Agroforest Syst
DOI 10.1007/s10457-015-9849-z

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Bamboo based agroforestry systems in Kerala, India: performance of turmeric (*Curcuma longa* L.) in the subcanopy of differentially spaced seven year-old bamboo stand

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Received: 23 October 2014 / Accepted: 3 October 2015

Abstract Bamboo-based agroforestry is a promising option for sustainable land management in India. Optimal management of bamboo-based mixed species production systems, however, requires an understanding of bamboo spacing, root activity and distribution of bamboo roots, and the soil nutrient capital of the site. We examined the performance of turmeric as an understorey crop in 7-year old bamboo (*Dendrocalamus strictus* (Roxb.) Nees) stands of varying spacing treatments (4 × 4, 6 × 6, 8 × 8, 10 × 10 and 12 × 12 m) at Kerala Agricultural University Campus, Thrissur, Kerala, India. In order to better understand turmeric and bamboo growth parameters, soil physico-chemical properties, understorey light availability and turmeric root activity by soil injection of ^{32}P were determined in mixed (turmeric + bamboo) and sole turmeric situations. To characterize root activity, ^{32}P was applied at 10 cm depth to the turmeric plants in raised beds established between the two central rows of bamboo in all experimental plots. Growth attributes of bamboo were recorded and the soil was analyzed for physico-chemical properties before intercropping. Results revealed that spacing treatments exerted profound influence on bamboo growth. For instance, clump height decreased by 19 % in the widest (12 × 12 m) bamboo spacing compared to that of the closest (4 × 4 m) spacing. However, widely spaced bamboo exhibited better clump diameter, crown coverage and turmeric rhizome yield, whereas, closest (4 × 4 m) spacing of bamboo plot recorded least rhizome yield of 8 Mg/ha; this was 58 % less compared to widest spacing of 12 × 12 m (19.32 Mg/ha). Soil N, P and K at widest spacing was 56, 45 and 33 % less compared to that of the closest spacing. NPK uptake by turmeric also increased in the wider spacing treatments. Factors contributing to reduction in growth of turmeric in the denser bamboo stands may be the high LAI (6.77 in 4 × 4 m spacing) as compared to widest spacing (0.44 in 12 × 12 m spacing) of bamboo, low understorey PAR (107 µmol/sec/m^2) and high root competition. Due to competition by bamboo, 89 % decline in ^{32}P absorption by turmeric at closest spacing of bamboo was observed compared to the bamboo-less plot. On a final note, turmeric, although a shade tolerant Zingiberaceae

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Published online: 08 October 2015

crop, may perform better if light transmittance is between 66 and 86 % and for optimal performance of the understorey turmeric in mixed species systems, wider bamboo spacings beyond 8 × 8 m are recommended.

Keywords *Dendrocalamus strictus* · Intercropping · Root competition · Oleoresin content · Light transmittance · Photosynthetically active radiation · Root activity

Introduction

Agroforestry with bamboos has considerable potential for providing food and nutritional security and for contributing to economic development of developing countries in the tropics. For example, in West Java, the bamboo 'talun-kebun' system not only combines short cycles of food and wood production but also sustains ecosystem integrity (Christanty et al. 1997). According to them, "the historical success of the system appears to be largely due to the 'nutrient pumping' action of bamboo, the slow decomposition of its silica-rich litter, and the extremely high biomass of bamboo fine roots". Bamboos are major woody components of many traditional land use systems and/or its modern variants in India too, which is home to many species of bamboo. Fast growing solid bamboo [*Dendrocalamus strictus* (Roxb.) Nees] in particular has varied uses, and is suitable for agroforestry, plantation forestry and social forestry (John and Nadagouda 1995). Furthermore, bamboos are distributed across India and are culturally linked to the local people (Nath and Das 2008).

Despite the wide distribution, occurrence of bamboo is mostly limited to farm boundaries, homesteads and marginal areas, often making it a shrinking resource base (Kumar 1997; Kumar and Divakara 2001). Although Divakara et al. (2001) evaluated root distribution of boundary planted bamboo and root competition with associated trees in two binary associations, very little information is available on aspects relating to intercropping of herbaceous crops with bamboo and on the compatibility of intercrops for various management objectives (Jha et al. 2004; Sinha and Nath 2007; Banerjee et al. 2009; Bhol and Nayak 2014). Indeed, there is a tacit assumption that the profusely growing fibrous root systems of bamboo may out-compete field/tree crops grown in association (Divakara et al. 2001; Kumar and Divakara 2001). Furthermore, if soil resources are limited, bamboo may be more effective in acquiring these scarce resources than other species grown in association (Kleinhenz and Midmore 2001).

Divakara et al. (2001) reported that proximity of trees/crops may alter the belowground root architecture in bamboo based systems and may lead to deeper root penetration, implying the role of bamboo spacing and intercropping practices in determining the magnitude of competitive interactions between bamboo and associated crops. The deeper spread of tree roots is also effective in recycling nutrients which leach out from the surface soil (safety net role of tree roots: Kumar and Divakara 2001; Lehmann and Schroth 2003; Smith 2010). However, there is little or no information available on the performance of understorey crops in differentially spaced bamboo plantations. Probably what deters farmers from adopting such bamboo based polyculture systems is the lack of information on management of bamboo based systems. Therefore, a study on optimization of bamboo (*Dendrocalamus strictus* (Roxb.) Nees) spacing and the performance of turmeric (*Curcuma longa* L., Family Zingiberaceae) in the understorey was taken up in order to optimize management strategies and tools for intercropping with better yield and productivity.

