



Bamboo hedgerow systems in Kerala, India: Root distribution and competition with trees for phosphorus

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Abstract

In a field study on bamboo (*Bambusa arundinacea* (Retz.) Willd.) hedgerow systems of Kerala, we tested the following three hypotheses: (1) Effective root foraging space is a function of crown spread, (2) Proximity of trees depress lateral spread of roots in mixed species systems and (3) The 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. Root distribution of boundary planted bamboo and root competition with associated trees in two binary mixtures, teak (*Tectona grandis*)-bamboo and Malabar white pine (*Vateria indica*)-bamboo, were evaluated using modified logarithmic spiral trenching and ³²P soil injection techniques respectively. Excavation studies indicate that rooting intensity declined linearly with increasing lateral distance. Larger clumps manifested wider foraging zones. Eighty three per cent of the large clumps (> 4.0 m dia.) extended roots beyond 8 m while only 33% of the small (< 2.5 m dia.) clumps extended roots up to 8 m. Highest root counts were found in the 10–20 cm layer with nearly 30% of total roots. Although nearness of bamboo clumps depressed root activity of teak and *Vateria* in the surface layers of the soil profile, root activity in the deeper layers was stimulated. ³²P recovery was higher when applied at 50-cm depth than at 25-cm depth implying the safety net role of tree roots for leached down nutrients. Inter specific root competition can be regulated by planting crops 8–9 m away from the bamboo clumps and/or by canopy reduction treatments.

Introduction

Bamboos are major woody components of many traditional land use systems and/or its modern variants in the tropics. *Bambusa arundinacea* (Retz.) Willd. is an important species in the home-gardens (Kumar 1997) and several teak plantations of Kerala (Chandrashekhara 1996). The bamboo 'talun-kebun' system of West Java 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'.

In the traditional land use systems of India and elsewhere, bamboos frequently occur on farmlands as scattered clumps and/or as hedgerows on boundaries. Nonetheless, the farmers apprehend severe competition for site resources between bamboo and other components. Chandrashekhara (1996) reported poor performance of teak in bamboo-rich plantations owing to inter specific

competition. There is a tacit assumption that the profusely growing surface (fibrous) root systems of bamboo may out-compete the field/tree crops grown in association. Furthermore, if soil resources are limited, bamboo may be more effective in acquiring these scarce resources than other species grown in association. Trenching to spatially isolate bamboo roots from the rest of the crops is, therefore, common in many agricultural holdings of India.

However, information on spatial distribution of bamboo root system, which decides its ability to acquire water and nutrients preferentially over other associated crops, is seldom available. In this study we attempted to characterise the root distribution pattern of boundary planted bamboos and evaluate the extent of competitive/complementary effects in mixed species systems involving woody perennials.

Three hypotheses were tested: First, the effective foraging space (where more than 80% of the active roots are present) of bamboo may be a function of its crown spread – the larger the crown spread, the greater will be the lateral expansion of roots. Secondly, the occurrence of two or more trees/species close to one another may favour diminished lateral spread and/or deeper root penetration of the woody components. In this connection, Lehmann et al. (1998) observed that in alley cropping systems involving *Acacia saligna* and sorghum, *Acacia*, with their deep root system invested more in the subsoil root zone to avoid competition for water and nutrients. However, this hypothesis remains untested for mixed species systems involving two or more woody perennials where root system plasticity perhaps may be more explicit. Finally, in mixed species stands involving bamboo, the closer the tree components are located the greater will be the subsoil ^{32}P recovery. This in turn, may provide further evidence to evaluate the safety-net hypothesis (van Noordwijk et al. 1996). Although Rowe et al. (1999) using ^{15}N placement at different soil depths evaluated the safety-net hypothesis in respect of hedgerow intercropping systems involving *Gliricidia*/groundnut and *Peltophorum*/groundnut in south east Asia, information relating to bamboo hedge rows is lacking. In addition, our approach differed from their study in that we selected two bamboo based systems involving important tropical tree

species and used the ^{32}P soil injection, a widely accepted technique (George et al. 1996; Jamaludheen et al. 1997; Thomas et al. 1998; Kumar et al. 1999) for characterising root activity in different soil strata.

Materials and methods

Study area and climate

The study was conducted at Vellanikkara, Thrissur district, Kerala ($10^{\circ}13'$ N latitude and $76^{\circ}13'$ E longitude and at an elevation of 40.29 m above sea level), during the period June 1997 to May 1998. Vellanikkara experiences a warm humid climate, having a mean annual (1985–1997) rainfall of 2824-mm, most of which falls 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 of the experimental site is a ustic, isohyperthermic Typic Plinthustult. Mean soil attributes with standard deviations ($n = 4$) are as follows: Soil pH (1:2 soil-water suspension): 5.74 ± 0.004 , total N (micro-Kjeldahl method): $0.13 \pm 0.004\%$, available P (Bray-1 extract and chloromolybdic blue colour method): $14.10 \pm 0.586 \text{ mg g}^{-1}$, available K (1N neutral $\text{CH}_3\text{COONH}_4$ extraction and flame photometry): $44.17 \pm 0.680 \text{ mg g}^{-1}$ and organic C (Walkley-Black method): $1.28 \pm 0.087\%$ (Jackson, 1958).

