trees and their ability to mop up greater resources at the expense of crops (Dhyani and Tripathi 1999; Narain et al. 1998 and Khybri et al. 1992). Cowpea—harvested for grain in this study—experienced greater yield reduction than fodder crops in agroforestry. Compared with 53% yield loss of intercropped cowpea in 2004, the fodder grasses experienced an average loss of only 26% in the subsequent year 2005. Competition of trees with intercrops for water could be particularly high in the post-rainy season, when crops were grown in this study, because of limited residual soil water on which both the trees and crops have to thrive.

Among the different spatial arrangements tested on eucalyptus in agroforestry, the treatments 10 × 1.5 TR and 11 × 1 PR recorded significantly greater intercrop yields compared with the closer spacing of 3 × 2 m from the second year onwards. Improvement in fodder yield was reported with increase in row spacing from 2.4 to 12.2 m in the fifth and the sixth growing season of loblolly pine alley cropping systems (Burner and Brauer 2003). In each treatment, intercrop yield at the center between any two tree rows was significantly greater than the yield adjacent (<1 m from tree row) to the tree rows (Fig. 1). For example, cowpea adjacent to the tree row in 10 × 1.5 TR during 2002–2004 produced only 50–66% of the yield observed at the middle of the

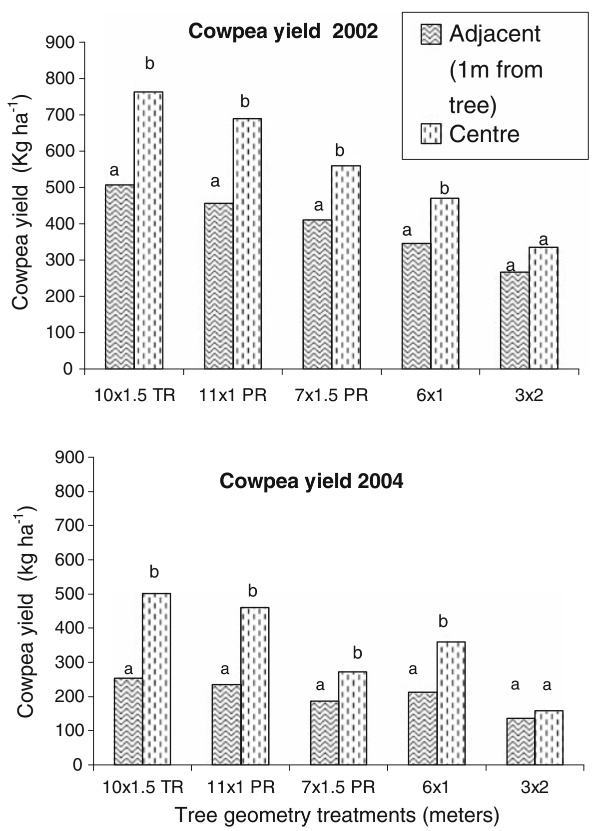

Fig. 1 Intercrop yields close to the tree row and at the centre of two rows as influenced by different spatial arrangements of eucalyptus in Andhra Pradesh, India. *Bars* with the same letter within each spatial arrangement are not significant at 5%

alley (i.e. between tree rows). Fodder yield adjacent to the tree row in 10 × 1.5 TR was 48% of the yield at the middle of the rows. In 3 × 2 m spacing, yields of all rows were equally depressed indicating that the tree competition extended uniformly all over the inter-row area. Although fodder yield increased with distance from the tree row in all the other treatments, the increase beyond 1 m was similar even up to 5 m away from the tree row (Fig. 1).

Light interception

In the first year (2001), even the first crop row close to trees received 83% of the open radiation as the trees were only 1.8 m tall and crop yields were not affected. During the second year (2002), the crop adjacent to the tree row in 3 × 2 m spacing received about 43% and the rows at the centre received about 49% of the open radiation (Fig. 2). Although clone no. 3 of *E. tereticornis* has less dense foliage compared to others, considerable reduction in light transmitted to the underneath crop indicates closure of tree canopy in this close spacing from the second year onwards. By 2005, the incident radiation on the row close to the tree was reduced to 30% and that at the centre between tree rows was reduced to 34% of the open radiation.