Turmeric is a potentially important medicinal and aromatic oil yielding herb which has great demand in *ayurvedic* industry and for culinary uses in India (Kirtikar and Basu 1988). Although Nair et al. (1991) recommended growing of turmeric and ginger (*Zingiber officinale* Roscoe; Zingiberaceae) in coconut based land-use systems, there is little or no information available on the performance of turmeric in the understorey of differentially spaced solid bamboo plantations. Against this backdrop, a field experiment was undertaken to explore the feasibility of bamboo-turmeric based agroforestry in humid tropical zone of peninsular India and to evaluate the rhizosphere competition using applied ^{32}P and understorey turmeric growth under varying spacings of bamboo. The specific objectives of the study were to assess the growth and productivity of understorey turmeric as influenced by planting density in a bamboo based agroforestry system, probe the root distribution pattern, understorey photosynthetically active radiation

(PAR) availability and aboveground and belowground production/carbon sequestration as a function of planting density of bamboo.

Materials and methods

Site description and experimental setup

The study was conducted in a 7 year old bamboo stand at Vellanikkara, Thrissur, Kerala, India (10° 13′ N latitude, 76° 13′ E longitude and 40.29 m elevation). This experimental stand was established in 2004 with five spacing treatments (4 × 4, 6 × 6, 8 × 8, 10 × 10 and 12 × 12 m with corresponding densities of 625, 277, 156, 100 and 69 clumps ha^{-1}) and a control plot (without bamboo). The trial was laid out in a randomized block design with three replications and the individual plots were of size 30 × 30 m.

Turmeric (var. Prathibha) was used for the intercropping trial. This is a tropical herb grown on different types of soil under irrigated and rainfed conditions. It is a shade tolerant crop with shallow roots suitable for intercropping where low to medium shade is available. The average yield of this variety is 7.23 (dry) Mg ha^{-1}, curcumin content is 6.20 %, oleoresin 16.2 %, essential oil 6.20 % and duration 225 days. Prior to planting, the turmeric rhizomes were treated with Dithane M 45 @ 3 g L^{-1} and Ekalux @ 1 mL L^{-1} as prophylactic measure against pests and diseases. The rhizome of average size 15 g were planted in planting hole of 5 cm depth at spacing of 25 × 25 cm in a bed area of 300 × 120 × 30 cm between the two central rows of bamboo in each plot during May 2012. Immediately after sowing, farm yard manure (FYM) at the rate of 35 Mg ha^{-1} (wet weight basis) was broadcast-applied on the beds as recommended (KAU, 2011) and mulched with leaves of *Macaranga peltata* and *Trema orientalis* at the rate of 15 Mg ha^{-1} fresh weight basis. Mulching was repeated at the same rate during the second and third month (KAU, 2011). Beds were weeded 60 and 120 days after planting. Fertilizers (50:50:50 kg N: P_2O_5: K_2O ha^{-1}) were applied at first weeding with light tillage and earthing up was done. To control rhizome rot, wilt and leaf spot diseases, *Pseudomonas fluorescens* P1/PGPR II was sprayed and soil drenched at 45 days after planting.

In addition to the turmeric planting in the understorey as explained above, an absolute control (no bamboo overstorey) was maintained replication-wise where turmeric was raised in the open (part of the original experimental design).

The precipitation pattern at the site is bimodal; both South–west (June–September) and North–east monsoons (October–December) supply moisture, with a mean annual rainfall of 3062 mm, most of which was received during the South-west monsoon. The mean maximum temperature during the experimental period ranged between 29.10 (July) and 35.49 °C (March). The mean minimum temperature varied between 22.19 and 24.83 °C in the months of December and May respectively. Soil of the experimental site was a Typic Plinthustult-Vellanikkara series midland laterite (*c.f.* Thomas et al. 1998).

Triplicate soil samples (0–20 cm layer) were collected from all plots (three replications and six treatments) randomly from between the bamboo rows before turmeric planting (April 2012). Soil bulk density was determined using a steel cylinder and soil pH measured in 1:2.5 soil: water suspension (Jackson 1958). Total soil nitrogen was determined by Kjeldahl method (Jackson 1958), available phosphorus by Bray No.1 extraction followed by reduced molybdate blue colour estimation method (Watanabe and Olsen 1965) and exchangeable potassium by neutral normal ammonium acetate solution followed by flame photometry (Jackson 1958).

Bamboo growth observations

Bamboo clump height and crown width were measured with the help of measuring tape. Diameter at sixth internode was measured using Vernier caliper. We determined crown widths of clumps (April 2012) by projecting the crown on the ground, in two perpendicular directions (NS and EW) and computing their means.

Stand leaf area index (LAI)

The leaf area index of bamboo was estimated using a plant canopy analyzer (LAI 2000, LI-COR Inc., Lincoln, Nebraska, USA). This instrument computes LAI indirectly from measurement of radiation above and below the canopy, based on a theoretical relationship between leaf area and canopy transmittance (Stenberg et al. 1994). Care was taken to ensure that the unit was facing the same direction both inside and outside the stand during measurement. A sun-lit canopy was avoided by taking measurements just after sunrise and just before sunset when the solar elevation is low. A view restrictor of 90° prevented direct sunlight reaching the sensor and occluded the measuring person from the 'view'.