Bamboo (*Bambusa arundinacea*, Family-Poaceae) was planted in the experimental area in June 1985. Containerised stock was used and a linear distance of over 0.5 km was planted along the field boundary in a single row. A teak (*Tectona grandis* Linn. f., Family-Verbenaceae) plantation was established in one part of the field by planting one-year-old teak stumps at $2 \times 2 \text{ m}$ spacing at about the same time. A field experiment on Malabar white pine (*Vateria indica* Linn., Family-Dipterocarpaceae) was established in another part of the field in July 1991. The strip neighbouring bamboo clumps followed a spacing of $3 \text{ m} \times 1 \text{ m}$. Weeding and pruning of lower branches were carried out in the teak and *Vateria* plantations at regular intervals.

There were about 40 bamboo clumps bordering teak stand 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). This irregularly spaced hedgerow probably represents the typical way in which bamboos occur in the farmers' fields of Kerala. The clump size was variable with a mean radius of 2 m (range: 0.43 to 3.0 m), mean height of 12.5 m (range: 5.4 to 19.2 m) and mean number of 40 culms per clump (range: 5 to 98).

Characterising root distribution using logarithmic spiral trench method

Eighteen bamboo clumps were randomly selected. Minimum distance between two selected clumps was 5 m. Based on diameter, the clumps were classified as small (1.0 to 2.5 m diameter), medium (2.5 to 4.0 m) and large (4.0 to 5.5 m), having six clumps in each category. Crown radius of the selected clumps, measured by projecting the crown edges to the ground, ranged from 5.4 to 12.2 m.

Root systems of each selected clump was partially excavated using a logarithmic spiral trenching technique (Huguet 1973). The spiral nature of the trench enables a large proportion of the root system to be examined with minimal damage to the clumps (Tomlinson et al. 1998). The dimensions of each trench was determined using the following formulae (modification of Tomlinson et al. 1998).

$$x = 0.75 (d) \quad (1)$$

$$y = [\ln (r/d)]/\pi/2 \quad (2)$$

$$z = xe^{y\theta} \quad (3)$$

where

d = clump diameter in m

r = the average of the crown radius at four cardinal points in m.

x = the distance of the starting point of the spiral from the clump in m.

y = natural logarithm of the ratio of crown radius to diameter of clump divided by $\pi/2$ and

z = the distance of any point on the spiral from the clump base in m.

Inside trajectory of each trench (A) was obtained by computing 'x' from a north facing point on the clump base, the origin (O), with the spiral bending clockwise in the opposite direction, thus sampling a 135° sector of the root system. θ was assigned 0°, 22.5° ($\pi/8$), 45° ($\pi/4$), 67.5° ($3\pi/8$), 90° ($\pi/2$), 112.5° ($5\pi/8$) and 135° ($3\pi/4$) to obtain the seven co-ordinates of the inside trench: OA, OB, OC, OD, OE, OF and OG as shown in Figure 1. Exterior side of the trench was fixed by stretching the co-ordinates for the internal side by 60 cm to give OA', OB', OC', OD', OE', OF', and OG'.

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 placing a 50 cm × 50 cm quadrat (subdivided into 10-cm depth intervals). Roots were classified into < 2 and 2–5 mm diameter classes at the time of counting (no roots exceeded the 5 mm diameter limit). The quadrats were placed along the spiral trench at 1-m interval up to 10 m from the origin. Radial distance of each quadrat 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 quadrat in small, medium and large clumps respectively. The corresponding figures for the last quadrat were 6.5 to 8.7 m, 6.7 to 9.5 and 7 to 9.7. Root counts were converted into rooting intensity (number of roots m⁻², Bohm, 1979).

Tracer studies to characterise root interactions

To assess root activity pattern and the nature and magnitude of root competition between bamboo and other associated tree components in mixed species systems, two field experiments involving binary associations of teak (*Tectona grandis*) – bamboo and Malabar white pine (*Vateria indica*) – bamboo were conducted. A ³²P soil injection technique described below was employed for this purpose.

