J. Bamboo and Rattan, Vol. 1, No. 1, pp. 43–58 (2001)

Proximity, clump size and root distribution pattern in bamboo: A case study of *Bambusa arundinacea* (Retz.) Willd., Poaceae, in the Ultisols of Kerala, India

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Abstract—Root distribution pattern and competitiveness of bamboo (*Bambusa arundinacea* (Retz.) Willd.) for below ground resources in mixed species systems were evaluated using logarithmic spiral trenching and ^{32}P soil injection techniques respectively. Excavation studies indicated that rooting intensity in different soil horizons declined either exponentially or quadratically with increasing lateral distance from the bamboo clump. Surface horizon (0–10 cm) of the soil profile showed the least bamboo rooting intensity. It was highest in the 10–20 cm soil layer with nearly 27% of the total roots. Clump size is another important determinant of bamboo rooting intensity. Smaller bamboo crowns/clumps showed the lowest rooting intensity, when measured at 5 m and 7.5 m lateral distances and increased linearly with increasing crown radius. Implicit in this is the potential for management practices to regulate competition in mixed species systems through controlling clump size/crown expansion. Our results also showed that ^{32}P uptake by bamboo in binary combinations involving teak (*Tectona grandis*) and vateria (*Vateria indica*) was proportional to bamboo rooting intensity, when the ^{32}P label was applied to the dicot trees. Root competitiveness in polycultural systems involving bamboo, therefore, is a function of the proximity of bamboo to the associated tree/crop, which in turn, decides the bamboo rooting intensity.

Key words: Logarithmic spiral trench; ^{32}P uptake; root architecture; root competition; root distribution; rooting intensity; *Tectona grandis*; *Vateria indica*.

INTRODUCTION

Bamboos are perennial grasses that occur in the tropical and subtropical evergreen and deciduous forest formations of Asia-Pacific. Over 75 genera and 1250 species of bamboos are reported to occur in the world [1]. Important uses of bamboo include paper and pulp, fuel, food, feed, house construction, scaffolding, making several articles of everyday use [2], controlling soil erosion and facilitating on-site

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nutrient conservation [3, 4]. Although bamboos are plants of enormous economic importance to the rural people in several regions of the world, nowhere is their usefulness as great as in South and Southeast Asia. India, with 9.57 million ha of bamboo forests, is perhaps the most important bamboo producer in the world [5]. One hundred and thirty wild and cultivated bamboo species are reported to occur in India [2]. They exist under diverse ecological conditions, often as an understorey in many forest types. For example teak plantations of site quality II and III are recolonised by bamboos [6].

Bamboo (*Bambusa arundinacea* (Retz.) Willd.), being an important renewable natural resource is planted extensively, both as plantations [7] and in agroforestry [8] in India. In Kerala state where teak is raised extensively, *B. arundinacea* is either under planted with teak after the penultimate thinning and/or planted along the riverbanks, after the final felling of teak. In agroforestry systems (e.g. home gardens) bamboos occur either as scattered clumps or hedgerows on farm boundaries.

Being perennial grasses, bamboos are thought to have higher root length densities than dicots [9]. Thus in mixed species systems, they out-compete the field/tree crops grown in association. Root competitiveness is the ability to absorb the mineral nutrient elements applied in the effective rooting zone of a neighbouring species. Chandrasekhara [7] reported poor performance of teak in bamboo-rich plantations owing to interspecific competition for soil resources and/or space. Although root distribution patterns of a few hedgerow species have recently been elucidated [10], information on woody monocot root systems in general is scarce except for some palms [11, 12]. Most research on bamboos have emphasised its taxonomy, flowering, utilisation, inventory, etc. [13–15], with some attempts to illustrate the nutrient cycling aspects [3, 4, 7] and population dynamics [16].

Thus, we began our study on root distribution pattern of boundary planted bamboos to evaluate its potential for below ground competition in mixed species systems involving bamboos and other woody perennials. Previous paper [17] dealt with three hypotheses: (1) Effective rooting volume is a function of crown spread; (2) Proximity of trees depresses lateral spread of roots in mixed species systems; and (3) Closer the trees are located, the greater will be the subsoil root activity, which in turn facilitates active absorption of nutrients from deeper layers of the soil profile. In that paper we suggested that inter-specific root competition could be regulated by planting crops 8–9 m away from the bamboo clumps and/or by canopy reduction treatments.

In this paper we deal with the architectural pattern of bamboo roots, which determines the agronomic success of mixed species production systems involving bamboo. Specific issues addressed are: (1) How clump size and crown dimensions influence root distribution pattern of bamboo and its rooting intensity at different lateral distances from the clump? (2) Whether root competitiveness is a function of proximity of the bamboo clumps, and (3) How rooting intensity influences foliar ^{32}P

recovery of bamboo in mixed species production systems involving selected dicot tree species?