Light transmitted to the intercrop significantly increased with increase in spacing between eucalyptus rows irrespective of their planting in single, paired or triple rows. Thus in 2002, there was about 99% of radiation at the centre of the rows compared to 66% close to the tree row in 11 × 1 PR and 10 × 1.5 TR (Fig. 2). However, 3 years later in 2005, light transmitted to the intercrop decreased considerably because of lateral spread of tree canopies with age. The widest spacing 11 × 1 PR permitted only about 40% radiation at 0.5 m from the tree row and 49% at

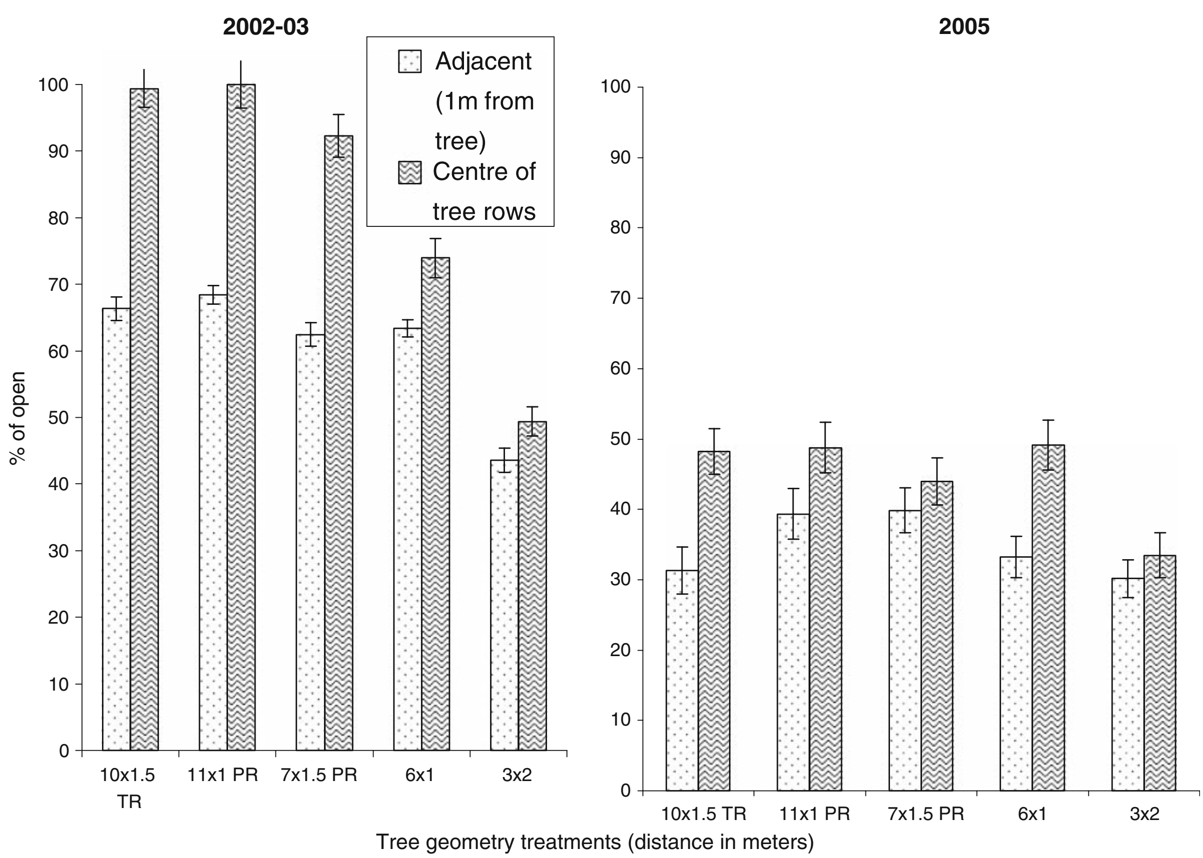

Fig. 2 Photosynthetically active radiation (*PAR*) transmitted to the crop in intercropping with eucalyptus in different spatial arrangements during 2002–2003 (60 days after sowing, November 23, 2002) and 2005 cropping seasons (18 November 2005) in Andhra Pradesh, India. *Vertical lines on top of the bars* are standard errors

the center of the rows during December–January months.

Nissen et al. (1999) reported reduced light under eucalyptus trees in similar pattern as in this study. Burner and Brauer (2003) reported reduction of solar radiation by 1-year-old pines in 2.4 m wide rows to about 45% compared with no shading in the middle of rows >9.7 m apart. In the present study, shade extended up to the center of the wide tree rows, but the southern side of the tree rows was unshaded. Insufficient radiation under eucalyptus was found to delay wheat tillering on either (northern or southern) side or both sides of tree rows at a distance of <3.7 m in northern latitudes during the *rabi* season (Kohli and Saini 2003).

Shade affects the growth and development of C4 plants (e.g. grasses) more severely than C3 plants (e.g. cowpea) (Wong 1991). Shade reduces production of tillers, leaves, and roots and results in thinner leaves with higher water content and higher specific leaf area (Wong 1991). However, in the present study no significant reduction in biomass production was observed beyond 1 m distance from trees in any of the three grasses. Reasonable yields of *P. maximum* and Congo signal grasses in intercropping with eucalyptus were probably because they can tolerate some degree of shade and their economic product is fodder, which generally is less affected by shade compared with grain. It seems sensible to grow fodder grasses such as guinea grass and Congo signal grass as intercrops in later years of eucalyptus when light transmission is considerably reduced.

Soil water availability

Soil water content progressively declined as the season advanced. In all the tree geometry treatments, soil water close to the tree row was low on both sides and it increased with distance from the tree row, resulting in highest soil water content at the center of the inter-rows. At the end of the rainy season in 2005, there was about 38 and 16% greater water content adjacent to the tree and at the center of the tree row at 0–20 cm soil depth in 10 × 1.5 TR compared with 3 × 2 m spacing in riversdale variety of guinea grass (Fig. 3).