Understorey photosynthetically active radiation (PAR) monitoring

We made continuous understorey measurements (0800–1800 h) of PAR in all treatment combinations of each replication (18 plots) from March 12 to April 22, 2012 using a line quantum indicator (LQI 2404, K131, Li-Cor, Lincoln, USA). Within each plot, the line quantum sensor was installed on wooden platforms in random bamboo alleys at 70 cm above the ground on two consecutive days. The line of the sensor was oriented east–west direction so as to receive maximum incident radiation. PAR incident above the canopy of each plot was simultaneously recorded by the data logger using a Point Quantum Sensor (LI-COR LI-191) mounted on a 10 m pole rising above the canopy. A battery powered data logger (LI 1000, LI-COR Inc) integrated the mean flux of PAR at hourly intervals (μ moles s^{-2} m^{-1}). PAR was then converted to canopy transmittance—the ratio of light below the canopy to light incidence on the top of the canopy expressed as percentage.

Measurement of crop growth and yield

To evaluate turmeric growth, the crop was harvested at 90, 180 and 230 days after planting (DAP). At every sampling a quadrat area of 0.5×0.5 m^2 was selected from three random locations per bed per plot excluding border plants. All turmeric clumps in the selected quadrats were uprooted and plant height, number of tillers per hill and number of leaves per plant recorded. The leaves, tillers, residual rhizomes (planted) and rhizomes were thoroughly cleaned and the aboveground composite samples of leaves, tillers and belowground composite portions of roots and rhizomes were separated and their fresh weights recorded. The samples were then oven dried at 70 °C until constant weights. The turmeric rhizome yield at final harvest (230 DAP) was also determined. Using the net harvested area, dry matter production and rhizome yield were scaled up to per hectare basis.

Phytochemical analysis

Finely ground (pass through 2 mm sieve size) leaf and shoot samples (one sample per replication) were analysed for N (microkjeldahl method, Jackson 1958), P (Vanado-molybdo phosphoric yellow colour method, Koenig and Johnson 1942) and K (flame photometry, Piper 1967). Finely ground samples of dried mature rhizomes were also analysed for oleoresin content by solvent extraction. For this, a 10 g finely powdered sample (one sample per replication) was placed in a filter paper pouch and distilled in a Soxhlet apparatus with 250 ml petroleum ether (boiling point 60–80 °C) for 8 h. The extract was then transferred to a 250 ml flask, petroleum ether was evaporated and the difference in weight of flask recorded for estimating oleoresin content.

Tracer studies to characterize root interaction

This trial was intended to provide insights into the extent of root competition between turmeric and associated bamboo component for nutrients applied to the former as influenced by different spacing of bamboo. For understanding the belowground interactions and to characterize root competition in intercropping systems without disturbing the root system, ^{32}P technique is considered as an appropriate method and the same has been used extensively in agroforestry systems (e.g., George et al. 1996; Thomas et al. 1998; Lehmann et al. 2001). Radioisotope tracer technique provides a very fast and direct means of measuring in situ root activity (IAEA 1975). Soil injection of ^{32}P was carried out on 22nd September, 2012 to evaluate the turmeric and bamboo belowground interaction when the turmeric plants were approximately 5 months old. The experimental units for ^{32}P application were selected on the basis of uniformity of growth and spatial isolation from each other. Minimum distance between any two treated turmeric beds was 6 m. There were altogether 18 experimental units representing three replicates of five spacing and one control plot ($5 \times 3 + 3$).

Sub plots of size 1×1 m^2 (16 plants) at the center of each turmeric bed were selected from each bamboo spacing and bambooless control (see Fig. 1) (open plot). Four turmeric plants in a row were selected and two holes were drilled on either side of the each plant (10 cm deep and 10 cm lateral distance) such that

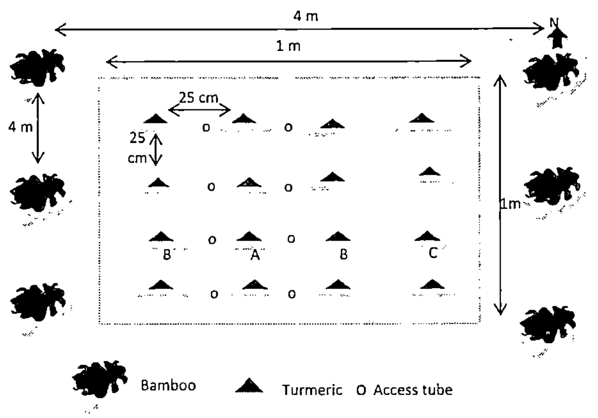

Fig. 1 Schematic representation showing turmeric plants, bamboo clumps and access tubes for ^{32}P application in the soil injection of ^{32}P study

there were eight equidistant holes per experimental unit. A day in advance of ^{32}P injection, PVC access tubes of 1.25 cm diameter were inserted into these holes with about 10 cm aboveground for ease of application and their open ends covered with plastic caps to prevent entry of rain water. Two mL of 1000 mg l^{-1} Phosphorus solution containing 1.176 mCi/plant of ^{32}P was dispensed into the access tubes around turmeric plants using specially designed field dispenser (Wahid et al. 1988). After dispensing, the radioactivity remaining on the sides of the access tube was washed down with a jet of about 15 ml of distilled water. High concentration of P was used in the carrier solution to reduce the soil fixation of the radioisotope.