MATERIALS AND METHODS

Study area and climate

The study was conducted at Vellanikkara, Thrissur district, Kerala (10°13′N latitude and 76°13′E longitude and at an elevation of 40.29 m above sea level), during the period from June 1997 to May 1998. Vellanikkara experiences a warm humid climate, having a mean annual (1985–1997) rainfall of 2824 mm, most of which is received during the southwest monsoon (June to August). The mean maximum temperature ranges from 28.6°C (July) to 36.5°C (April) and mean minimum temperature varies from 21.8°C (July) to 25.6°C (April). The total rainfall received during the study period was 3247.3 mm. The soil at the experimental site is an ustic, isohyperthermic Typic Plinthustult with the following physico-chemical properties: soil pH (1 : 2 soil-water suspension), 5.74; total N (micro-Kjeldahl method), 0.13%; available P (Bray-1 extract and chloromolybdic blue colour method), 14.10 mg kg^{-1}; available K (1 N neutral CH_3COONH_4 extraction and flame photometry), 44.17 mg kg^{-1}; organic C, 1.28% (Walkley-Black method). *B. arundinacea* was planted in the experimental area in June 1985 along the boundary line of the field (Fig. 1).

Root distribution

As described in Divakara *et al.* [17], six small (<2.5 m clump diameter), medium (2.5 to 4.0 m) and large (>4.0 m) clumps each were randomly selected from the boundary planted bamboo (age 12 years). Diameters of the selected clumps at 1.37 m above ground level ranged from 1.2 to 2.3 m for small, 2.6 to 3.7 m for medium and 4.1 to 5.4 m for large clumps (Fig. 2). Crown radius of the selected clumps was measured by projecting the crown edges to the ground and it ranged from 5.4 to 7 m for small, 6.84 to 9.43 m for medium and 7.74 to 12.21 m for large clumps.

The root system of each selected clump was partially excavated using a logarithmic spiral trenching technique [18]. The spiral nature of the trench enables a large proportion of the root system to be examined with minimal damage to the clumps [19]. The dimensions of each trench were determined using the formulae given in Divakara *et al.* [17] and the contours of both internal and external spirals were marked on the ground using a plastic rope. The trench was then dug to a depth of 60 cm and to a breadth of 60 cm taking care that the sides remained intact. Severed bamboo roots (living) on the internal and external trench walls were counted by using square grids of $50 \times 50\ cm^2$ (subdivided into 10 cm depth intervals). Roots were classified into <2 and >2 mm diameter classes at the time of counting (no

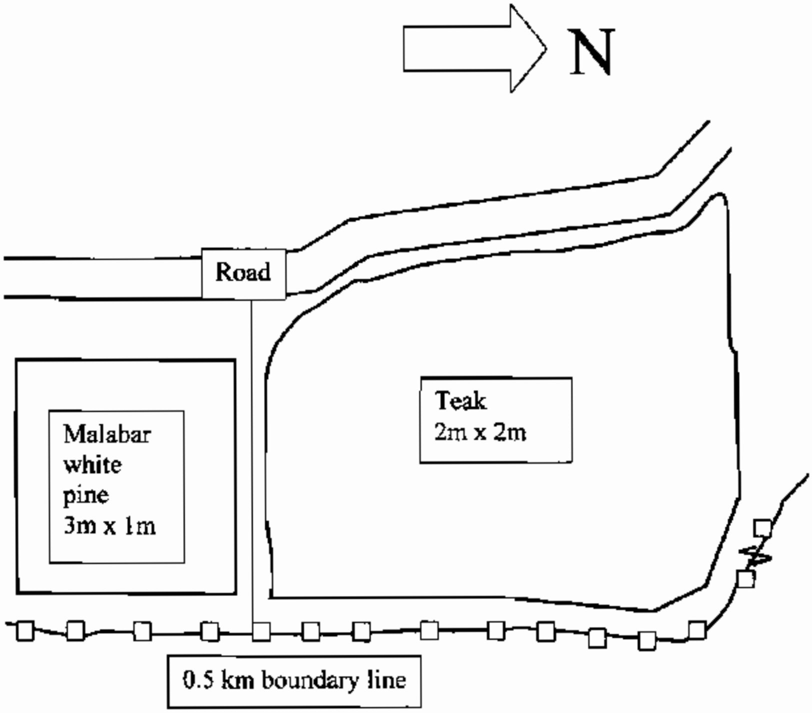

Figure 1. Schematic diagram showing bamboo (□) planting pattern at the study site (not-to-scale). Containerised bamboo seedlings were planted along the boundary line at irregular distances in 1985. One-year-old teak stumps (at 2×2 m spacing) and Malabar white pine (vateria) seedlings (3 m $\times$ 1 m) were planted in June 1985 and July 1991 respectively. There were about 40 bamboo clumps bordering teak with a mean spacing of 21 m (range: 7.6 to 64.2 m) and about 25 clumps adjacent to vateria at a mean spacing of 11 m distance (range: 3.5 to 22.2 m).

roots exceeded 5 mm diameter). The grids were placed along the spiral trench at 1 m intervals. The radial distance of each grid from the clump's periphery (outer culms) was measured. It ranged from 0.9 to 1.75 m, 1.95 to 2.8 m and 3.0 to 4.1 m for the first grid in small, medium and large clumps, respectively. The corresponding figures for the last grid were 6.5 to 8.7, 6.7 to 9.5 and 7 to 9.7 m.