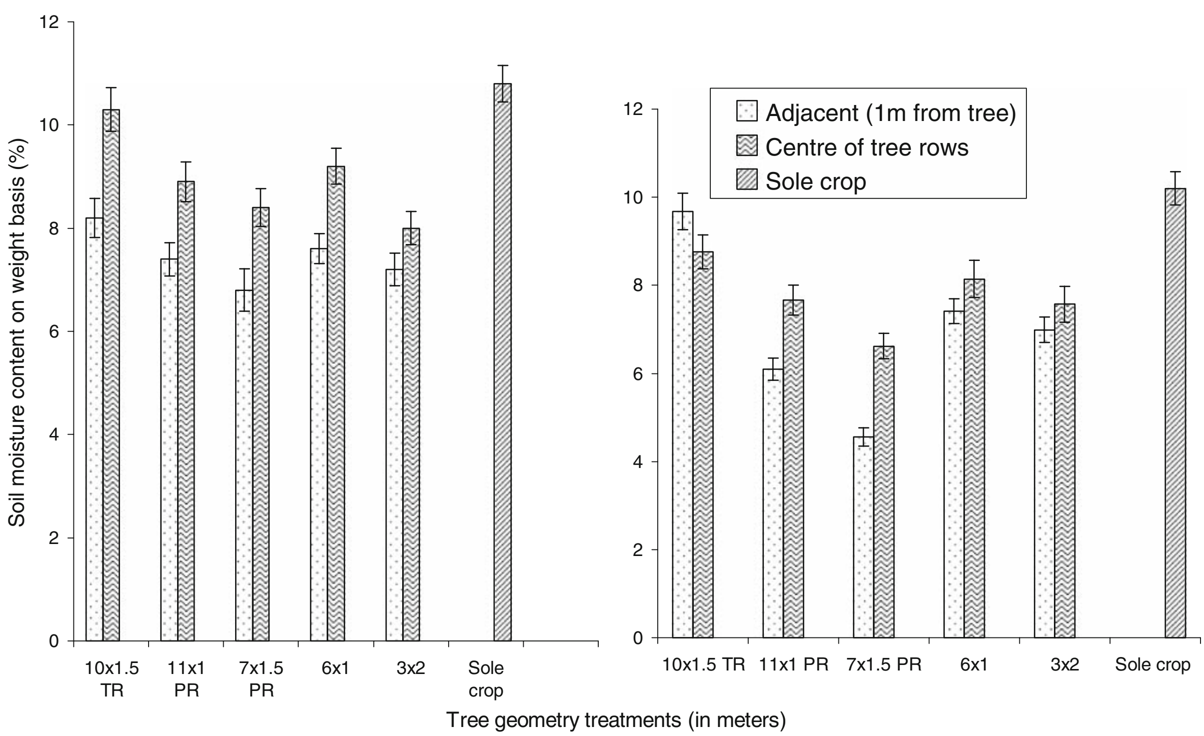

Fig. 3 Soil water content (%) in intercropping with eucalyptus (0–20 cm depth) in different spatial arrangements during 2002–2003 (59 days after sowing, 22 November 2002) and 2005 (19 November 2005) cropping seasons in Andhra Pradesh, India. *Vertical lines on top of the bars* are standard errors

The low water content up to 40 cm depth in the vicinity of tree rows was due to water uptake by trees. Tree roots might have contributed to the water uptake as clonal plants have up to 53% of fine roots concentrated in 0–25 cm surface soil layer (Bouillet et al. 2002). Grasses such as *Panicum* and *Brachiaria* when intercropped with eucalyptus restrict the lateral development of tree roots which results in greater density of tree roots in surface soil layers (Schaller et al. 2003). Crop rows that were nearer to trees on both sides were worst affected due to competition from trees for water. Szott et al. (1991) and Salazar et al. (1993) also reported that root competition for water and nutrients is primarily responsible for yield depression at the tree–crop interface in agroforestry. In the present study, seedlings of cowpea and grasses adjacent to eucalyptus grew poorly and remained stunted throughout the season. Competition for both the water and light contributed for the suppression of growth and consequently yield of crops close to the tree rows. The effect was severe during the 2002 *rabi*, which received only 784 mm of rainfall in 42 rainy days against the average of 1,119 mm in 68 rainy days. Negative effects of tree rows on seasonal crops due to competition for water were widely reported in semi-arid and arid climates (Rao et al. 1991). In other seasons, competition for light appeared to be the major factor than water for reduced intercrop yields as rainfall exceeded 1,000 mm. Eucalyptus-based intercropping systems are a better choice under rainfed areas which frequently experience the risk of drought, as the decline in tree productivity in the event of low rainfall would not be as much as in the case of annual crops.

The wider between row spatial arrangements formed by widening the row width or grouping of two or three rows of eucalyptus reduce the number of tree rows directly interfaced with crop rows in agroforestry. Increased crop yields in these modified tree arrangements compared with narrow spacing of trees could be attributed to the reduced tree–crop interface. The paired- and triple-row arrangements conferred another advantage to the intercrops in that the poor quality eucalyptus litter was confined mostly to the tree area, so that the inter-row area was relatively free from eucalyptus litter, which is known to have inhibitory allelopathic effects on certain crops (Singh and Singh 2003). Increased within-row competition in wider-rows was reported to force sorghum to root deeper and exploit soil water at depth (Blum and Naveh 1976). Similar mechanism may operate in wide- and grouped-row arrangements used for eucalyptus in this study.