Leaf sampling and radioassay

The most recently matured turmeric leaves from the treated and neighbouring untreated turmeric plants were sampled for radioassay on 15, 30 and 45 days after application of ^{32}P. This was based on the assumption that the radioactivity associated with the leaf samples could be a reasonable indicator of the root activity (Wahid et al. 1988; Kumar et al. 2001). Foliage samples from neighbouring turmeric plants, similarly situated were pooled to make composite samples, row-wise. The oven dried leaf samples were assayed for ^{32}P at the Radiotracer Laboratory, Kerala Agricultural University, Vellanikkara. The method consisted of wet digestion of one gram of plant sample using a 2:1 mixture of HNO_3 and $HCLO_4$. The digest was then transferred into a counting vial and made up to 20 mL volume. Vials were counted in a liquid scintillation counter (Model: Trialther-Hidex) by the Cerenkov counting technique (Wahid et al. 1985). Bamboo clumps adjacent to turmeric beds were also sampled to assess the extent of root interaction. For this, bamboo leaves were radio-assayed on 15, 30 and 45 days after application of the isotope to the turmeric clumps.

Statistical analysis

The data on growth of bamboo and turmeric were analysed following the SPSS statistics for Windows at $p < 0.05$ following randomized-block design, with spacing of bamboo as treatments. Least significant difference (LSD) was used for comparing differences between means. Standard error between the replications was also calculated. Regression equations were fitted linking rhizome yield of turmeric and mean daily understorey PAR. Count rates (counts per minute, cpm) were corrected for background and decay and subjected to $\log_{10}(x + 1)$ transformation. The data on recovery of ^{32}P activity in the leaves of turmeric and adjacent bamboo were analyzed using SPSS statistics for Windows. The counts per minute (cpm) corresponding to 15, 30 and 45 days after ^{32}P application were decay-corrected and $\log_{10}$ transformed before being subjected to analysis of variance (RCBD) in SPSS (Ver. 14) for evaluating the differences in ^{32}P uptake patterns by treated and untreated turmeric as a function of population density of *D. strictus* ($p < 0.05$). Also, to study the ^{32}P uptake by bamboo in response to lateral distance from the treated turmeric plants, analysis of variance (RCBD, SPSS ver 14) was computed.

Results

Growth attributes of *D. strictus*

Data presented in Table 1 clearly highlight the effect of planting density (spacing) on the height growth of bamboo. Greater heights were associated with closer spacing which decreased with increase in planting spacing ($p < 0.05$). For instance, closest spacing (4 × 4 m) recorded the highest clump height of 9.11 m, while the widely spaced bamboo (12 × 12 m) showed 19 % reduction in height. Conversely, clump

Table 1 Growth parameters of differentially spaced 7 year old bamboo (*Dendrocalamus strictus*) in central Kerala, India

Spacing (m)	Height (m)	Clump DBH (m)	Crown width (m)	Number of culms/clump
4 × 4	9.11 (0.06)[d]	1.03 (0.01)[a]	4.69 (0.10)[a]	47.66 (6.69)[a]
6 × 6	8.18 (0.12)[c]	1.28 (0.02)[b]	6.61 (0.13)[b]	75 (12.50)[b]
8 × 8	8.03 (0.03)[c]	1.44 (0.01)[c]	7.36 (0.09)[c]	103.66 (5.69)[c]
10 × 10	7.6 (0.10)[b]	1.55 (0.004)[d]	7.79 (0.09)[d]	111.33 (1.85)[cd]
12 × 12	7.31 (0.05)[a]	1.58 (0.003)[d]	8.13 (0.08)[e]	130 (5.36)[d]

Values in the parenthesis are standard error of the mean

[a,b,c,d] Values followed by same superscript in a column do not differ significantly ($p = 0.05$)

diameter and crown width were significantly ($p = 0.05$) higher in the wider (12 × 12 m) spacing compared to the closer ones. Number of culms per clump also followed a similar trend.

Leaf area index (LAI) and understorey PAR availability

As can be seen from Fig. 2, bamboo spacing and LAI were inversely related. LAI of bamboo in the 4 × 4 m spacing was 6.8-fold higher compared to that of 12 × 12 m spacing. Bamboo spacing also significantly influenced the understorey PAR availability ($p < 0.05$): the trends, however, were in contrast to LAI (Fig. 3). As the spacing of bamboo increased from 4 × 4 to 12 × 12 m, understorey PAR availability levels also increased. For example, at 14.00 h, the overstorey recorded highest PAR (1248 μmol $s-^{1}$ m^{-2}); the corresponding understorey PAR availability was only 10 % of overstorey PAR in 4 × 4 m spacing, while it was as much as 97 % under widest spacing (12 × 12 m), implying greater interception of the incoming solar radiation by the canopy of the closely spaced bamboo clumps. Higher understorey PAR transmittance was also associated with widely spaced bamboo such as 10 × 10 m (85 % of overstorey midday PAR). Diurnal variation in understorey PAR also consistently varied with time with peak PAR during midday (1–2 pm).

