Bamboo (*Dendrocalamus strictus* (Roxb.) Nees) based agroforestry system: planting density effects on biomass accumulation, carbon sequestration, root distribution pattern and understorey crop productivity.

By

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THESIS

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DECLARATION

I hereby declare that this thesis entitled **"Bamboo (*Dendrocalamus strictus* (Roxb.) Nees) based agroforestry system: planting density effects on biomass accumulation, carbon sequestration, root distribution pattern and understorey crop productivity"** is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society.

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Introduction

1. INTRODUCTION

Bamboos are unique group of monocotyledonous, fast growing, perennial, arborescent plants belonging to the tribe Bambuseae of the family Poaceae. They occur in the tropical and subtropical evergreen and deciduous forest formations of Asia-Pacific. India, China and Myanmar have 19.8 million hectares of bamboo which is about 80 per cent of world bamboo forests; of this India's share is 45 per cent. The principal bamboo species are *Bambusa bambos* and *Dendrocalamus strictus* with an overall annual production of 5 million tons. Important uses of bamboos include paper and pulp, food, feed, house construction, scaffolding, making articles of everyday use, controlling soil erosion and facilitating on-site nutrient conservation etc. (Christanty *et al.*, 1996, 1997). Bamboo has the potential to mitigate global warming through carbon sequestration, and substitute non-biodegradable and high energy-embodied materials such as plastics and metals with polymer composites. Also bamboos are excellent carbon sinks and may form part of clean development mechanism (CDM) projects in the near future (Kumar, 2011).

In general, bamboos, because of their varied uses and fast growth are suitable for agroforestry, plantation forestry and social forestry programmes (John and Nadagouda, 1995). In Kerala, homegardens forms a predominant land use activity and bamboo is an important component (Kumar *et al.*, 1994; Kumar, 1997). The total area occupied by bamboo in the homesteads of Kerala is estimated to be about 581 ha. with 39 million culms (Krishnankutty, 1990). Bamboo (*Dendrocalamus strictus* (Roxb.) Nees) forms one of the predominant bamboo species in Kerala (Kumar and Takeuchi, 2009). Despite the wide distribution, its spread is mostly limited to farm or homestead boundaries and isolated marginal areas. A potential limitation in the intimate integration of bamboos in polyculture systems is the perceived competition with understorey crops especially when grown in compact blocks. Probably what deters farmers from such bamboo based polyculture systems is the lack of information on the development and management of bamboo production systems. Practically no information is available on the intercropping options under bamboo, compatibility of intercrops, optimum planting densities for diverse management objectives etc.

Agroforestry researchers in Kerala are encountering great challenge in developing bamboo based cropping system models. Understorey productivity in polyculture systems is largely a function of the competitive interactions for light and space, both belowground and aboveground. However, the intricacies associated with these interactions have not been unraveled so far for bamboo based agri-silviculture systems. The proposed study was aimed to probe understorey PAR availability as affected by planting density of bamboo.

Yet another factor affecting field crop productivity in mixed species system is root competition (Schroth, 1999; Bayala *et al.*, 2004). Owing to the methodological complexities involved in the assessment of belowground interactions, such studies are very much limited in tree based intercropping systems. Radio-tracer techniques are prominent non-destructive methods for root activity study especially in polyculture system involving trees. The depth of penetration and root activity are the basic information that could be well correlated with plant growth. Conventional techniques used in the field for root studies are tedious and may not be accurate. Radioisotope tracer technique, however, provides a very fast and indirect means of measuring *in situ* root activity of crops (IAEA, 1975). However, studies on functional relation between planting density/spacing and understorey productivity of medicinal crops in bamboo based agroforestry systems are by for scarce (Thomas *et al.*, 1998; Rowe *et al.*, 1999 and Kunhamu *et al.*, 2010). Some information exists about the root activity and distribution of the major tropical crops like acacias, *Cocos nucifera*, *Theobroma cacao*, *Elaeis guineensis*, *Coffea arabica*, *Musa paradisiaca*, *Citrus Medica* and other fruit trees (IAEA, 1975 and Lehmann *et al.*, 2001). It is very important to explore the resource utilization patterns in bamboo based intercropping systems, in order to provide management strategies for deriving optimum yield and productivity.

Zingiberaceae members are important medicinal and aromatic oil yielding herbs and have a great demand for ayurvedic and culinary use. Their tuberous rhizomes possess a camphoraceous odour with a bitter taste. The medicinal properties of Zingiberaceae members are innumerable and very ancient. Kirtikar and Basu (1988) stated that the rhizome is very pungent, bitter, healing, laxative, anthelmentic, vulnerary, tonic, alexeteric and emollient. It is also having antioxidant (Chen *et al.*, 2008), anti-inflammatory, anti-cancer activity (Wohlmuth, 2008), antibacterial (Bhunia and Mondal, 2012) and antipyretic (de Padua *et al.*, 1999) properties. Growing of Zingiberaceae members in coconut based land-use systems has been recommended by Nair *et al.* (1991). Very limited information is available on the intercropping options under bamboo, especially the compatibility of intercrops, optimum planting densities for diverse management objectives etc. in Kerala. The present work throws light on the feasibility of prominent herbaceous medicinal crops for intercropping with *Dendrocalamus strictus*.