Eucalyptus cultivation raises environmental concerns because of its reported high water use. In dry areas, this species has been reported to transpire more water than the average rainfall recorded over the same period (Jagger and Pender 2000; Calder et al. 1997). However, recent literature shows that some of the improved hybrids of eucalyptus are efficient in using water and more suitable for the semi-arid tropics than existing eucalyptus material and other agroforestry tree species (Shem et al. 2009). Unlike the seedlings, the clonal plants of eucalyptus have 53% of fine roots concentrated in 0–25 cm surface soil layer (Bouillet et al. 2002), which may limit their ability to extract deep soil water. In humid areas, eucalyptus does not transpire large amounts of water when soil water is not limiting (Myers et al. 1996). However, research is required to address the long-term impacts of eucalyptus on soil water resources and associated crop performance during the successive ratoon cycles, particularly in areas where rainfall is around 1,000 mm and eucalyptus is popular.

Financial evaluation

Initial investment was high for eucalyptus-based systems because of high cost of the clonal planting material, its transportation to the field, pitting and planting (Table 4). For this reason, net returns from all the eucalyptus systems in the first year (i.e. 2001) were negative (Table 5). Despite high investment there was no income from sole eucalyptus until the trees were harvested 51 months after planting. In contrast, intercropping in eucalyptus provided some income from annual crops every year. However, net returns were still negative for intercropping in closely planted eucalyptus at 3 × 2 m because of reduced crop yields from the second year. Although intercropping in 6 and 7 m wide rows/alleys improved crop yields, they still did not completely cover the costs. Only intercropping in 10–11 m wide alleys gave positive returns from the second year. Sole eucalyptus incurred a total expenditure of Rs 49,545 which was 60% higher than the expenditure for annual crops. Intercropping in eucalyptus required only an extra expenditure of Rs 21,646 over sole

Table 4 Inputs and their costs, and values of outputs (for one ha.) for sole eucalyptus, arable crops and eucalyptus-based agroforestry systems during the 4-year period of the study in Andhra Pradesh, India

No	Year/item	Sole tree stand	Sole crops	Agroforestry system	Unit cost (Rs)
	2001				
1	Tree seedlings (number)	1,666	–	1,666	4 per sapling
2	Initial land ploughing (number)	3	3	3	1,000 for each ploughing by tractor
3	Labour for pit making, fertilizer application, transplanting and watering of trees (man days)	40	–	40	75 man day^{-1}
5	Fertilizers for trees (single super phosphate)	100 g SSP	–	100 g SSP	290 per 100 kg SSP
6	Termite control (chloripyriphos)—two times	@ 10 ml/ tree + 4 man days	–	@ 10 ml $tree^{-1}$ + 4 man days	194 l^{-1}
7	Ploughing for sowing intercrop	–	–	1	1,000
8	Sowing intercrops—seed cowpea (bullock pairs + 2 labour)	–	Seed 25 kg ha^{-1} + 2 bullock pairs	Seed 25 kg ha^{-1} + 2 bullock pairs	Seed 25 kg^{-1} 200 bullock $pair^{-1}$
9	Fertilizer for cowpea and its application	–	20 kg N and 17.5 kg P + 3 man days	20 kg N and 17.5 kg P + 3 man days	P: Rs 45 kg^{-1} (DAP)
10	Interculture (tractor/bullock pair)	1 with tractor	2-bullock pair days	2-bullock pair days	200 bullock $pair^{-1}$
11	Crop harvest (labour)	–	15	15	75 man day^{-1}
12	Fertilizers for trees and their application	46 kg N, 23 kg P, 45 kg K 4 man days	–	46 kg N, 23 kg P, 45 kg K 4 man days	N: 10.8; P: 45; K: 8.3 Rs kg^{-1} nutrient
	2002–2004 and 2005[a]	Costs for items 7–12 reoccur			
13	Labour for tree harvest and debarking	192	–	192	75 man days
14	Saleable wood yield (Mg ha^{-1})	95	–	89 – 100	1,340 Mg^{-1}