To assess the potential for interspecific competition between bamboo and the associated crops grown at variable distances from the clump, we examined the bamboo rooting intensity in different soil layers at 5 m and 7.5 m away from the bamboo clumps, as rooting intensity at these distances may provide useful insights on intercropping. However, these are not rigid limits of bamboo root zones, and they were selected arbitrarily to indicate the potential for interspecific competition, if crops are planted at these distances. The surface layer (0–10 cm), however, was excluded from this analysis as it contained relatively fewer number of bamboo roots.

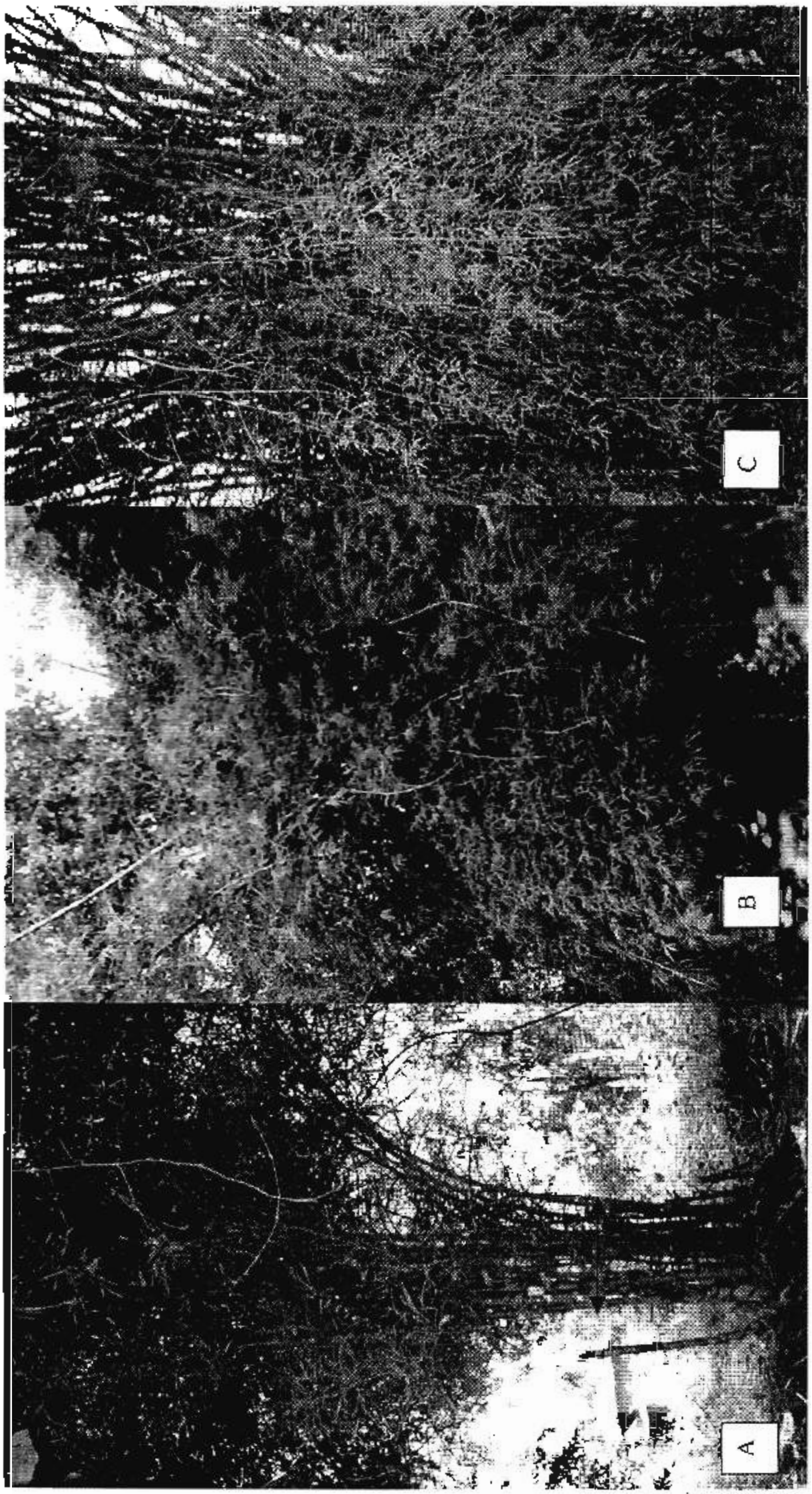

Figure 2. Variations in bamboo clump sizes. A — small, B — medium and C — large bamboo clumps. Arrows roughly represent breast height positions.