Absorption of water and nutrients from the soil by bamboo depends on the growth habit and functionality of their roots and rhizomes. With the exception of few studies on the distribution of bamboo roots down the soil profile (Kumar and Divakara, 2001; Bhol and Nayak, 2014), little or no research has been conducted on more important parameters such as root intensity or efficiency of absorption of nutrients. The fine roots and root hairs of the bamboo root system play a significant role in supporting high productivity (Tripathi and Singh, 1996). It is generally known that root systems of bamboo do not usually elongate to higher soil depth, but rather develop profuse mat of highly efficient fine roots within the uppermost soil layer (Christanty *et al.*, 1997). The root and rhizome system is usually confined to the topmost soil layer with only a few roots extending below 40 cm depth. Hence, the study on pattern of root activity and distribution are important aspects for standardizing the spatial arrangement of various components for optimizing productivity in bamboo based polyculture systems.

However, this requires sound knowledge on the elements of growth such as soil attributes, root distribution pattern, biomass accumulation and C sequestration potential under variable planting density/spacing for bamboo. Apart from high biomass production, bamboo also sequester substantial carbon in the biomass and soil. Thus by contributing to reduction in GHG emissions and mitigation of climate change. Bamboo roots by virtue of spreading nature may contribute to enrich the soil carbon pool even at higher depth. Quantifiable information on such ecological benefits from *Dendrocalamus strictus* are lacking. Despite its economic value and relatively high biomass production potential (Scurlock *et al.*, 2000), little is known about their biomass, nutrient accumulation, dynamics (Tripathi and Singh, 1999) when grown under diverse stand density regimes. Complete harvesting of bamboo clumps has been seldom attempted in biomass estimation studies (Kumar *et al.*, 2005), because of high labour involvement for felling whole clumps.

Apart from the belowground attributes, the photosynthetically active radiation (PAR) availability is yet another fundamental factor that influence understorey productivity. Regulation of planting density/spacing in bamboo considerably influence the understorey PAR, which in turn affect the growth of understorey crops. There is genuine lack of information on the PAR availability for different intercrops under varying spacings of *Dendrocalamus strictus*. With this back drop the following objectives has been undertaken to explore the diverse factors that influence the overall productivity of bamboo-medicinal herbs based agroforestry system under variable planting densities of 7 year old *Dendrocalamus strictus*.

1. Measurement of LAI and PAR under varying spacings of bamboo
2. The growth performance of the bamboo and selected herbaceous intercrops viz., turmeric, ginger and chittaratha as a function of bamboo spacings
3. ^{32}P isotope study for rhizosphere interaction between overstorey bamboo and turmeric under varying spacings of bamboo
4. Study on root activity of bamboo using ^{32}P isotope
5. Characterization of root distribution pattern in bamboo using modified logarithmic spiral trenching method

6. Biomass production, nutrient uptake and carbon accumulation potential of bamboo
7. The nutrient dynamics and soil productivity changes due to varying spacings of 7 year old bamboo.

Review of Literature

2. REVIEW OF LITERATURE

2.1 Bamboo distribution and diversity

Bamboos are fast-growing arborescent plants belong to the family Poaceae, subfamily Bambusoideae, tribe Bambuceae (Calderon and Soderstrom, 1980). It is known as "Green Gold" because of its faster growth and multifarious uses. This green gold is sufficiently cheap and is plentiful to meet the vast needs of human populace, that is why sometimes referred to as "poor man's timber". Bamboo is becoming an increasingly important economic asset in poverty eradication, economic and environmental development (FAO, 2005). It is distributed widely across the tropics and subtropics of Asia, Africa, Latin America with the highest concentration of species occurring in south and southeast Asia. Bamboo occupies a central role in the development of culture and civilization with utilitarian, functional as well as spiritual significance.

Although Asian bamboo constitute an important non-timber forest product of major cultural and economic importance, a detailed regional assessment of their distribution patterns have not been made. Bystriakova *et al.* (2003) studied the distribution and conservation status of bamboo diversity in the Asia-Pacific region, over 6.3 million km of Asian forests potentially contains bamboo, with highest densities indicated from north-eastern India through Mayanmar to southern China and through Sumatra to Borneo.

India is the second richest country in bamboo genetic resources after China. These two countries together have more than half of total bamboo resources globally. The forest area, over which bamboos occur in India, is about 14 million hectares under 12 per cent of the total geographical area of the country (FSI, 2011). It is reported that about 125 indigenous and 11 exotic species of bamboos are found in the country (FSI, 2011). The bamboo forms an understorey component in several forest types. The tropical moist-deciduous forests of northern and southern India and the deciduous and semi-evergreen forests of north-eastern India are the natural habitats of bamboos (Appasamy and Ganapathi, 1992). Fifty eight species of bamboo belonging to 10 genera are distributed in the northeastern states alone. The principal bamboo genera occurring in India are *Dendrocalamus, Arundinaria, Bambusa, Chimonobambusa, Dinochloa, Gigantochoa* etc. *Dendrocalamus* and *Bambusa* species are found under tropical conditions, whereas Arundinaria and its allies occur in the temperate region and are most commonly found on higher elevations. Arunachal Pradesh is having maximum bamboo bearing area (1.6 m ha) followed by Madhya Pradesh (1.3 m ha) Maharashtra (1.15 m ha) and Orissa (1.03 m ha).