[a] During 2005, interculture (item no. 10) was not done. Cost of grass seed replaces the cost of cowpea seed in earlier years

Average cost for transporting clonal saplings: Rs 450 ha^{-1}, sale price of fodder: Rs 2,000 Mg^{-1}, price of cowpea grain: Rs 18,000 Mg^{-1}, eucalyptus debarked wood: Rs 1,340 Mg^{-1} on fresh weight basis

SSP single superphosphate

eucalyptus but the extra returns more than compensated the investment. Intercropping in different wide spacings of eucalyptus gave net returns varying between Rs 99,249 and Rs 100,262 over a 4-year period, which were significantly greater than those from the farmers' practice of intercropping in closely spaced eucalyptus (Rs 87,503), sole eucalyptus (Rs 80,435), and sole annual cropping (Rs 27,440).

Net present value (NPV) and benefit/cost ratio of intercropping in widely spaced eucalyptus were significantly greater than for sole tree system, annual crops, and farmers' practice of intercropping in 3 × 2 m. Sole eucalyptus gave a NPV of Rs 36,905, which was 69% greater than the NPV of annual crops at 12% discount rate (Table 6). The farmers' agroforestry system gave 20% greater NPV than sole eucalyptus. In contrast, intercropping in the alleys of triple rows at 10 m (10 × 1.5 TR) increased the NPV by 24% over the farmers' practice at 12% discount rate. Other wider row spatial arrangements (11 × 1 PR; 7 × 1.5 PR; 6 × 1 m) recorded significantly higher NPV than the farmers' practice at 6 and 12% discount rates. The return per investment from sole woodlot and agroforestry systems were relatively higher over that of sole annual crops at 6 and 12% discount rates. At lower and medium

Table 5 Financial analyses of sole eucalyptus, sole crop and eucalyptus-based agroforestry systems in Andhra Pradesh, India

System/spacings	Total costs (Rs ha^{-1})	Gross returns (Rs ha^{-1})	Net returns (Rs ha^{-1})					Total net returns (Rs ha^{-1})
			Year 1 (2001)	Year 2 (2002)	Year 3 (2003)	Year 4 (2004)	Year 5 (2005)	
Agroforestry systems								
10 × 1.5 m (triple rows)	71,737a	171,178a	−7,947a	3,347a	2,932a	700a	100,509a	99,441a
11 × 1 m (paired rows)	71,362a	170,611a	−9,693b	2,077a	1,690a	−32a	105,204ab	99,246a
7 × 1.5 m (paired rows)	71,145a	170,581a	−10,095b	−431b	880b	−2,246bc	111,360b	99,468a
6 × 1 m	71,437a	171,699a	−11,493c	−1,547b	−74c	−1,526b	111,569b	100,262a
3 × 2 m (farmers' practice)	70,275a	157,774b	−10,941c	−3,965c	−4,366d	−3,853c	110,629b	87,503b
Sole eucalyptus	49,545b	129,980c	−22,325d	−3,205c	−3,205e	−3,205c	112,375b	80,435b
Arable cropping	30,842c	58,282d	10,886e	5,671d	7,524f	5,160d	−1,801c	27,440c

US $ 1 = Rs 40 (August 2007); values indicated by different letters are significantly different ($P < 0.05$)

Table 6 Net present value (NPV) and benefit/cost ratios (B:C) at different discount rates for eucalyptus based systems in Andhra Pradesh, India