Tracer studies to characterise root interactions

To evaluate the relationship between bamboo rooting intensity and its competitiveness, two binary associations, namely, teak (*Tectona grandis* Linn. f., Family-Verbenaceae) + bamboo and Malabar white pine (vateria, *Vateria indica* Linn., Family-Dipterocarpaceae) + bamboo, were used. A ^{32}P soil injection technique was employed for this purpose (see Ref. [17] for details). Eighteen experimental units of teak + bamboo and 12 vateria + bamboo units were selected taking into consideration factors such as size of bamboo clumps/other tree components and distance between them. The distance between teak and bamboo ranged from 1.5 to 4.4 m in the teak + bamboo association, and that between vateria and bamboo ranged from 2.3 to 6.5 m in the vateria + bamboo system. For soil application of ^{32}P, eight equally spaced holes were dug to either 25 cm or 50 cm at a radial distance of 50 cm from the trunk of the selected teak/vateria tree using a soil auger of 2 cm diameter. ^{32}P solution at a carrier level of 1000 mg l^{-1} P was dispensed into the access tube at the rate of 2 ml per hole during the north-east monsoon on November 4, 1997, using a device fabricated for the purpose [20]. The total radioactivity applied per plant was 116.92 MBq (3.16 mCi).

Foliar ^{32}P count rates of bamboo at 31 days after application of the label, was assayed as described in Divakara *et al.* [17]. The method consisted of wet digestion of one gram of plant sample (of most recently matured leaves, after oven drying) using a diacid mixture (HNO_3 and $HClO_4$ in 2 : 1 ratio). The digest was then transferred to a counting vial and made up to 20 ml volume. The vials were counted in a liquid scintillation counter (Pharmacia-LKB, Finland) by the Cerenkov counting technique [21]. The count rates (counts per minute, cpm per g dry weight) were corrected for background as well as for decay.

Computations and statistical analyses

Root counts were converted into rooting intensity (number of roots m^{-2}; [22]) and regressed on lateral distance from the bamboo clumps (i.e. proximity) depth-wise in SPSS for Windows (Release 6.0). The best-fitting equations for each soil depth based on standard error of estimate (SEE), coefficient of determination (R^2) and bias by lateral distance from the clump are given in Table 1. Root intensity data from the excavation studies were analysed for difference between clump size and lateral distance using ANOVA with repeated measures (MANOVA) employing the statistical package SPSS (Advanced Statistics, version 2.0; [23]). The general model is $y_i = \mu_i + e_i$, for individual i, $(i = 1, \ldots, n)$ where y_i is the vector of p measurements on an individual, μ_i is the corresponding mean vector and e_i is a vector of random errors associated with the measurements on the ith individual, and is assumed to be constant across individuals, with mean 0 and variance-covariance matrices $V(e_i) = \Sigma$; thus Σ is of order $p \times p$ [24]. The common tests employed for evaluating differences between groups are Pillais trace, Wilk's lambda and Hotelling's trace [25].

Table 1.
Regression models linking bamboo rooting intensity and distance from the clump for small, medium and large sized bamboo clumps in different horizons of the Ultisols of Kerala, India (y = rooting intensity, # m^{-2} and x = distance in m, n = number of observations)

Soil depth (cm)	Model	R^2	N	F sigf	Standard error of estimates
Small					
0–10	$y = 494.3679 - 146.8148x + 11.5426x^2$	0.79	13	0.000	51.397
10–20	$y = 1005.8503e^{-0.2792x}$	0.91	15	0.000	0.188
20–30	$y = 792.7482e^{-0.2413x}$	0.91	15	0.000	0.158
30–40	$y = 684.9391e^{-0.2500x}$	0.89	15	0.000	0.183
40–50	$y = 550.6825e^{-0.2579x}$	0.85	15	0.000	0.233
Medium					
0–10	$y = 712.1747 - 181.8384x + 11.8971x^2$	0.93	15	0.000	29.710
10–20	$y = 983.9518 - 123.6092x + 2.1585x^2$	0.97	16	0.000	38.33
20–30	$y = 1188.1259e^{-0.2515x}$	0.89	17	0.000	0.180
30–40	$y = 1244.8662e^{-0.2841x}$	0.87	17	0.000	0.226
40–50	$y = 949.8837 - 175.1271x + 8.3823x^2$	0.92	16	0.000	51.755
Large					
0–10	$y = 364.0316e^{-0.1653x}$	0.46	18	0.002	0.339
10–20	$y = 1714.3478e^{-0.3232x}$	0.92	18	0.000	0.180
20–30	$y = 954.9620e^{-0.2288x}$	0.85	18	0.000	0.178
30–40	$y = 1355.8161e^{-0.3052x}$	0.91	18	0.000	0.183
40–50	$y = 919.3577e^{-0.2545x}$	0.83	18	0.000	0.218

Regression analysis was used to relate bamboo rooting intensity at 5 and 7.5 m lateral distances to crown radius (Microsoft Excel) and correlation analysis to elucidate the nature of relationships between bamboo rooting intensity and ^{32}P activity in the leaves of bamboo (when the ^{32}P label was applied to either teak or vateria in the teak + bamboo and vateria + bamboo combination). Bamboo rooting intensity at 5 m and 7.5 m, and for the whole range of lateral distances between bamboo and the ^{32}P treated teak/vateria (1.5 to 6.5 m) for particular soil horizons (20 to 30 cm or 40 to 50 cm corresponding to 25 and 50 cm depths of ^{32}P placement respectively) and clump sizes, were estimated using the prediction equations given in Table 1.