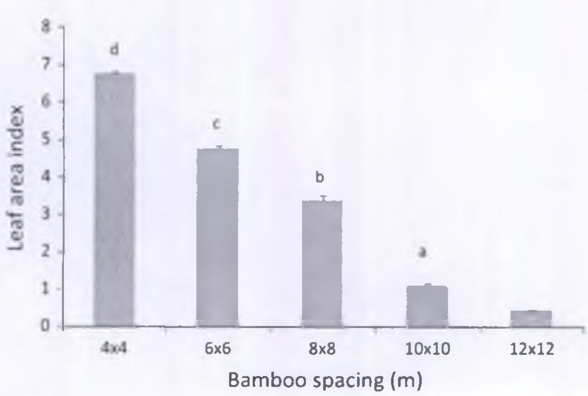

Fig. 2 Leaf area index (LAI) of 7 year old bamboo (*Dendrocalamus strictus*) as influenced by different spacing treatments in central Kerala, India. Values followed by same superscript do not differ significantly ($p = 0.05$). *Error bars* indicate standard error of the mean values

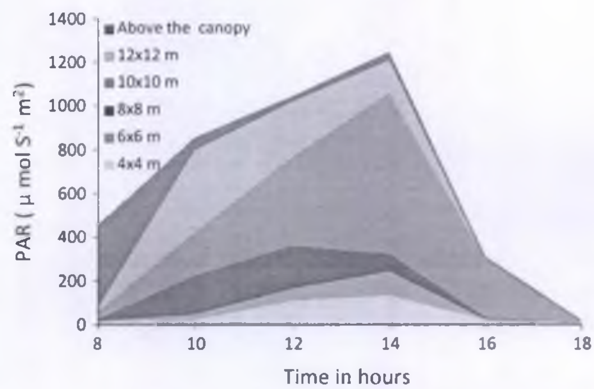

Fig. 3 Diurnal variation in transmittance of photosynthetically active radiation (PAR) as influenced by varying spacing in 7 year old bamboo (*Dendrocalamus strictus*) from 0800 to 1800 h (March 12–April 22, 2012) in central Kerala, India

Growth and yield of turmeric

In general, height, number of tillers and rhizome yield of turmeric increased over time (Fig. 4). Turmeric plants were consistently taller at wider spacing of bamboo. For instance, at 230 days after planting, turmeric plants in the 12 × 12 m spacing treatment were almost two-fold taller than that in the closest spacing (4 × 4 m). Also, the height growth in this

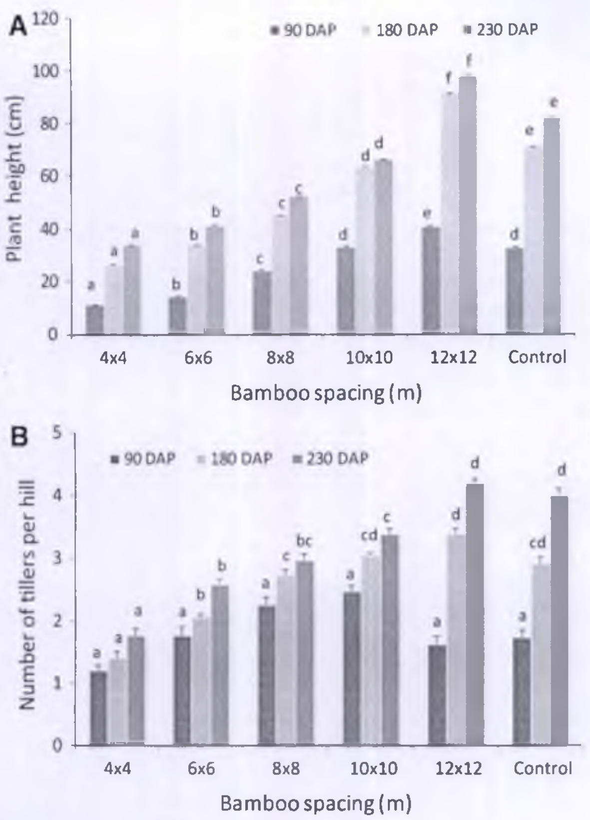

Fig. 4 Plant height (A) and number of tillers (B) in understorey turmeric at various growth stages (90, 180 and 230 days after planting, DAP) as influenced by different spacing of 7 year old bamboo (*Dendrocalamus strictus*) in central Kerala, India. *Error bars* indicate standard error of the mean values

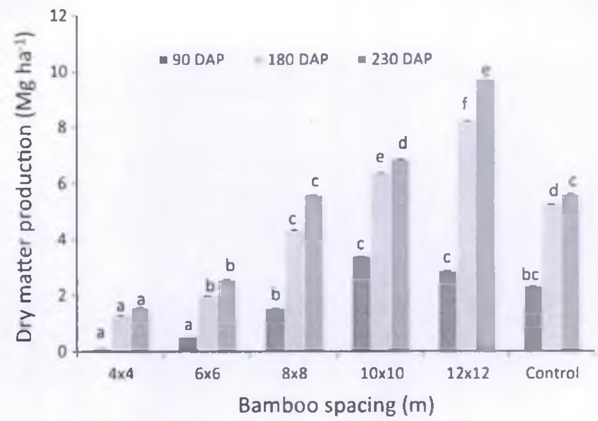

Fig. 5 Dry matter production in understorey turmeric at various growth stages (90, 180 and 230 days after planting, DAP) as influenced by different spacing of 7 year old bamboo (*Dendrocalamus strictus*) in central Kerala, India. *Error bars* indicate standard error of the mean values