In Kerala, bamboos are found distributed right from the sea coast to the high ranges, *Dendrocalamus strictus, Bambusa bambos, Ochlandra travancorica, Ochlandra scriptoria* and *Oxytenenthera ebracteata* have been found associated with different forest types in the state (Bahadur and Varma, 1980). Among these, *Dendrocalamus strictus, Bambusa bambos* and *Ochlandra travancorica* are economically important and commercially exploited bamboos (Mohanan, 1994). Homegardening forms a pre-dominant land use activity and bamboo is an important component of the homegardening system in many parts of the state (Kumar, 1997). The total area occupied by bamboo in the homesteads of Kerala is estimated to be about 581 ha with 39 million culms (Krishnankutty, 1990). Hence the economic impact of the bamboo based agroforestry system may influence general economic development considerably.

2.2 Ecological requirements of bamboo

Bamboo occurs best in localities, where the soil is deep and loamy in texture with less humus or humified matter, a topography of middle to lower slopes of the hills and also in valleys where drainage is good (Khan, 1960). It prefers humid condition, but tolerates water logging to some extent (Hussain, 1980). Normally, shoots will emerge during the growing or rainy season. Very few shoots if ever there are, arise during the dry season when the soil moisture is at its lowest (Uchimura, 1978). In warm regions with frequent and well-distributed rainfall throughout the year, the growth may be virtually continuous (Latif and Liese, 1998).

According to Uchimura (1978), vegetative growth of bamboos is more affected by soil moisture rather than by temperature. In general, it grows well on soils rich in aluminium, manganese and potassium (Yadav, 1963). Bamboo being an extremely fast growing species can consume large quantities of nutrients. Studies have shown that, the supply of nutrients considerably increased growth and biomass production of bamboo (Shi *et al.*, 1987 and Kleinhenz and Midmore, 2001).

Chandrashekara (1996) assessed the contribution of bamboo to the vegetation structure and nutrient cycling pattern in 15 to 20 year bamboo plantations in the Kariem-muriem forest range, Kerala. The study indicated the role played by bamboo in conservation of exchangeable potassium, lesser accumulation of calcium in biomass and higher fractional annual turnover rate of calcium which suggested the adaptability of the species to calcium-poor soils. Furthermore, bamboo tolerates poor soils which makes it useful for planting on degraded land (Hunter, 2003).

2.3 Production and marketing of bamboo

Bamboo has become an important trade commodity globally and provides direct or indirect livelihood support to about 2.5 billion people (INBAR, 1999). The international trade in bamboo ranges between $5 to $10 billion. Most of the bamboo traded internationally is exported by China (Parker, 2005), ranging from 75% to 95% of total bamboo traded in the world. The annual production of bamboo in India is about 4.6 million tonnes of which about 1.9 million tonnes is used by the pulp industries. Total number of culms at the national level has been estimated to be about 23,297 million out of which 79% are green sound, 16% are dry sound and 5% are decayed (FSI, 2011). The annual yield of bamboo per hectare varies between 0.2 and 0.4 tonnes with an average of 0.33 tonnes per hectare, depending upon the intensity of stocking and biotic interferences. Average productivity of bamboo from forests is around 1.5 tonnes per ha. per year. Annual production is estimated at between 15-20 million tonnes of fiber implying that, it is highly significant as a livelihood material (Williams and Rao, 1994).

With growing demand of timber, bamboo is a viable alternative/substitute of timber. For processing, normally does not require skilled labour and can be started at a minimal cost (FAO, 2005). The uses of bamboo are many and vary from place to place, depending on local preferences and resource availability (Das, 1990). As such, bamboo is highly suited to diversified agricultural systems, constituting one of several livelihood resources for farmers (INBAR, 2004). Because of varied uses and fast growth, bamboo forms a species suitable for agroforestry, plantation forestry and social forestry (John and Nadagouda, 1995). Sustainable bamboo plantations provide direct employment for many rural unskilled people in areas where opportunities for economic development are low. Outgrower schemes and revenue from the sale of carbon credits provides additional potential for poverty alleviation and economic diversification. Yet for a multitude of reasons, the market for bamboo within India is in its beginning. The disconnect between agronomists, financiers and potential end users has resulted in the slow commercialization of this valuable species. Furthermore, the gregarious flowering pattern of bamboo requires careful consideration for commercial reforestation (INBAR, 2004).

2.4 Ecological requirement and distribution of medicinal plants

Turmeric (*Curcuma longa*) is one of the important spices in India. It can be grown in most areas of the tropics and subtropical areas receiving sufficient rainfall or irrigation. Important varieties grown in Kerala are Pratibha, Duggiral, Alleppey Sudarshan etc. The turmeric rhizomes are sown during pre-monsoon showers at the spacings of 25 x 25 cm with a seed rate of 2000-2500 kg/ha (KAU, 2011). It can tolerate partial shade and can be mostly grown as mixed or intercrop with *Crotalaria juncea*, *Cocos nucifera* and *Areca catechu* plantations (Sanyal and Dhar, 2008). Lesser galangal (*Alpinia calcarata* Roscoe) known as rasna in Sanskrit, Kulainjan in Hindi and chittaratha in Malayalam, is a perennial herb with non-tuberous pungent rootstock. This rainfed crop is planted with the onset of monsoon in May-June. The optimum spacing is 25 x 25 cm under good fertility soil (KAU, 2011). No verities are released in Kerala, only locally available planting material used for cultivation. It is extensively grown in gardens for its showy flowers and aromatic leaves and rhizomes. Another important spice crop grow in humid tropics is ginger (*Zingiber officinale* Rosc.). The crop tolerates shade upto some extent, because of shallow roots suitable for intercropping and as a component in homesteads where partial shade is available. Some of the important varieties grown in Kerala are Wayanad, IISR-Varada, IISR-Rejatha, Maran etc.