RESULTS AND DISCUSSION

Root architecture of B. arundinacea

B. arundinacea has an extensive and ramified network of primary (arising directly from the pachymorphic rhizomes) and secondary roots (Fig. 3). Most roots show a diatropic (syn. plagiotropic, see [26], p. 45) growth pattern while some roots

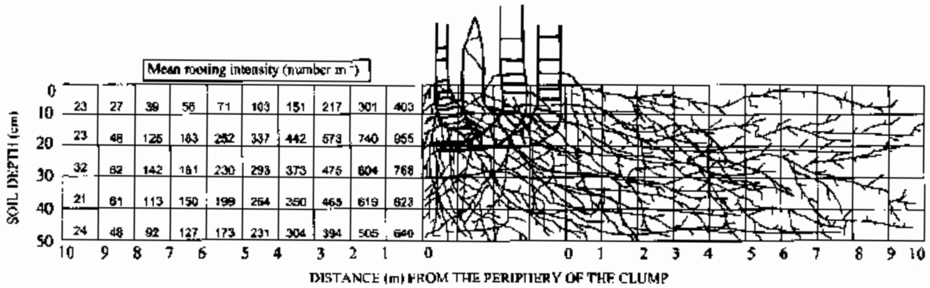

Figure 3. Schematic presentation of the root architectural pattern of a typical bamboo clump in the Ultisols of Kerala, India. Note that although most primary roots arise from the rhizomes, a few are seen emerging from the transitional zone between rhizomes and culms (above ground) also. Figures on left indicate estimated mean (for small, medium and large clumps) rooting intensities at different lateral distances within a given soil layer (calculated using the regressions given in Table 1).

especially those beneath the clumps follow a positropic mode (syn. orthotropic). Root systems in the present study were only partially excavated following the logarithmic spiral trenching technique. Implicit in this method is the assumption that typical bamboo root systems are approximately symmetrical, suggesting that architectural patterns observed in the present study by excavating one side of the clump mirrors the growth pattern on the opposite side. Other bamboo species are also expected to follow a similar architectural pattern. However, we did not come across any previous studies dealing specifically with bamboo root architecture.

The majority of bamboo roots were in the 'less than 2 mm diameter' class with fewer than 10% of the roots in the 2–5 mm class. Woody monocots in general possess profusely branched fibrous root systems and bamboos are perhaps no exception to this general rule. It is also well known that the functional attributes of roots are associated with their diameter [27] and the fine roots comprise most roots involved in nutrient uptake. However, experimental data available in this respect mostly confined to dicots. Large number of smaller roots (Fig. 3) also implies the potential of *B. arundinacea* to absorb soil nutrients preferentially over other crops growing in the vicinity. In addition, it underscores the potential of bamboos for on-site conservation of nutrients, especially in respect of leachable elements such as potassium [7, 17], which may be intercepted and re-absorbed in the plant biomass, lest it is lost through hydrological outputs. Decomposing fine roots also act as a source of soil organic matter and nutrient enrichment [28].

Regarding the lateral root spread of mature *B. arundinacea* clumps, roots extended up to a maximum distance of 9.5 m at this Ultisol site (Fig. 4). Mean rooting intensity also declined exponentially or quadratically with distance from the clump (Fig. 4 and Table 1). Larger clumps obviously had greater lateral root spread, while smaller clumps extended their roots to a maximum distance of little over 8 m, with less than 4% of total roots beyond 8 m from the base of the clump. The corresponding figures for medium and large clumps were 5.4% and 9.3%,