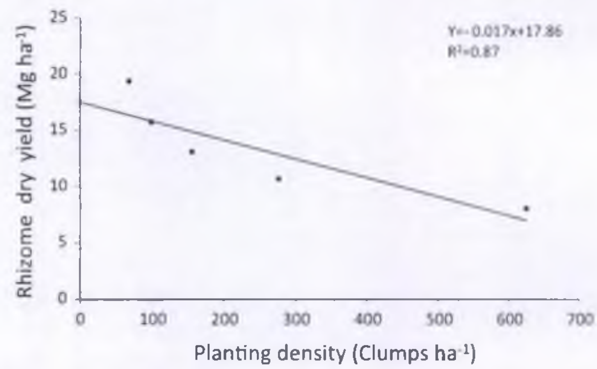

Fig. 6 Rhizome yield of turmeric (at harvest) as influenced by different spacing (spacing treatments: 4 × 4, 6 × 6, 8 × 8, 10 × 10 and 12 × 12 m) of 7 year old bamboo (*Dendrocalamus strictus*) and bamboo-less control plot in central Kerala, India

density regime was even higher than the bamboo less control ($p < 0.05$). Similarly, the number of tillers/hill also were significantly ($p < 0.05$) higher in the wider bamboo spacing which was at par with bamboo less control. In general, most of the growth attributes associated with the turmeric intercrop under bamboo showed better performance under wider spacing especially at 8 × 8 m, 10 × 10 m and 12 × 12 m which were marginally lower or at par with the turmeric growth under open bambooless conditions.

Dry matter production and rhizome yield also increased significantly with increasing spacing of bamboo ($p < 0.05$) (Figs. 5 and 6) which were respectively 600 and 241 % more in the widest spacing (12 × 12 m) compared to the closest spacing (4 × 4 m). Interestingly, bamboo at widest spacing registered higher total dry matter production and rhizome yield compared to the treeless open.

Strong functional relation is observed in the present study between rhizome yield and understorey PAR with high coefficient of determination ($r^2 = 0.88$) (Fig. 7). The observed increase in the rhizome yield with increasing planting spacing is very much consistent with the corresponding increase in understorey PAR. The midday PAR (1–2 pm) in the overstorey (1248 μmol/sec/m^2) did not significantly vary with that of understorey PAR in wide spacing like 10 × 10 m (1059 μmol/sec/m^2) and 12 × 12 m (1210 μmol/sec/m^2) which imply that, nearly same amount of PAR reached the ground in wide spacing as that reached in overstorey.

Uptake of NPK by turmeric significantly ($p = 0.05$) increased with increasing spacing of bamboo (Table 2). The highest uptake of N (66.99 kg ha^{-1}) was recorded for the widest spacing (12 × 12 m),

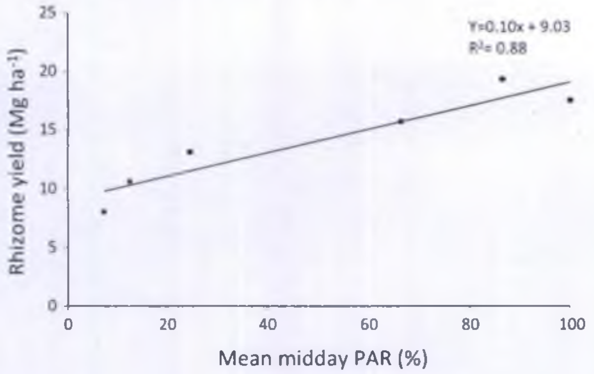

Fig. 7 Relationships between mean photosynthetically active radiation (PAR) level and rhizome yield of turmeric in central Kerala, India

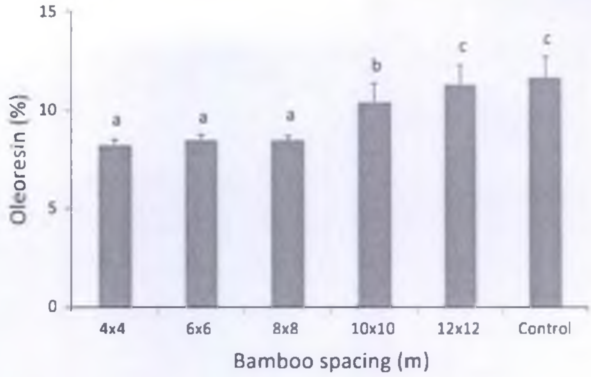

Fig. 8 Oleoresin content of turmeric rhizomes as influenced by varying spacing treatments of 7 year old bamboo (*Dendrocalamus strictus*) in central Kerala, India

which was 450 % more that of the 4 × 4 m spacing. Likewise, the P and K uptake by understorey turmeric in the widest spaced bamboo was 295 and 115 % higher compared to closest spacing. The NPK uptake by turmeric without overstorey bamboo was by and large similar to that of turmeric grown under bamboo at 8 × 8 m spacing, but was clearly inferior to the nutrient uptake recorded in the spacing treatments wider than that (e.g., 10 × 10 m and 12 × 12 m). Oleoresin content of turmeric was lowest (8 %) in the closest spacing and was highest in bambooless plots (11.68 %), which was statistically at par with that of 12 × 12 m spacing of bamboo (Fig. 8).