Selection of experimental units

Lateral distance between bamboo clump and the nearest teak/*Vateria* was measured all along the boundary, mentioned earlier. Eighteen experi-

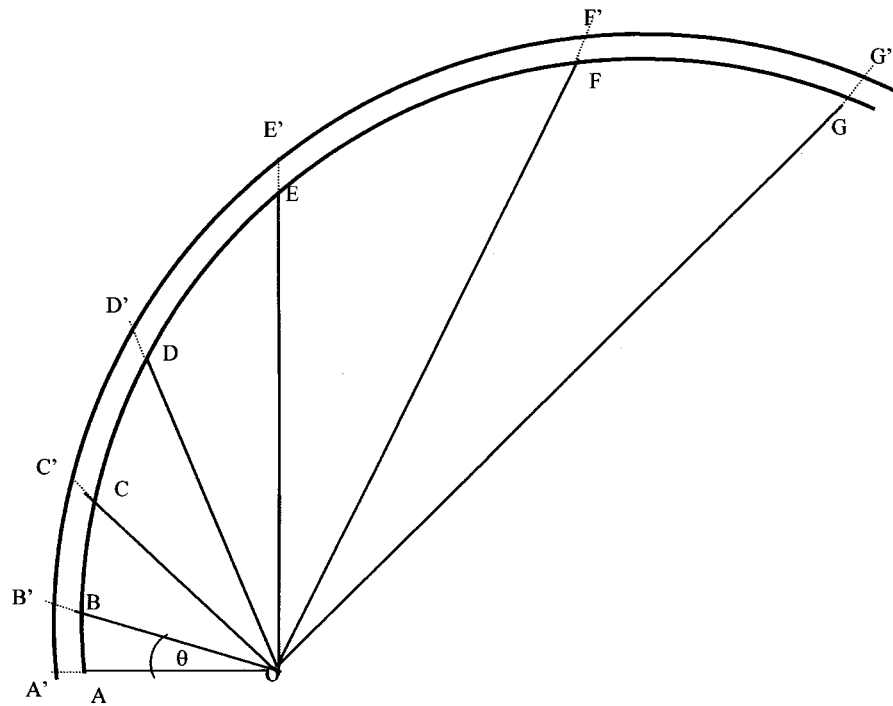


Figure 1. Diagram showing co-ordinates of the logarithmic spiral trench (after Huguet 1973). O-origin of the spiral at a north facing point on the bamboo clump, OA, OB, OC, OD, OE: co-ordinates of the internal spiral at $\theta = 0^\circ, 22.5^\circ, 45^\circ, 67.5^\circ, 90^\circ, 112.5^\circ$ and 135° (see equations in the methods section).

mental units of teak-bamboo and twelve of *Vateria*-bamboo were selected taking into consideration factors such as size of bamboo clumps/other tree components and distance between them. DBH of teak in the experimental units varied from 6 to 27.3 cm (mean 13.5 cm) and height from 5.85 to 16.85 m (mean: 11.4 m). The respective figures for *Vateria* were 2.7 to 12.7 cm (mean DBH: 6.7 cm) and 3.2 to 6.75 m (mean height: 5.51 m). Distance between teak and bamboo ranged from 1.5 to 4.4 m, and *Vateria* and bamboo from 2.3 to 6.5 m. Although we planned to have eighteen experimental units each for both experiments, sufficient units involving *Vateria*-bamboo were not available. A minimum distance of 10 m was maintained between any two experimental units. However, owing to the fewer number of utilisable *Vateria*-bamboo pairs available, in four cases this rule of thumb was disregarded. But 70-cm deep and 10-m long trenches separated them, to ensure least interference between adjacent units.

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 trunk of the selected teak/*Vateria* tree using a soil auger of 2-cm diameter. PVC access tubes were inserted into these holes and their open ends covered with plastic caps to prevent rain water entry. ^{32}P solution at a carrier level of $1000 \text{ mg L}^{-1} \text{ P}$ was dispensed into the access tube at the rate of 2 mL per hole during north-east monsoon on November 4, 1997 using a device fabricated for the purpose (Wahid et al. 1988). The total radioactivity applied per plant was 116.92 MBq (3.16 mCi). After dispensing, the access tube was washed down with a jet of about 15-mL water to clean the residual activity remaining in the tube. The carrier in the ^{32}P solution was intended to minimise the chances of soil fixation of the radiosotope (IAEA 1975).

Leaf sampling and radioassay

Most recently matured leaves of treated plants, neighbouring plants of the same species and the

associated bamboo clumps were sampled separately for radioassay. Sampling was done thrice at 15, 31 and 45 days after application of ^{32}P (count rates, which peaked frequently at 31 days only are reported presently). The leaf samples were air-dried for one day and oven dried at 75°C and radioassayed separately for ^{32}P content. The method consisted of wet digestion of one gram of plant sample using 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 (Wahid et al. 1985). The count rates (counts per minute, cpm) were corrected for background as well as for decay.