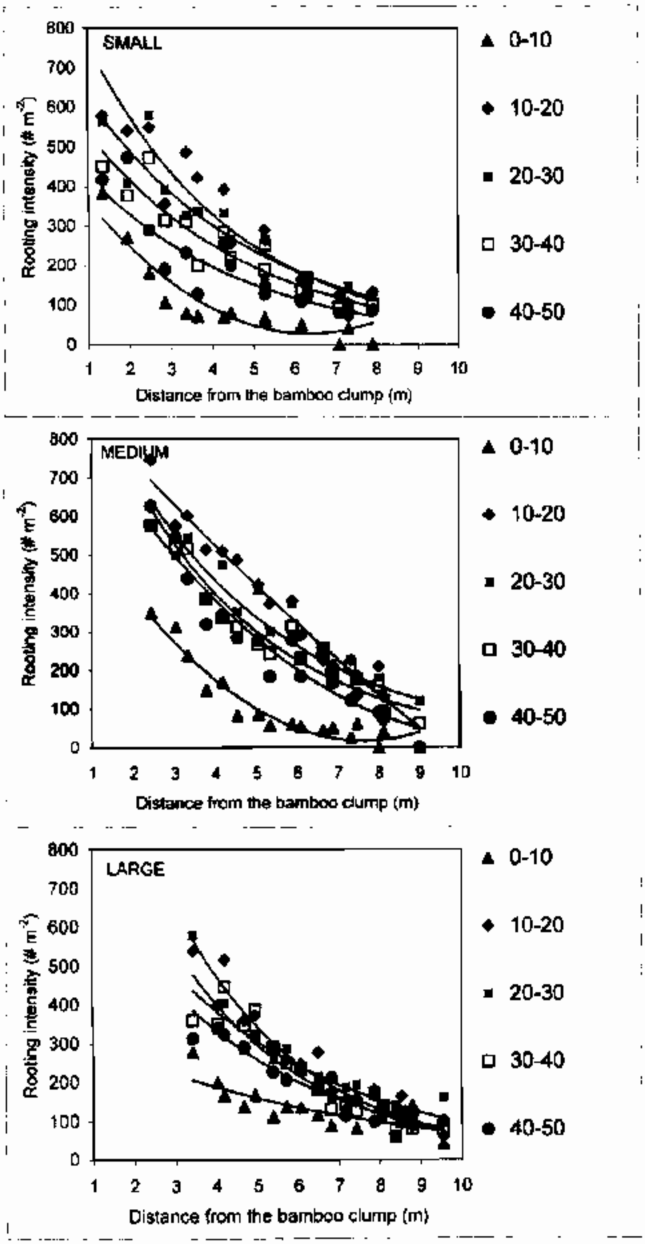

Figure 4. Rooting intensity of boundary planted bamboos in different soil layers at different lateral distances for small (<2.5 m diameter), medium (2.5 to 4.0 m) and large (>4.0 m) clumps in the Ultisols of Kerala, India (see Table 1 for fitted equations).

respectively. Other root studies on dicot trees within the humid tropical zones of peninsular India, however, found a less extensive lateral spread of roots. For instance, most of the physiologically actives roots of eight and a half year old

Table 2.
Relationships between bamboo rooting intensity (number m^{-2}) and crown radius (range: 5.4 to 12.21 m) for different soil layers at 5 m and 7.5 m away from the bamboo clumps in the Ultisols of Kerala, India (Model: $y = a + bx$, where y is the rooting intensity, x is the crown radius, a is the intercept and b slope; n = number of observations, p = probability level of significance)

Soil depth (cm)	Lateral distance (m)	Rooting intensity (# m^{-2}) Mean	Min	Max	Intercept a	Slope b	R^2	Standard error	n	p
10–20	5	365	50	600	−350.7055	81.3302	0.83	89.50	11	<0.001
	7.5	144	20	360	−71.3214	24.4270	0.34	83.56	11	0.06
20–30	5	336	70	560	−274.7791	69.3964	0.74	100.26	11	<0.001
	7.5	158	40	320	12.5074	16.5539	0.21	77.73	11	0.152
30–40	5	276	110	632	−246.7269	59.4095	0.75	83.15	11	<0.001
	7.5	165	20	380	−189.6350	40.3511	0.73	59.80	11	<0.001
40–50	5	211	60	487	−149.7359	40.9988	0.59	84.18	11	0.006
	7.5	119	20	320	−190.1575	35.1419	0.78	45.49	11	<0.001

Artocarpus hirstus (average diameter at breast height, 7.75 cm) were confined to 3 m radial distance [29]. Our data (Table 2) also suggest that bamboo-rooting intensity at 5 m (10–50 cm soil layer) ranged from 50 to 600 roots m^{-2} depending on crown size. Other studies on root density also report similar wide variations in rooting intensity. For instance, Tufekcioglu *et al.* [30] found that root density of multispecies land use systems involving poplar (*Populus X euroamericana' Eugenei*), switch grass (*Panicum vigratum*), corn (*Zea mays* L) and soybean (*Glycine max* (L) Merr.) ranged from 0.2 to 44.2 per square decimeter and declined significantly with increasing depth.

A comparison of the data in Fig. 4 indicates that rooting intensity in different soil layers decreased with depth except for the surface horizon (0–10 cm), which incidentally registered the least value. The highest rooting intensity was observed in the 10–20 cm layer with nearly 27% of all roots (Fig. 3). The pattern of root distribution according to depth observed in *B. arundinacea* is similar to that of dicot root systems in this locality, where most roots were concentrated in the upper 20–50 cm of soil [29, 31–33]. Although bamboo roots may be present below 50 cm also, the rooting intensity may be substantially lower. Since our studies did not examine root growth beyond this depth, we cannot make further generalizations in this regard.

Factors affecting root bamboo distribution

As expected, the influence of clump size on bamboo root distribution was paramount (Fig. 4). MANOVA indicated statistically significant variations for lateral distances, clump sizes, soil depth and their interactions. Pillais trace, Hotelling's trace and Wilk's lambda were highly significant ($p < 0.001$). A strong correlation between root spread and average crown radius was reported by Divakara *et al.* [17] for bamboos and Tomlinson *et al.* [19] for dicot trees such as *Parkia biglobosa* (Jacq.) Benth.

Lower rooting intensity in the surface horizon (Fig. 4) can be explained by the relatively lower soil moisture availability during the dry season with little or no rainfall (March to May), when the study was conducted. Seasonal variations in the vertical distribution pattern of physiologically active roots for bamboo clumps especially in the surface horizons of the soil profile are, therefore, probable on account of variations in moisture availability. This in turn suggests that bamboo root distribution is co-determined by the interaction between clump size and environment, including pedo-climatic factors, microbial and faunal interactions. In general, roots grow preferentially in those soil layers that are rich in organic matter and are well aerated. Low moisture availability and/or presence of a 'root floor' such as a hard pan ([26], p. 207), however, impede root spread/deeper root penetration thus blocking architectural development of whole root systems. Lehmann *et al.* [34] also reported similar findings for dryland agroforestry systems in Kenya.