System/spacings	6%		12%		18%	
	NPV	B:C	NPV	B:C	NPV	B:C
Agroforestry systems						
10 × 1.5 m (triple rows)	73,494a	2.20	55,012a	2.03	41,669a	1.90
11 × 1 m (paired rows)	72,690a	2.17	53,833a	2.03	40,268a	1.86
7 × 1.5 m (paired rows)	72,243a	2.17	52,981a	2.03	39,182a	1.83
6 × 1 m	72,346a	2.17	52,630a	2.00	38,585a	1.83
3 × 2 m (farmers' practice)	62,074b	2.07	44,237b	1.86	31,584a	1.66
Sole eucalyptus	54,808b	2.29	36,905b	2.00	24,292b	1.74
Arable cropping	24,374c	1.93	21,859c	1.97	19,750b	2.00

Treatment means indicated by different letters are significantly different ($P < 0.05$)

discount rates pure forest systems and agroforestry systems were reported to be more profitable than pure agriculture (Price 1995). The internal rates of return (IRR) for the modified tree geometry treatments (88–56%) were higher than that for 3 × 2 m (44%) and sole eucalyptus woodlot (28%). Labour wages have substantially gone up recently from Rs 75 to Rs 125 day^{-1} partly due to alternative employment opportunities and also due to the government sponsored employment guarantee programmes. Even in such a scenario agroforestry systems in wider rows continue to be profitable and net returns from modified agroforestry systems (i.e. widely spaced eucalyptus) average about Rs 83,662 which are higher than from the farmers' agroforestry practice (Rs 72,373), sole eucalyptus (Rs 68,085) and annual cropping (Rs 24,740) at 12% discount rate. The NPV and B:C ratios of modified agroforestry systems were still higher than for other systems in spite of substantial increase in labour wages.

Eucalyptus plantations can be retained for four cycles of 4 years each. As the cost of planting material is only in the first cycle, NPV of eucalyptus-based systems in subsequent cycles would be much greater than NPV from arable crops. Some additional labour may be required to manage the coppice shoots during the second to fourth cycles but total labour during these cycles may not be higher than the labour required during the first cycle when operations such as pitting, transplanting and weed control require additional labour. Agroforestry systems required about 78 man days of labour ha^{-1} year^{-1} compared with 65 man days ha^{-1} year^{-1} for sole eucalyptus and 22 man days ha^{-1} year^{-1} for sole annual cropping. Digging of pits for tree planting, harvesting, debarking, and transport of wood demand high labour input. Tree harvesting provides employment for labour during October–January, when other employment avenues are less in rural areas. Some studies in India also reported greater NPV from eucalyptus-based agroforestry systems compared with other agroforestry systems (Viswanath et al. 2000). All the financial parameters indicate that agroforestry based on widely spaced eucalyptus is more profitable than arable cropping and the current practice of intercropping in eucalyptus only in the first year. Similar conclusions were also made by Dube et al. (2003) in the case of eucalyptus and by Singh et al. (1997) in the case of poplar. Modified spacing for eucalyptus permitted better cash flow from improved intercrop yields over an extended period during the growth phase of eucalyptus.

Conclusions

Different spatial arrangements evaluated at a constant density of 1,666 trees per ha did not affect eucalyptus growth in terms of height, dbh and total biomass because of the compensatory growth of the trees. So row spacing for eucalyptus can be increased from the current practice of 3–6 m or even 7–11 m by grouping 2 or 3 rows. Wide-row arrangements permit intercropping with economical yields all through the 4-year period of the short rotation eucalyptus grown for pulpwood. Intercropping in widely spaced eucalyptus is more economical than intercropping in the farmers' spacing of 3 × 2 m, sole woodlot or sole annual cropping. Width of tree rows can be selected based on the intercrop to be grown and convenience for field operations using animal-drawn implements. While 11 × 1 PR or 10 × 1.5 TR is preferable for grain crops such as cowpea, even 7 × 1.5 PR is suitable for fodder crops. Eucalyptus-based agroforestry using wide-row arrangement is an important strategy for integrating wood and annual crop production for smallholders and to overcome the concerns of declining food production due to shift in acreage from crops to woodlots.

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