Statistical analyses

Root intensity data (number m^{-2}) 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). The general model is $y_i = \mu_i + e_i$, for individual i ($i = 1, \dots, n$) 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 i th 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 $p \times p$ (see Moser et al. 1990). The common tests employed for evaluating differences between groups are Pillais trace, Wilk's lambda and Hotelling's trace (Morrison 1976). Hierarchical cluster analysis was performed as the multivariate tests for clump size by distance, clump size and distance effects were significant. Clustering was done using average linkage between groups (Everitt 1974). The distance measure used was squared Euclidean distance. Regression analysis (Microsoft Excel 97) was used to elucidate the nature of relationships between radial distance from bamboo clumps to the quadrats (independent variable) and rooting intensity, width of effective foraging space (where $> 80\%$ of the roots are present) of bamboo and crown radius besides ^{32}P activity in the leaves of

treated teak/*Vateria* and adjacent bamboo clumps to distance/proximity of bamboo occurrence.

Results

Spatial distribution of bamboo roots

Rooting intensities were higher nearer to the base of the bamboo clumps (Figure 2). MANOVA

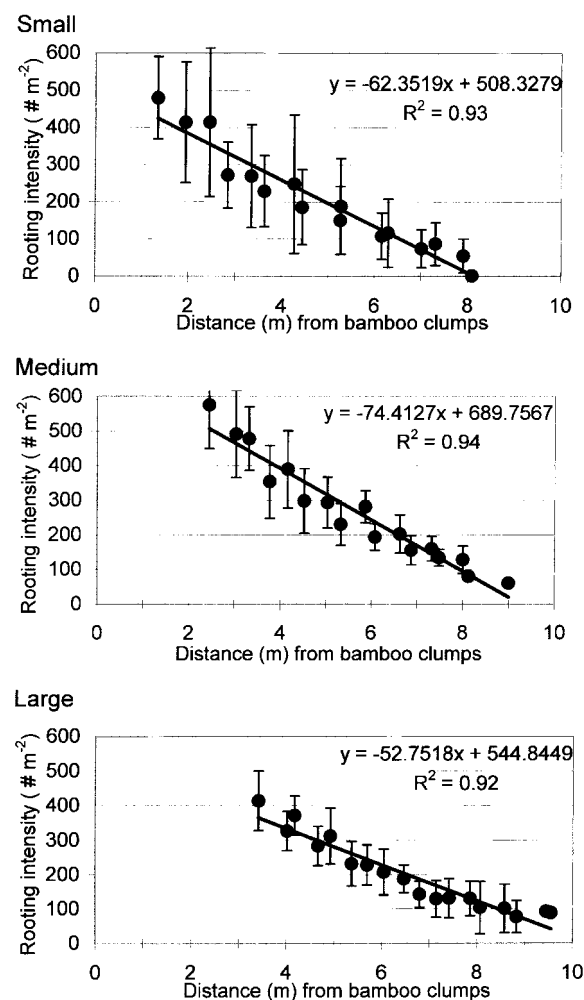


Figure 2. Rooting intensity (number of roots m^{-2}) of boundary planted bamboos at different radial distances (0–50 cm soil depth) for small (1.0 to 2.5 m diameter), medium (2.5 to 4.0 m) and large (4.0 to 5.5 m) clumps in Kerala, India (Tests involving Within-Subject Effect (MANOVA) significant for distance ($P < 0.0001$), clump-size by distance ($P < 0.0001$), depth by distance ($P < 0.0001$) and clump-size by depth by distance ($P = 0.659$)). Error bars show standard deviations.

indicated statistically significant variations for lateral distances, clump sizes, depth and their interactions. Pillais trace, Hotelling's trace and Wilk's lambda were all highly significant ($P < 0.001$). Mean rooting intensity declined linearly with distance from the clump. Regressions linking mean rooting intensity and lateral distance from the clump base gave R^2 values ranging from 0.92 to 0.94. Although root data for < 2 mm and 2–5 mm diameter size classes were collected, only their sums (total roots) are presented here. Both root diameter classes were similar in respect of lateral spread. However, number of roots in the less than 2-mm diameter class was substantially greater than that in the 2–5 mm category. The latter accounted for only about 10% of total roots.

Size of the bamboo clumps showed discernible differences in respect of spatial root distribution pattern (Figure 2) and the width of effective foraging zone (Figure 3). Lateral root spread extended up to 8.1 m for small clumps. Medium clumps had roots up to about 9 m, while large clumps extended their roots beyond 9.6 m implying wider foraging spaces for larger crowns. Effective foraging zone (having 80% of the observed root counts) extended up to 5.3, 6.1 and 7.2 m in the case of small, medium and large clumps. There were only about 0.24%, 6% and 13% of the observed rooting intensity at lateral distances beyond 8 m, in small, medium and large clumps respectively. Linear regression linking effective forage zone of bamboo with crown radius of the clump was significant (Figure 3).