2.5 Competitive interaction in agroforestry

Competition for native and applied resources among component crops is an important factor that limits productivity of agroforestry systems (George *et al.*, 1996). In Haryana *Acacia nilotica* based agroforestry systems reduced the yield of wheat (Puri *et al.*, 1995). Reduction of crop yield in agroforestry system may be observed due to several reasons, but it may also be compensated in the long term by microclimate modification (Kohli and Saini, 2003) and residual nitrogen after removal of old trees as a result of enhanced N fixation under the acacia. Root competition for nutrients is a complex combination of soil supply and plant uptake mechanisms (Gillespie, 1989). Vandenbeldt *et al.* (1990) reported that soil nutrition and competition for soil water is dependent on root distribution pattern. Plants with deep root system generally decrease competition, whereas shorter thick roots quickly deplete adjacent nutrient pools, promoting steep and extensive nutrient gradients (Gillespie, 1989). Ong *et al.* (1991) found that tree roots can exploit water and nutrients from the sub-soil whereas field crops having shallow roots are actively involved in surface soil.

Okorio *et al.* (1994) demonstrated that aboveground and belowground competition are important under boundary plantings. During the study, root mesh was used to prevent lateral root spread. When 3.5 year old four trees of four species were intercropped with field crops, the yields adjacent to trees without root mesh were 20 to 55 per cent. When root mesh was installed to 0.5 m depth and 0.5 m away from trees, yields increased by 152 per cent adjacent to *Maesopsis eminii*, 57 per cent adjacent to *Markhamia lutea* and 16 per cent adjacent to *Casuarina cunninghamiana.*

George *et al.* (1996) studied the root competition for phosphorus between the tree and herbaceous components of silvipastoral systems in Kerala using ^{32}P. The results reveal that *Acacia auriculiformis* and *Leucaena leucocephala* caused lower foliar ^{32}P content in the component grasses due to surface concentration of their roots.

Thomas *et al.* (1998) while working on root competition for phosphorus between ginger and *Ailanthus triphysa* found that about 41 % and 60 % of the physiologically active roots were distributed within 40 cm lateral distance from the tree trunk. Their study reveal that ailanthus trees upto an age of four to five years exert a positive influence on ^{32}P uptake by ginger, despite variation in tree density. The study suggested that at least in the initial stage, tree density was not a strong determinant for belowground competition in a system with fertilized management.

Root competition for phosphorus between coconut, multipurpose trees viz. *Vateria indica*, *Ailanthus triphysa* and *Grevillea robusta* (MPT's) and kacholam (*Kaempferia galanga*) was studied in Kerala, India (Kumar *et al.,* 1999). Interplanted MPTs substantially altered absorption of ^{32}P by coconut. The overall high ^{32}P absorption in the coconut-silver oak plots indicated complementary root level interactions between the species. ^{32}P absorption by MPT's was generally higher closer to the trees owing to greater root concentration of the MPTs, which in turn suggested the possible root interference between MPTs and coconut. They also suggested that selection of tree species with low root competitiveness and/or trees with complementary root interaction is of strategic importance in agroforestry.

Root studies revealed lack of spatial complementary between the tree and crop components in water use, as a large percentage of fine roots of many species were in the top 0.5 m soil layer where crop roots were also concentrated (Rao *et al.*, 1993). Competition of trees for aboveground factor can be managed to some extent by pruning, maintaining the appropriate density and sequential thinning. However, the scope for management of below ground competition is limited to the manipulating of root densities through species or cultivar selection for known soil nutrient deficiencies and by regulating spacing (Gillespie, 1989).

Chowdhury *et al.* (2007) investigated the effect of fertilizer and lime on the performance of ginger and *Melia azedarach* based agroforesrty system. They revealed that ginger with application of organic and inorganic fertilizers had highest rhizome yield (26.37 t ha^{-1}) followed by application of organic fertilizers only (26.13 t ha^{-1}) and lowest (13.60 t ha^{-1}) in open plot (control) without application of fertilizers and lime.

Performance of ginger under agroforestry system was studied in Bangladesh by Amin *et al.* (2010). The ginger was grown under three agroforestry systems viz. under *Psidium Guava* trees with 70% shade, below *Albizia odoratissima* trees providing 60% shade and underneath mango trees having 50% shade and open field. They reported that, ginger-mango intercropping having 50% shade recorded maximum rhizome yield of ginger (12.42 t/ha) compared to ginger-guava system (5.07 t/ha).