^{32}P tracer uptake by turmeric and bamboo in bamboo + turmeric system

^{32}P absorption by treated turmeric increased with increase in bamboo spacing (Table 3) which was highest for the widely spaced treatment (12 × 12 m) at all stages of monitoring (e.g., 15, 30 and 45 days after application). ^{32}P uptake by treated turmeric plants in the bambooless plots was statistically similar to that for 8 × 8, 10 × 10 and 12 × 12 m spacing treatments. ^{32}P uptake by the neighbouring untreated turmeric plants decreased drastically as the distance of the untreated plants increased from the treated turmeric plants (e.g., 25 and 50 cm away from the treated plants). Furthermore, it also increased as the inter row spacing of bamboo increased. For instance, the untreated turmeric at 25 cm away from the treated plant in closest spacing (4 × 4 m) recorded 778 cpm and at same distance under widest spacing of bamboo recorded 6039 cpm at 15 days after ^{32}P application. Despite the reduction in ^{32}P uptake by the untreated plants with increase in distance from the treated plants, there was considerable uptake at wider spacing. For example, while the absorption by the untreated turmeric at 50 cm away from the treated plant was

Table 2 Uptake (kg ha^{-1}) of N, P and K by understorey turmeric as influenced by varying spacing for 7 year old bamboo (*Dendrocalamus strictus*) in central Kerala, India

Spacing (m)	N	P	K
4 × 4	12.15 (0.45)^a	2.41 (0.06)^a	31.38 (0.32)^a
6 × 6	20.90 (0.80)^b	3.98 (0.22)^b	40.43 (1.02)^b
8 × 8	33.35 (0.82)^c	5.98 (0.41)^c	47.08 (0.91)^c
10 × 10	50.84 (0.54)^e	7.38 (0.31)^d	57.33 (0.57)^d
12 × 12	66.99 (0.67)^f	9.52 (0.12)^e	67.62 (2.78)^e
Bambooless control	43.87 (2.58)^d	6.00 (0.19)^c	47.51 (0.53)^c

Values in the parenthesis are standard error of the mean

^{a,b,c,d,e,f} Values followed by same superscript in a column do not differ significantly ($p = 0.05$)

Table 3 Absorption of applied ^{32}P by turmeric grown under different spacing of 7 year old bamboo (*Dendrocalamus strictus*) in central Kerala, India

Spacing (m)	^{32}P counts per minute (cpm g^{-1}/min) at 15, 30 and 45 days after application								
	15			30			45		
	Treated plant	N25	N50	Treated plant	N25	N50	Treated plant	N25	N50
4 × 4	2706^{a} (3.40)	778^{a} (2.87)	417^{a} (2.60)	1045^{a} (2.74)	164^{a} (1.94)	102^{a} (2.10)	420^{a} (1.46)	85^{a} (0.68)	34^{a} (0.72)
6 × 6	$4868^{a,b}$ (3.64)	1089^{a} (3.03)	$928^{a,b}$ (2.94)	1220^{a} (3.07)	1026^{a} (3.01)	$925^{a,b}$ (2.41)	1260^{a} (2.97)	$1063^{a,b}$ (2.46)	$520^{a,b}$ (2.69)
8 × 8	$7579^{b,c}$ (3.86)	4482^{b} (3.62)	$892^{a,b}$ (2.93)	$5449^{a,b}$ (3.71)	$3921^{a,b}$ (3.30)	$2333^{a,b}$ (3.22)	5513^{b} (3.73)	1981^{b} (3.04)	$1865^{a,b}$ (3.14)
10 × 10	9778^{c} (3.98)	6904^{b} (3.73)	$2929^{b,c}$ (3.45)	7242^{b} (3.85)	$4652^{a,b}$ (3.59)	$2746^{a,b}$ (3.37)	5433^{b} (3.73)	2719^{b} (3.41)	$2222^{a,b}$ (3.27)
12 × 12	$11{,}003^{c}$ (4.03)	6039^{b} (3.71)	2682^{b} (3.41)	7310^{b} (3.82)	9276^{c} (3.49)	4269^{b} (3.47)	5247^{b} (3.69)	2881^{b} (3.42)	$2333^{a,b}$ (3.26)
Bambooless control	$10{,}911^{c}$ (4.03)	7437^{b} (3.85)	4973^{c} (3.43)	7302^{b} (3.79)	$5738^{a,b}$ (3.71)	4618^{b} (3.60)	4581^{b} (3.65)	$3283^{a,b,c}$ (3.38)	1624^{b} (3.12)

Values in the parenthesis are $\log_{10}(x + 1)$ retransformed values of cpm

N25 untreated turmeric plant at 25 cm away from the treated plant, *N50* untreated turmeric plant at 50 cm away from the treated plant

^{a,b,c} Values followed by same superscript in a column do not differ significantly ($p = 0.05$)

merely 34 cpm at 4 × 4 m spacing, the corresponding uptake at 12 × 12 m was 2333 cpm.

The recovery of ^{32}P by bamboo located at half the planting spacing from the treated turmeric varied significantly ($p < 0.05$) with an expected decline with increase in bamboo spacing (Table 4) till intermediate distances (4 × 4, 6 × 6 and 8 × 8 m), beyond which no tracer activity was detected in the bamboo plants. The recovery at closest spacing was 154.27 cpm at 15 days after application, which decreased to 40.65 cpm under the intermediate spacing of 8 × 8 m. A similar trend was discernible at other stages of sampling also.