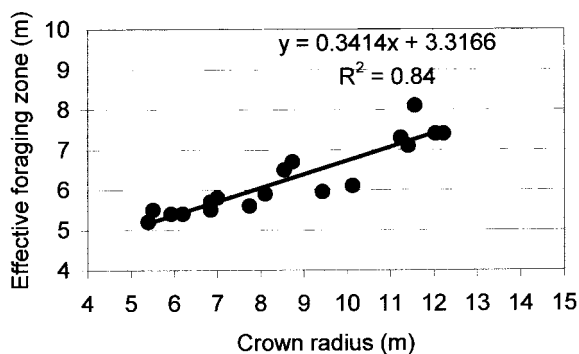


Figure 3. Effective lateral foraging space of bamboo roots (> 80% of the total roots present) as influenced by bamboo crown radius in Kerala, India.

Depth-wise distribution of bamboo roots

There were significant differences in bamboo rooting intensity at different soil depths (Figure 4). A comparison of the data indicate that surface horizon (0–10 cm) registered the least rooting intensity and the underlying 10–20 cm layer the highest root counts with nearly 30% of total roots. Rooting intensity declined thereafter with increasing depth, although modestly. The pattern was similar at all lateral distances and for all clump sizes, despite a general declining trend in rooting intensity with distance.

Absorption of ^{32}P by different components in teak-bamboo combination

Leaf assay of the treated and neighbouring plants revealed that ^{32}P applied was absorbed not only by the treated teak trees but also by surrounding trees of the same and other species. Leaf assay, however, can lead to misleading information in comparisons involving ^{32}P absorbed by different species and individuals of the same species having different size/biomass contents. Hence only within species comparisons of ^{32}P activity expressed as cpm values are made.

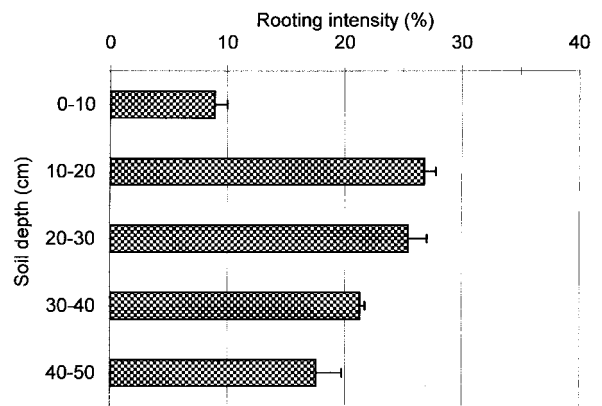


Figure 4. Mean percentage rooting intensity of boundary planted bamboo at different depth intervals (internal side of the trench) in Kerala, India (Tests of Between-Subject Effects for small, medium and large size clumps (MANOVA) significant for depth ($P < 0.0001$), clump size ($P = 0.003$) and clump size by depth ($P = 0.882$)). Error bars show standard deviations.

Absorption of ^{32}P by treated teak

^{32}P uptake by teak increased exponentially as lateral distance of bamboo occurrence increased, when the tracer was applied in the surface horizons of the soil profile (25-cm depth). ^{32}P activity for teak at a distance of 1.5 m from bamboo clump was least (cpm g^{-1} dry wt. = 5.3) and it increased to 748 at 4.5 m distance. The trend was similar at all stages of observation (15, 31 and 45 days after application), hence only the data showing peak absorption (31 days after application) are presented here (Figure 5). With deeper placement (50 cm), ^{32}P recovery by teak declined as lateral distance of bamboo occurrence increased. Proximity of bamboo clumps favoured better recovery of the label placed at this depth. The relationships are best illustrated by exponential/power functions (Figure 5).

Absorption of ^{32}P by bamboo clumps neighbouring treated teak

Overall, ^{32}P uptake by bamboos adjacent to treated teak trees was inversely related to the distance between teak and bamboo (Figure 6). Comparisons involving bamboo clumps at 1.5 m and 4.5 m showed that ^{32}P recovery by the bamboo clumps was 66, 43 and 55 per cent greater in the former, when the isotope was applied at 25 cm depth, respectively at 15, 31 and 45 days after ^{32}P treatment (data not shown for 15 and 45 days).

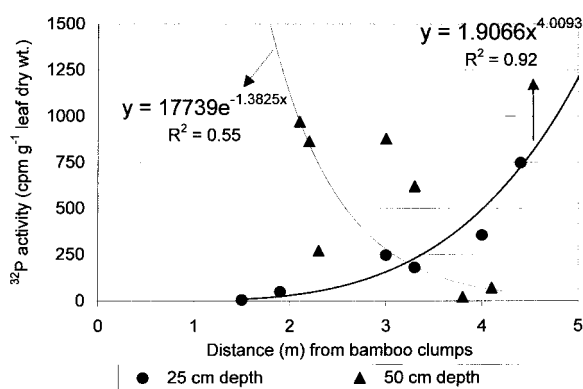


Figure 5. ^{32}P activity recovered in teak leaves at 31 days after application of the label as affected by depth of label placement and proximity (lateral distance) of boundary planted bamboo in Kerala, India.