Lott *et al.* (2009) examined the intercepted radiation, spatial distribution of shade in *Zea mays* grown in intercropping system and sole crop in semi-arid Kenya. Their study revealed that trees decreased photosynthetic photon flux density incident on understorey maize by 30%, the yield reduction was much greater than in the 25% shade. *Zea mays* yield was unaffected by 50% artificial shade but decreased with increasing shade. The others also reported that with increasing spacing, stand leaf area index (LAI) will reduce and the amount of light penetrating the canopy can increase. The fraction of above-canopy light penetrating to the understorey is inversely related to basal area of the residual stand (Comeau *et al.*, 1998). Following thinning, the canopy of trees expand and over time, the amount of light reaching the understorey starts decrease.

Gao *et al.* (2013) studied photosynthesis, growth and yield of *Glycine max* and *Arachis hypogaea* by measuring photosynthetically active radiation, net photosynthetic rate, soil moisture and soil nutrients in a plantation of apple (*Malus pumila*) at a spacing of 4 x 5 m in China. The results showed that soil moisture was the primary factor affecting the crop yields followed by light. Compared with soybean, peanut was more suitable for intercropping with apple trees. They concluded that apple-soybean and apple-peanut intercropping systems can be practical and beneficial. However, the distance between crops and tree rows should be adjusted to minimize interspecies competition. Agronomic measures such as regular canopy pruning, root barriers, additional irrigation and fertilization also should be applied in the intercropping systems.

2.6 Intercropping with bamboo

Seshadri (1985) observed that, growing of *Glycine max* as an intercrop of *Dendrocalamus strictus* during the first six years is technically feasible and economically viable. He also reported that the period of intercropping can be extended further in wider spacings of the bamboo and judicious manipulation of the bamboo canopy.

Balaji (1991) reported that the scope of *Bambusa bambos* in agroforestry is very wide because of the uncertain weather condition and increasing cost of labour involved in agriculture. Bamboo forms an important component in silvi-horti based agroforestry system. In an investigation on systematic bamboo plantation intercropped with *Mangifera indica*, *Anacardium occidentale*, *Artocarpus heterophyllus*, *Garcinia indica* and *Hevea brasiliensis* in the Konkan region of Karnataka, bamboo was reported to be the most profitable among the crops studied and cashew nut and mango ranked next to bamboo (Wagh and Rajput, 1991). Bamboos in the farm boundaries not only act as wind-break but also form shade tree for shade-loving understorey components. Shanmughavel and Peddappaiah (2000) recommended the intercropping of *Glycine max* and *Curcuma longa* in the initial stages of *Dendrocalamus strictus* plantations. Intercropping bamboo (*Fargesia nitida*) and cash crops (Zea mays and *Camellia sinensis*) is commonly practiced by farmers in Thailand (Thammincha, 1985).

Singh *et al.* (1992) studied the effect of *Bambusa nutans* shade on the yield of some agricultural crops at mid hills of eastern Himalaya. They reported that, bamboos are allowed to grow or are planted along the farm boundaries or drainage lines and or uncultivated wastelands in the Himalayan hills. Through the study, they found that agriculture land near bamboos can be effectively utilized for growing Zingiber officinale, Curcuma longa, *Elettaria cardamomum*, *Dactylis glomerata* and *Panicum repens* upto a distance of 11-15 m from the bamboo rows. Beyond this distance, *Oryza sativa*, *Eleusine coracana*, *Glycine max*, *Setaria incrassata* and *Paspalum virgatum* grass were suitable crops.

In a study conducted to restore degraded agricultural lands in central India, Behari (2001) developed successful seven agroforestry models with three bamboos (*D. strictus* and *B. bamboos*, *B. nutans*). The intercrops were *Glycine max*, *Streptanthus niger*, *Vigna radiata*, *Triticum aestivum*, *Vigna mungo*, *Cajanus cajan* and *Brassica Nigra*. He concluded that *Glycine max*, *Vigna mungo* and *Triticum aestivum* performed best under *Bambusa nutans* and reported as promising agroforestry system.

Shanmughavel and Francis (2002) studied intercropping performance of four crops viz., *Cajanus cajan*, *Glycine max*, *Zingiber officinale* and *Curcuma longa* with *Bambusa bambos* in Tamil Nadu. They found that intercropping of pigeon pea and soyabean are more productive than ginger and turmeric. The land equivalent ratio (LER) of intercropping *B. bambos* with pigeon pea and soyabean was equivalent to that of 1.2 ha under monoculture. They also found higher net returns when pigeon pea was intercropped in 1:1 rows at 3x3 m spacing (250 plants/ha) in comparison to 1:2 rows spaced at 2x2 m (500 plants/ha).

Jha *et al.* (2004) reported that intercropping of soyabean with *Melocanna baccifera* and *Dendrocalamus longispathus* was feasible on degraded Jhum land of Mizoram and gave better results than pure bamboo stands. Tiwari (2001) conducted a study to determine the financial feasibility of *Dendrocalamus strictus* based agroforestry system of Kheda district of Gujarat using seven management models.

Results indicated that, the profitability of bamboo was high and the crop was financially feasible even at high discount rate and the socio-economic factors are believed to be favorable to the domestication of bamboo as an agroforestry crop in that region.