Proximity of other species/individuals favours competitive downward displacement of bamboo roots [17]. Schroth [35] reported that plants tend to avoid excessive root competition both at the root system level and at the single root level by spatial segregation. Hence limited lateral root spread of bamboo may be expected if plant species differing in their soil occupation strategies are grown in association with bamboo. Also, in highly structured systems such as the present one involving mixed species plantations and agroforestry, wherein planted bamboos follow specific geometry and/or are managed to regulate clump/canopy spread, the root architecture may be different from that of natural bamboo bearing forests, where such controls seldom operate.

Differential bamboo root spread as a function of clump size also implies the potential for clump management practices to regulate lateral spread of bamboo roots. Management practices such as culm thinning, which generally controls clump size, and branch pruning, which regulates crown spread, have the potential to reduce lateral root spread, when judiciously applied. Root management practices, such as trenching to spatially separate bamboo root systems, are also advisable when tree/arable crops are to be grown at close proximity.

Root distribution and root interactions

The central hypothesis of agroforestry is that different life forms such as trees and arable crops occupy to some extent different soil strata and their root systems lead to a certain degree of spatial complementarity in resource use [36]. The potential to form deep root systems is, therefore, a desirable feature of woody perennial components in agroforestry. Coincidentally, rooting depth determines to what extent plants can use subsoil water and nutrients that make them less dependent on the supply from the topsoil. Deep-rooted plants make available subsoil resources

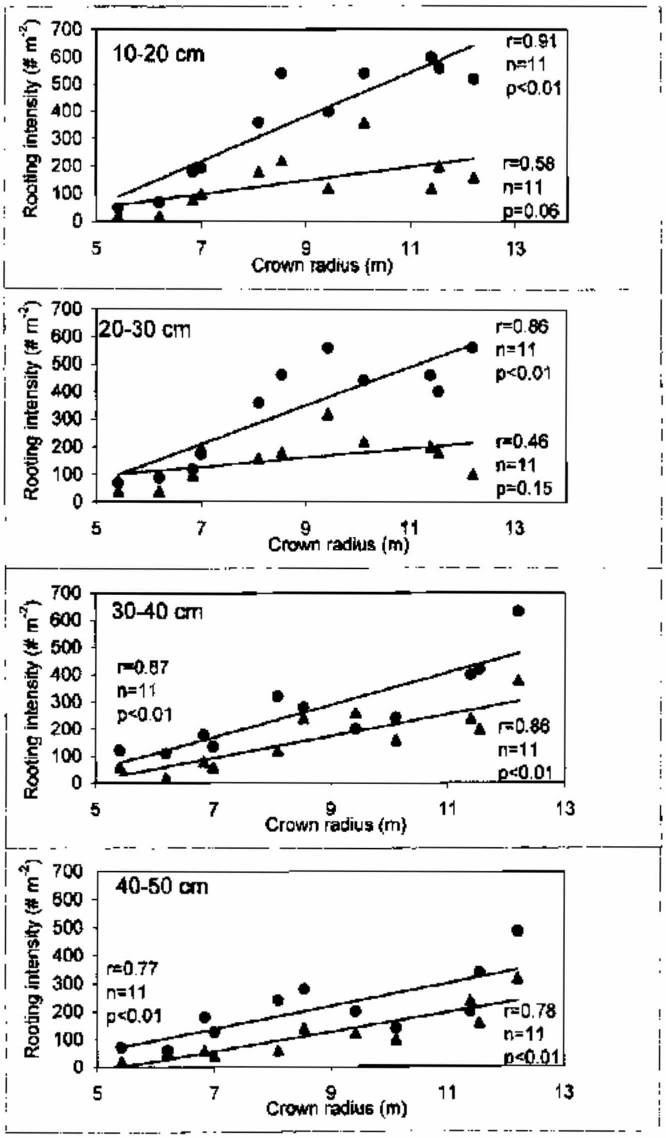

Figure 5. Rooting intensity of boundary planted bamboo at different depth intervals in the Ultisols of Kerala, India as influenced by crown radius (circles and triangles represent two arbitrarily selected lateral distances from the clump, namely 5 m and 7.5 m lateral distance, respectively — see Table 2 for fitted equations).

to associated plants with shallower root systems through nutrient pumping and hydraulic lift [35, 37].