Placement of the label at 25-cm depth resulted in lower ^{32}P uptake than deep placement, when the neighbouring bamboos were at close ranges. Shallow placement of the radioisotope, however, resulted in higher uptake by neighbourhood bamboos, when the bamboo clumps were farther apart. Variations in the data set as a function of lateral distance are best explained by second-degree polynomial functions.

Absorption of ^{32}P by different components in *Vateria*-bamboo combination absorption of ^{32}P by treated *Vateria*

Absorption of ^{32}P by *Vateria* saplings also was strongly influenced by the proximity of bamboo clumps and depth of placement of the label (Figure 7). *Vateria* absorbed more radioactivity when the bamboo clumps were farther apart and the label was applied at 25 cm depth. There was an 86 per cent increase in radioactivity absorbed by *Vateria* when bamboos were at 6.3 than at 1.3-m distance (at 15 days after application, data not shown). Occurrence of bamboo at close proximity consistently depressed the uptake of the isotope placed at 25-cm depth in the root zone of *Vateria*. Deeper placement (50 cm), however, resulted in greater ^{32}P recovery. Regression equations (polynomial) fitted linking ^{32}P activity with lateral distance of bamboo occurrence yielded reasonably high R^2 values.

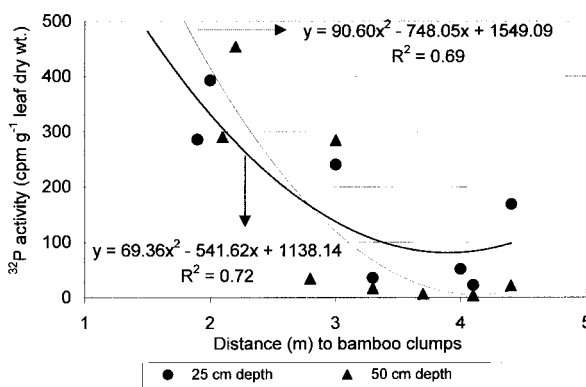


Figure 6. ^{32}P activity recovered in the leaves of adjacent bamboo clumps in combinations involving teak and bamboo at 31 days after application of the label as affected by depth of label placement and lateral distance from treated teak trees in Kerala, India.

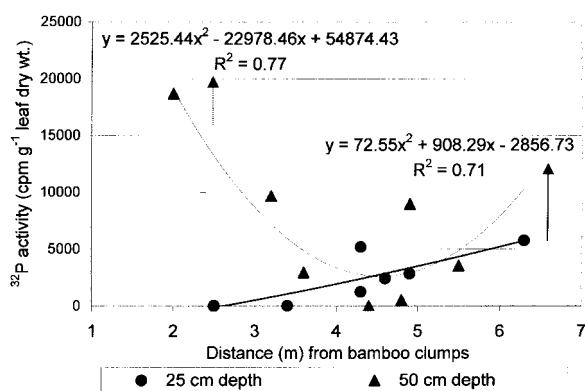


Figure 7. ^{32}P activity recovered in *Vateria* leaves at 31 days after application of the label as affected by depth of label placement and proximity (lateral distance) of boundary planted bamboo in Kerala, India.

Absorption of ^{32}P by bamboo clumps neighbouring treated *Vateria*

Bamboo foliar ^{32}P activity declined with increasing lateral distance from treated plants (Figure 8). The fitted equations gave reasonably good R^2 values. Lateral distance of bamboo occurrence and depth of isotope application showed marked variations. Higher ^{32}P absorption was recorded by bamboo clumps at closer distances compared to those farther apart. Similarly deeper placement (50 cm) resulted in higher ^{32}P recovery compared to shallow placement (25 cm).

Discussion

Root distribution pattern of boundary planted bamboo

The data show that maximum bamboo root spread ranges from 8.1 m to 10.3 m (see equations in Figure 2). Clump size appears to be a major determinant of maximum root spread and the width of effective foraging space. Larger clumps showed greater lateral spread and wider foraging zones. In an investigation on the root distribution of isolated *Parkia biglobosa* trees in Burkina Faso, Tomlinson et al. (1998) also observed that lateral spread is a function of crown spread. They, however, suggested that for trees with an average crown radius