Patil and Patil (1982) evaluated suitable companion crops that can be grown along with *Dendrocalamus strictus*. It was found that, the growth and dry matter production of bamboo is not adversely affected by planting trees like *Sesbania grandiflora*, *Macroptillium atropurporeum*, *Leucaena leucocephala*, *Lotononis bainessi* and *Casuarina equisetifolia* as intercrops. The *Santalum album* is one of the important tree crops in the southern India which was found growing well with the bamboo (Venkatesan, 1980).

Growing space requirement for *Bambusa tulda* in conjunction with agricultural crops was studied by Sheikh (1983) at the Pakistan Forest Institute, Peshawar and found that, there was not much difference in diameter of the *Dandrocalamus hamiltonii* but the number of culms per clumps was much more in the widest spacing (6x6 m) and almost double than that of the 2x2 m and 3x3 m spacing.

Mathauda (1959) reported that initial spacing is governed by the size of bamboo culm and the site quality. The study was conducted to evaluate the effect of silviculture and management on *Bambusa bambos*. However, when bamboo is grown with agriculture crops, 6x6 m to 9x9 m spacings were considered optimal.

Bhol and Nayak (2014) studied *Dendrocalamus strictus* based agroforestry system in two varying spacings (12x10 m and 10x10 m). The growth of bamboo clumps and root intensity were significantly higher in intercropping compared to sole bamboo. In kharif, four intercrops viz. *Vigna unguiculata*, *Vigna mungo*, *Vigna radiata* and *Sesamum indicum* were grown along with bamboo and in the rabi season, *Vigna radiata*, *Helianthus annuus*, *Brassica rapa* and *Vigna mungo* were grown. Their results found that all the intercrops performed better in the wider spacings (12x10 m) compared to close spacing (10x10 m). They concluded that bamboo based agroforestry is most economical if the understorey crops are properly incorporated in the widely interspaced bamboo plantations.

The intercropping with bamboo was studied in Jhargram, West Bengal by Banerjee *et al.* (2009). The intercrops, namely, *Oryza sativa*, *Arachis hypogaea*, *Cajanus cajan*, *Vigna unguiculata*, *Abelmoschus esculentus*, *Lagenaria siceraria*, *Curcuma longa*, *Colocasia esculenta* and *Amorphophallus paeoniifolius* were grown in between bamboo plantations. The yield of all intercrops was higher in wider spacing (12 x 10 m) as compared to closer spacing (10 x 10 m).

Phyllostachys incarnate- *Gallus gallus* agroforestry system is a new and common pattern in the hilly regions of southern China and has high potential for extension throughout the China (Zhao *et al.*, 2006). Soil nutrients and earthworm dynamics under this system was evaluated and found that soil nutrients were improved, but soil organism indicators were more sensitive than chemical ones. Earthworm quantity and mass between bamboo-chicken system and only bamboo forest were significant.

A study on feasibility of intercropping of *Alpinia calcarata* (chittaratha) in *Elaeis guineense* (palm) based cropping system in Kerala was done by Jessykutty and Jayachandran (2009). The chittaratha seedlings were grown in the inter-rows of oil palms in different age groups viz., 5 year old (young), 5-11 year old (medium) and above 11 year old (matured) palm plantations and in open plot. The amount of dry matter production under medium and mature palms was lower compared to open plot. The maximum rhizome yield of 7.34 t/ha was recorded in open field followed by young (4.33 t/ha) and mature (4.09 t/ha) oil palm plantation. They also reported that after analyzing benefit-cost ratio, chittaratha is a profitable intercrop in oil palm based agroforestry systems.

Venugopal and Sheela (2014) studied feasibility of intercropping under *Musa acuminata*. The banana intercropped with chittaratha recorded maximum shelf life (10.33 days). Highest uptake of nitrogen by banana was registered with chittaratha as intercrop. Chittaratha recorded yield of 23 t/ha when intercropped with banana. However they concluded that intercropping of chittaratha is more economic than pure crop.

A plantation of 5 year old *Dendrocalamus asper* (5x5 m) was intercropped with potato, tomato and ginger in Jharkhand (Sinha and Nath, 2007). It was observed that, growth of bamboo intercropped with vegetables was better than the monoculture of bamboo. Additional three culms per clump emerged from bamboo when intercropped with the vegetables.

Vishwanath and Danya (2007) revealed that intercropping of *Bambusa burmanica* with ginger at 6x6 m spacing maximizes the NPV. They also reported that increasing bamboo spacing to 6 x 10 m to accommodate more intercrop of ginger may not be profitable as the wider spacing arrangement results in lower NPV and B/C values.

A study was conducted by Nolin (2006) to test species (*Bambusa bluemeana*, *Acacia mangium* and *Tephrosia candida*) for simulating and comparing filter effects of different agroforestry systems with intercropping, hedgerows or fallow rotation in Vietnam. The study revealed that bamboo accounted higher (714 %) of income than trees (1-10 %) in the total household economy. Intercropping with bamboo showed reduced run-off and lower erosion in comparison to *Acacia mangium* and *Tephrosia candida* agroforestry systems.