Physico-chemical properties of soil

Bamboo clumps exerted favourable impact on soil bulk density which was significantly ($p = 0.05$) higher (1.54) in the plots without bamboo cover than the plots with bamboo (Table 5). Among the varying spacing treatments of bamboo, widest spacing (12 × 12 m) had the highest (1.44) and closest spacing (4 × 4 m) had the lowest (1.11) bulk density (Table 2). Soil pH was not substantially altered by bamboo spacing. But N, P and K content of the soil significantly ($p = 0.05$) varied with and without bamboo. NPK contents (0–20 cm) were consistently lower in the bambooless plots. As regards to bamboo spacing treatments, total N content was highest (2198 kg ha^{-1}) in the 4 × 4 m spacing, which decreased by 56 % in the 12 × 12 m treatment. Likewise, available P and exchangeable K were 21.32 and 203.49 kg ha^{-1} (4 × 4 m), which decreased by 45 and 33 % respectively in the 12 × 12 m spacing.

Discussion

Widely spaced bamboo clumps, in general, were shorter in stature and had greater clump diameter and crown coverage than closely spaced bamboos, implying competitive interactions (Table 1). The ability of bamboo to grow taller in denser stands and to produce larger clump size in less denser stands is consistent with the findings of Kibwage et al. (2008). Less number of culms and reduced crown spread in close spacing may be attributed to reduced growing space available above and belowground, imposing severe

Table 4 Recovery of ^{32}P by adjacent 7 year old bamboo (*Dendrocalamus strictus*) under varying spacing in central Kerala, India

Bamboo spacing (m)	^{32}P counts per minute (cpm g^{-1}/min) at 15, 30 and 45 days after application		
	15	30	45
4 × 4	154.27^{c} (2.18)	28.86^{c} (1.52)	4.30^{c} (0.79)
6 × 6	106.15^{b} (2.06)	17.78^{b} (1.34)	2.25^{b} (0.35)
8 × 8	40.65^{a} (1.67)	12.72^{a} (1.22)	0.88^{a} (0.30)
10 × 10	0	0	0
12 × 12	0	0	0

Distance of neighboring bamboo clumps from the treated turmeric plants is half of the respective spacing

Values in the parenthesis are $\log_{10}$ (x + 1) retransformed values of cpm

^{a,b,c} Values followed by same superscript in a column do not differ significantly (p = 0.05)

Table 5 Soil physico-chemical properties of differentially spaced 7 year old bamboo (*Dendrocalamus strictus*) plantation prior to understorey turmeric planting in central Kerala, India

Spacing (m)	Bulk density (Mg m^{-3})	Soil p^{H}	Total N (kg ha^{-1})	Avail. P (kg ha^{-1})	Avail. K (kg ha^{-1})
4 × 4	1.11 (0.01)^{a}	5.83 (0.15)^{a}	2197.70 (34.76)^{e}	21.32 (0.29)^{e}	203.49 (0.47)^{d}
6 × 6	1.18 (0.01)^{b}	5.8 (0.05)^{a}	1807 (17.38)^{d}	19.02 (0.26)^{d}	202.39 (0.78)^{d}
8 × 8	1.24 (0.01)^{c}	5.93 (0.12)^{a}	1556.50 (5.77)^{c}	17.20 (0.17)^{c}	192.77 (1.79)^{c}
10 × 10	1.31 (0.01)^{d}	6.0 (0.06)^{a}	1466.71 (17.38)^{b}	15.99 (0.22)^{b}	164.26 (0.31)^{b}
12 × 12	1.44 (0.01)^{e}	6.1 (0.10)^{a}	1404.97 (11.69)^{a}	14.73 (0.19)^{a}	153.26 (0.26)^{a}
Bambooless control	1.54 (0.01)^{f}	5.96 (0.09)^{a}	1396.41 (9.22)^{a}	14.43 (0.05)^{a}	152.86 (0.77)^{a}

Values in the parenthesis are standard error of the mean

^{a,b,c,d,e,f} Values followed by same superscript in a column do not differ significantly (p = 0.05)

restriction on resource acquisition for optimum growth. Several previous researchers also reported that height growth of dicot trees increased with decreasing spacing (e.g., Hummel 2000; Kunhamu et al. 2011). On the contrary, reports also suggest the insensitivity of height to initial planting density. Height growth generally remains unaffected by stand density except where the stand is extremely dense or so open that the trees are distinctly isolated (Schmidt et al. 1976; Seidel 1984). However, early faster increase in height growth for closely planted stands has been reported by Singh (2000) for *Alnus nepalensis*. The increase in clump diameter with increasing planting density is again consistent with growth observations for trees (Sjolte-Jorgensen 1967; Smith 2010). The trends were similar for crown width also both implying the significance of density regulation on the growth and productivity of bamboo. Probably the effect of planting density is more evident in terms of the increase in the number of culms per clump. Implicit is the overwhelming importance of density regulation on the productivity of bamboo.

Leaf area index assume greater importance in poly culture systems especially when intercrops are integrated as understorey. LAI, defined as the hemi-surface leaf area per unit soil area (Gower et al. 1999) would provide a powerful model parameter and also a valuable indicator of management practices and ecosystem services in polyculture systems such as agroforestry (Taugourdeaua et al. 2014). The close linkage between the understorey productivity and stand LAI is well established (Wythers et al. 2003; Jolly et al. 2004).

Stand management practices such as density regulation may influence the LAI which in turn can modify the understorey light regimes considerably. Knowledge on the optimal LAI for maximizing understorey productivity needs to be evolved for various agroforestry systems. In the present study, the higher bamboo LAI for the closely spaced treatments (Fig. 2)