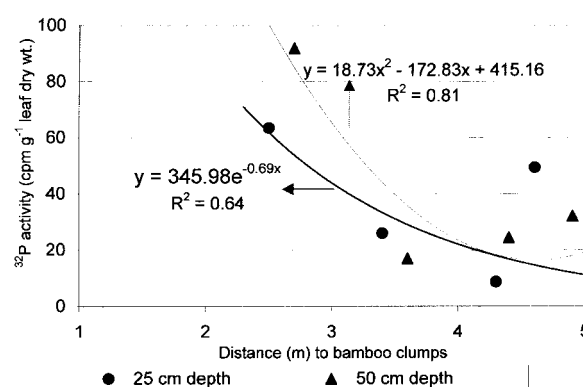


Figure 8. ^{32}P activity recovered in the leaves of adjacent bamboo clumps in combinations involving *Vateria* and bamboo at 31 days after application of the label as affected by depth of label placement and lateral distance from treated *Vateria* trees in Kerala, India.

of 7 m, the maximum root spread is at least twice that of the crown. Our study reveals that for bamboos on the hedgerows, the lateral expansion of roots is probably lower than that of dicot trees such as *P. biglobosa*, grown in the dry areas. Also, we observed a one to one correspondence between width of the effective foraging zone and average crown radius at the lower end of the curve (Figure 3). But there was no such conformity at the higher end of the curve, suggesting the area frequently exploited by roots is probably lower than the crown width for larger clumps. Moreover, in mixed species systems involving other woody perennials, lateral spread of bamboo may be lower than that of open grown clumps. Lehmann et al. (1998) postulated that in mixed species systems involving annuals and woody perennials, tree root system expand more into the subsoil and get confined below the tree canopy.

Regarding the vertical distribution of roots, bamboo rooting intensity was highest in the 10–20 cm soil horizon. Lower rooting intensity in the surface layers (0–10 cm) compared to lower depths observed in the present study is at variance with that reported by many previous workers. Although strict comparisons are impossible, in the humid West Africa, Schroth et al. (1995) found root maximum of nine tree legumes in the upper 10 cm. Lehmann et al. (1998) also observed consistently higher root length density in the topsoil at 0–15 cm depth for *Acacia saligna* stands

in northern Kenya. Using ^{32}P , Jamaludheen et al. (1997) showed that maximum root activity for *Artocarpus hirsutus* was in the top 30 cm as opposed to lower depth up to 90 cm. However, in the arid region in north-western India, five out of 12 tree species had more roots in 15–30 cm than in the 0–15 cm layer (Toky and Bisht 1992).

Low root abundance in the surface horizon (0–10 cm) can be explained by the relatively lower soil moisture availability there during the dry season. Since our study was conducted during the dry period (March to May 1998), lower soil water contents in the surface horizons of the soil profile are probable. This implies seasonal variations in the vertical distribution pattern of the physiologically active roots of bamboo. It is, however, difficult to characterise it based on the results of the present study.

Root activity of teak and Vateria in binary mixtures involving bamboo

Root activity of teak and *Vateria* in surface/sub soil layers, as exemplified by their respective ^{32}P uptake (measured at a radial distance of 50 cm from the trunk) in binary mixtures involving bamboo, is mainly dependent on the proximity of bamboo clumps (Figures 5 and 7). Lower teak/*Vateria* root activity in the surface horizons and higher activity in the deeper layers, when bamboo clumps were nearby and vice versa when they were farther apart, may provide indirect evidence to evaluate the hypothesis concerning diminished lateral spread/deep penetration of the dicot roots in bamboo based mixed species systems. Root systems of teak and *Vateria* are perhaps laterally compressed when bamboo clumps are present at closer ranges. This in turn, may have stimulated deeper penetration of these roots, as signified by the higher root activity at deeper layers. However, as distance between bamboo and the associated tree components increase the relative root distribution in subsoil and surface soil may change dramatically. Proximity of the associated tree components in binary mixtures is, therefore, a major determinant of below ground architecture in mixed species stands.

Root activity of bamboo in binary mixtures involving teak and Vateria

Although we expected a higher bamboo root activity in the surface horizons of the soil profile, it was modestly higher in the subsoil when bamboo clumps and other trees were nearby (Figures 6 and 8). Being a shallow rooted species, most of the bamboo root activity is thought to be in the surface horizons. Hence a higher ^{32}P uptake from the shallow placement was anticipated. However, occurrence of other woody perennials in the vicinity has apparently altered this pattern. Despite small differences, higher ^{32}P recovery from deeper horizons when bamboo clumps were nearby (Figures 6 and 8), signify heavier investment in the subsoil, than when the clumps are farther apart from the associated trees. Just as propinquity of bamboo clumps altered below ground architecture of teak and *Vateria*, proximity of these latter species presumably compressed the bamboo root systems laterally and/or facilitated deeper root penetration. Although higher bamboo root activity at depths greater than 50 cm is probable in mixed species systems involving woody perennials in the immediate neighbourhood, present results do not allow further generalisations in this regard. Specific distances (between bamboo and associated trees) where the bamboo root abundance shifted from subsoil to surface also varied between the teak and *Vateria* systems. This in turn implies that bamboo root spread/architecture is probably dependant on the nature of associated/neighbouring tree components. Differential root abundance in the surface and subsoil as influenced by the nature of associated tree component has important implications in respect of competitive interactions. It underlies the need for selecting specific tree/crop combination in agroforestry for obtaining best results.