However, the elaborate and profusely branched bamboo root systems and the concentration of feeder roots in the surface horizons (10–50 cm) of the soil profile at this Ultisol site obscure the chances of mixed species production systems involving *B. arundinacea* at close proximity. Although fewer roots are reported in the surface

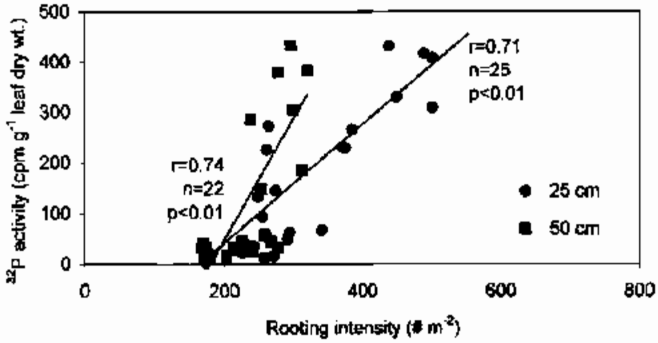

Figure 6. Relationships between bamboo rooting intensity and foliar ^{32}P recovery at 31 days after application of the ^{32}P label in binary associations involving teak + bamboo or vateria + bamboo, in the Ultisols of Kerala, India. Rooting intensity of bamboo for a particular combination of lateral distance (corresponding to the distance between bamboo and the ^{32}P labelled teak/vateria) and depth of ^{32}P placement (20–30 or 40–50 cm) was estimated using the prediction equations in Table 1 (cpm-counts per minute).

horizon (0–10), which in turn signifies some vertical root stratification, there is little evidence otherwise, to show that *B. arundinacea* forms a deep root system. Rooting intensity was highest in the 10–20 cm soil horizon with nearly 27% of total roots. While many trees are likely to develop roots systems deeper than this [35], field crops mostly have roots within the top layers of the soil profile. Therefore, if soil resources (e.g. nutrients and water) are in limited supply, bamboos may be more effective in acquiring these resources than the other associated crops.

But the ability of roots to proliferate into the lower layers of the soil profile cannot be ignored owing to the plasticity in root system responses [17, 38], particularly when bamboos are grown in association with other species. Tilman [39] showed that a large number of competing species coexist in a spatially structured habitat. This, in turn, suggests that bamboos both in natural and agroecosystems are bordered by fuzzy root zone limits. In bamboo-based agroforestry, arable crops are typically grown at variable distances from the clumps. Our data (Fig. 5) suggest that rooting intensity increased linearly with increasing crown radius in all soil layers at arbitrarily selected lateral distances from the clump, such as 5 and 7.5 m. Competition for below ground resources between trees and agronomic crops is, therefore, a distinct possibility in bamboo-based simultaneous agroforestry systems, if crops are planted at these distances and it may seriously reduce associated crop yields. However, spatial segregation of the roots of associated plants may abate such inter-specific competition. Spatial segregation can be achieved either by planting crops 8–9 m away from bamboo clumps or by clump management practices such as pruning, culm thinning and/or by soil trenching.

To evaluate the hypothesis that root competitiveness in bamboo is a function of its rooting intensity, we related bamboo-rooting intensity (at the respective lateral distance from bamboo clump) to ^{32}P uptake by bamboos adjacent to ^{32}P treated teak/vateria trees. We observed that ^{32}P absorbed from 25 and 50 cm depth increased linearly as rooting intensity increased (Fig. 6), despite low R^2 values (0.5 and 0.55 respectively for 25 and 50 cm). In general changes in rooting intensity mirrors variations in lateral distance to bamboo clumps. Although Schroth [35] reported that high fine root length densities are likely to be more competitive than plants with lower root length density, direct evidence from mixed species systems involving bamboo were scarce in this respect.

In polyculture systems, trees in general exert either a competitive or complementary influence depending on the nature of the species involved [31]. Greater ^{32}P uptake by bamboo at higher rooting intensity implies overlapping root systems and therefore, potentially competitive influences. However, this may also reflect complementarity of below ground resource use, especially from deeper soil layers and increased overall ^{32}P recovery, as reported by Divakara *et al.* [17].

CONCLUSIONS

Although several of our findings may be site-specific, we feel that the concepts considered have general applicability in the management of bamboo based agroforestry systems. Most bamboo roots showed a diatropic growth pattern and their intensity declined either exponentially or quadratically with distance from the clump: the larger the clump, the greater was the lateral root spread. Nonetheless, caution should be used in extrapolating data in this way, as proximity of other species/individuals and the edaphic factors that control root extension and turnover need to be taken into account when considering the lateral spread of roots. Uptake of ^{32}P by bamboo was influenced by proximity to teak/vateria. ^{32}P absorption by bamboos was generally higher when the bamboos were closer, owing to the greater root concentration. This in turn suggests the need for standardising planting geometry and tree management practices for 'ecological competition-free agroforestry' practices. To ease potential root competition between bamboo and the associated species in such systems, associated crops should be planted either at 8–9 m away from the bamboo clumps and/or root pruning and crown manipulation strategies that modify the soil occupation strategies of bamboo roots must be adopted. Reduction in root length density by trenching or tillage is an important strategy in this respect.

Acknowledgements

Field and laboratory facilities provided by the Associate Dean, College of Forestry and Professor, Radiotracer Laboratory, Kerala Agricultural University, Vellanikkara, are gratefully acknowledged. Professor Dr. R. A. A. Oldeman and another anonymous reviewer provided useful comments on a previous version of the manuscript.

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