Rahangdale and Pathak (2012) in Madhya Pradesh evaluated the soil physico-chemical properties under different agricultural crops (*Vigna radiata*, *Glycine max* and *Oryza sativa*) incorporated with three year old *Dendrocalamus strictus*. Decrease in p^H and electrical conductivity under bamboo based agroforestry may be attributed to decomposition of leaf litter. The organic carbon content of soil increased from 0.81% to 0.85%, available nitrogen from 255.33 to 279.50 kg/ha, available phosphorus from 24.40 to 26.66 kg/ha. The available potassium of the soil increased from 181.48 to 186.83 kg/ha. They concluded that integration of bamboo species in farming system may give positive impact on soil physico-chemical properties.

2.7 Competitive interactions in bamboo based system

Many researchers reported that bamboos produce some relevant compounds. Root exudates can suppress growth of *Zea mays*, *Arachis hypogaea*, or other understorey crops (Liese, 1985; Seethalakshmi and Kumar, 1998). Young shoots of some bamboo species contain significant amounts of a toxic cyanide, taxiphyllin. Fortunately, this toxin degrades rapidly in boiling water during normal preparation of edible bamboo shoots (Hunter and Yang, 2002).

Eyini *et al.* (1989) also reported that the aqueous leaf extract of *Dendrocalamus strictus* inhibited the growth of groundnut seedlings and decreased the leaf area, plant height, total chlorophyll and protein content. Six phenolic acids namely, chlorogenic, ferulic, coumaric, protocatechuic, vanillic and caffeic were identified in the extract of fallen leaves of bamboo and these may be responsible for its allelopathic effect. The comparative allelopathic studies in bamboo and conifer revealed that radicle growth of *Lactuca sativa*, *Oryza sativa* and *Lolium perenne* was inhibited by the leachate and aqueous extract of bamboo leaves but not by those of conifer leaves (Chou and Yang, 1982). The competition for sunlight, belowground space, moisture and nutrients in bamboo plots was higher when intercropped with vegetables as compared to open plot (Sinha and Nath, 2007). Farmers are not willing to sacrifice large farm areas for raising bamboos since subsistence crops are far more important to them. Hence, in the peninsular India cultivation of bamboo as sole crop is seen only in industrial plantations. However, farmers often apprehend that the competition of bamboo roots for space and site resources is higher, their perception make the farmer unwilling to grow bamboo on their farm fields (Kumar *et al.*, 2005). Chandrashekara (1996) reported poor performance of teak in bamboo dominant plantations owing to inter specific competition. Bamboos are thus confined to the field margins only (Hocking, 1993). Therefore, it is essential to have a thorough understanding of the technical, social, economic and biophysical constraints of bamboo based farming systems.

The nitrogen leaching and nitrogen use efficiency by trees with the injection of ^{15}N at different soil depths within established hedgerow intercropping systems was evaluated in Indonesia (Rowe *et al.*, 2001). More ^{15}N recovered by maize and *gliricidia sepium* from placements at 5 cm depth than from placements at 45 or 65 cm depth. *Peltophorum ferrugineum* recovered similar amounts of ^{15}N from placements at each of these depths, and hence had a deeper N uptake distribution than *Gliricidia* or maize. A greater proportion of the ^{15}N recovered by maize was found in grain following ^{15}N placement at 45 cm or 65 cm depth than following placement at 5 cm depth, which reflected the later arrival of maize roots in these deeper soil layers. Their study concluded that trees have an important role in preventing N leaching from subsoil during early crop establishment.

Ahlawat (2014) evaluated the economic viability of solid bamboo (*Dendrocalamus strictus*) based agroforestry system in semi-arid region of central India. He revealed that, growth of bamboo was better in 10×10 m spacing. Reduction in grain yield of sesame and chickpea was observed when intercropped with bamboo. Maximum reduction in intercrop yield was recorded nearby (0.5 m distance) of bamboo clumps, while there was no reduction in crop yield at >3 m distance from bamboo clump. The soil p^H, organic carbon and available phosphorous increased when intercropped with bamboo.

2.8 Root activity and distribution pattern

Agroforestry land use systems are relatively complex. Root isolation of overstorey tree and understorey crops is most essential. For this, information on the distribution of active roots is a pre-requisite (Wahid *et al.,* 1989). Also it is important to understand the extent of soil space explored by component species in polyculture in view of competition/complementary root level interactions (Willey, 1979). Further, the geometry of planting also decides the proportion of space exploited by the component species in the intercropping systems. Therefore, a better understanding of the interactions are necessary for elucidating the scientific underpinning of traditional as well as evolving land use systems. Studies relating to root distribution pattern in bamboo is scarce owing to methodological complexities. Nevertheless, relative studies on other species cited below gives an extensive idea on rooting pattern of the various tree species.

Usually the rooting pattern, rooting intensity, its depth vary with varying planting density and other eco-physiological factors. In a study conducted on *Bambusa tulda* to ascertain the roots distribution, White and Childers (1945) observed that, the roots were seen at a distance of more than 17 feet from the clump. Most of the roots (83 per cent) were present in the subsurface where roots serve best in controlling soil erosion. The percentage of roots at lower layers were, 30 cm to 60 cm depth (12 per cent), 60 to 90 cm depth (4 per cent) and 90 to 120 cm depth (1 per cent). Among various methods of rooting study, the root excavation method probably gives a clear picture of the entire root system of a plant as it exists naturally. However, the excavation methods are laborious and time consuming and also incapable of characterising the functional roots (Physiologically active roots). Nevertheless this study gives detailed information regarding root length, size, shape, colour, distribution of each individual roots, and also the interrilationship between competing root systems of other plants (Coker, 1959; Kolesnikov, 1971). This method is usually practiced for woody trees and shrubs than for annual crops (Bohm, 1979).