Root interactions

Our study indicates that neighbouring bamboo clumps absorbed substantial ^{32}P applied to either teak or *Vateria*, regardless of the depth of placement (Figures 6 and 8). Implicit in here is the possibility of interspecific competition between bamboo and the associated tree components. In polyculture systems, trees exert either a competi-

tive or complementary influence depending on the nature of the species involved (George et al. 1996). Greater ^{32}P uptake by bamboo and the associated dicot tree component from the subsoil, when bamboo clumps were closer, although suggests overlapping root systems, may reflect complementarity of below ground resource use, as it increases overall ^{32}P recovery in the system. Schroth (1999) observed that plants tend to avoid excessive root competition both at the root system level and at the single root level by spatial segregation. Therefore, associated plant species may develop vertically stratified root systems under certain conditions leading to complementary in use of soil resources.

Many previous workers have also reported such complementary interaction in agroforestry. Thomas et al. (1998) observed that the effective root zones of ginger (*Zingiber officinale*) and *Ailanthus triphysa* trees in mixed culture though overlap, competitive influences are negligible, if the ginger crop is adequately fertilised. Lehmann et al. (1998), however, observed that when intercropping trees and field crops (*Sorghum bicolor*), the crop was more aggressive in securing soil resources and was able to replace the tree root system. They also postulated that a higher N availability in the top soil stimulated crop root production and the trees possibly acted as a 'hydraulic lift' to supply the intercrop with water, implying favourable below ground resource sharing between the components.

Safety-net role of tree roots

Isotope studies have also shown that deep placement favoured higher ^{32}P uptake, both by the treated trees as well as neighbouring bamboo clumps, especially when spatial separation of the associated components was relatively small. This in turn, implies a vertical stratification of bamboo and associated tree roots – greater abundance in the subsoil. Proximity to the associated tree component, however, is a major determinant of such plastic responses in tree root distribution. The closer the associated tree components, the greater will be its potential to capture the lower leaching nutrients and thus accomplish on-site nutrient conservation. Although present results do not permit

generalisations on species differences in this respect, Rowe et al. (1999) showed that *Peltophorum dasyrrhachis* exhibited a significant potential to act as a safety-net, as it could take up a substantial proportion of the ^{15}N from deeper layers, while *Gliricidia sepium*, recovered little ^{15}N from any depth.

According to Young (1997) presence of trees in the field will improve overall nutrient use efficiency if these trees actively take up nutrients which would otherwise have been lost by leaching. On soils with sufficient nutrient reserves in the subsoil, deep-rooted trees can act also as 'nutrient pumps', bringing in nutrients to the surface via litterfall (van Noordwijk and Prunomosidhi 1995). Thus agroforestry systems involving two or more woody perennial species can be expected to lead to a more closed nutrient cycling.

Implications for cropping in association with bamboo

In the humid tropical regions of South and Southeast Asia, numerous trees and field crops are often grown in association with *Bambusa arundinacea* and other bamboos. Homegardening is a prominent example in this respect. Productivity of field crops grown in association with bamboo clumps has generally been low, probably due to root competition and/or shading. On account of their profusely branching fibrous root systems bamboos are thought to be highly competitive.

Our excavation studies reveal that, root spread of bamboo clumps may range from 8 m to 10 m from base of the clumps. But, higher rooting intensities (> 80% of the observed roots) are seen up to 5–8 m, depending on the clump size. Thus, a considerable overlap between boundary planted bamboo and crop roots is possible in this zone. With respect to the vertical distribution of roots, more roots are found in the 10–30 cm soil horizon implying lower interspecific competition with field crops. Results of the isotope study also reiterate that root competition by neighbouring bamboo clumps may be substantial up to an area of about 5–6 m radial distance from the clump base. Spatially separating the competing root systems may alleviate such inter specific competition for site resources in bamboo-based agro-

forestry systems. This can be achieved either by planting crops 8–9 m away from the bamboo clumps or by trenching/other soil treatments that restrict lateral expansion of roots. Canopy reduction treatments are also expected to restrict the lateral spread of bamboo/other tree roots, in addition to occluding the shading effects. However, caution should be exercised in extrapolating the data to other sites and age classes as micro-site factors, nature of associated tree/crop species and tree age variations can alter root distribution pattern quite substantially.

Proximity of other trees frequently change the below ground root architecture in bamboo based systems. Bamboo, teak and *Vateria* root systems contracted and grew deeper in mixed species systems when the tree components are located close to one another. Consequently, root competition may be lower in the topsoil under mixed species systems. In addition, it may utilise the 'unused' resources in the subsoil and thereby improve on site nutrient conservation/nutrient pumping.

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