To characterise the root distribution pattern of trees in relation to their stem diameter and crown spread, Tomlinson *et al.* (1998) employed spiral logarithmic trench for investigating the root distribution pattern in *Parkia biglobosa*. They found that tree roots extended upto 10 m from the trunk, thereby exploiting an area twice that of the crown. This technique gained an advantage over the excavation of entire root system, which is less time consuming and importantly the tree need not be felled for the study.

Das and Chaturvedi (2008) observed a large variation in root depth and horizontal root spread in four-year-old individuals of five agroforestry tree species *viz.*, *Acacia auriculiformis*, *Azadirachta indica*, *Bauhinia variegata*, *Bombax ceiba* and *Wendlandia exserta* studied at Pusa, Bihar. The maximum root depth was recorded in *W. exserta* (2.10 m) and minimum in *B. variegata* (1.00 m). Horizontal root spread was 2.05 m in *Bombax ceiba* and 8.05 m in *Acacia auriculiformis*. Root spread exceeded crown cover for all species and the primary roots were more horizontal than the secondary roots.

Root distribution pattern was studied in four year old *Gmelina arborea* planted at four different spacing in agrisilviculture system in the sub humid region of central India (Swamy *et al.*, 2003). Results showed that most of the coarse roots were distributed in the top 40 cm of soil, whereas fine roots were concentrated in the top 20 cm. The lateral spread of root systems was confined beneath the tree canopy in the case of 2x2 m and 2x3 m stands. However in the case of widely spaced stands roots extend beyond canopy. The depth of coarse roots spread increased from 35 cm at 2x2 m spacings to 75 cm at 2x5 m spacings.

Kumar and Divakara (2001) examined root distribution pattern of 15 year old bamboo (*Bambusa bambos*) in mixed species systems using logarithmic spiral trenching. The excavation studies revealed that rooting intensity in different soil horizons declined exponentially 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 27 % of the total roots. Smaller bamboo clumps showed the lowest rooting intensity, when measured at 5 m and 7.5 m lateral distances and increased linearly with increasing crown radius.

Samritika (2013) studied the root distribution in varying depths and lateral distances on Silver oak trees in Kerala. The study revealed decrease in rooting intensity with increasing depth and lateral distance from the tree base along the spiral trench. About 74 % and 78 % of silver oak roots were found at 1.55 m lateral distance and within top 30 cm soil depth and concluded that active foraging zone lies within top 30 cm depth and 150 cm lateral distances. Similar results are also reported by Niranjana and Viswanath (2008) in the *Camellia sinensis* and *Grevillea robusta* mixed plantations of Kerala.

Bhol and Nayak (2014) studied spatial distribution of roots of *Dendrocalamus strictus* in agroforestry system with two spacings (10x10 m and 12x10 m). The growth of bamboo clumps and root intensity were significantly higher in intercropping system compared to sole bamboo. The root intensity decreased with increase of distance from clump. At 1 m distance the total number of roots was 330 /m^2 while at 4 m distance 222 roots/m^2. The highest root intensity was found at 0-15 cm depth (317 root/m^2) and lowest in 30-45 cm depth (29 roots/m^2).

In any plants fine roots have foremost importance for nutrient absorption and translocation to other parts and vary spatially and temporally. Temporal variations in the spatial distribution of fine-root mass and nutrient concentrations were studied by Tripathi *et al.* (1999) in harvested and mature bamboo savanna sites in the dry tropical Vindhyan region in India. They reported that, the fine-root net production ranged from 486 to 749 g m^{-2} yr^{-1} in the harvested site and 485 to 875 g m^{-2} yr^{-1} in the mature site. All fine-root mass fractions decreased with increase in distance from the base of bamboo clumps and also reported that bamboo fine roots were better developed in the 10-20 cm soil depth.

Methods involving radioactive isotopes have gained significance in ecological root research considering the limitations of excavation approach. ^{32}P is a most commonly used isotope because of its short half-life (14.3 days). It is also mobile in plants to become rather uniformly distributed in root system in a short time and is relatively in-expensive (Bohm, 1979). However, tracer methods do have some limitations, as it cannot be used in rocky, crevices and cracks and also the data obtained is not easy to relate with those from another (Page and Gerwitz, 1974). Nonetheless, it is used as it gives information on uptake of nutrients from different soil layers and provides root information without separating from soil.

The study conducted by Wahid *et al.* (1989) in *Theobroma cacao* and *Anacardium occidentale* using ^{32}P reveal that, the cashew is a surface feeder with 80 per cent of roots confined to the top 15 cm of soil layer and 72 per cent of roots activity was found within the radial distance of 2 m from the tree. In case of cocoa, 85 per cent of the feeder roots were found within the area of radius 150 cm around the tree. Also, Jamaludheen *et al.* (1997) employed this technique to characterise the root distribution of an eight-and-half year old wild *Artocarpus heterophyllus* and found that roots are concentrated up to 75 cm distance and 30 cm depth.

George *et al.* (2009) studied the root distribution pattern in 18 year old rubber (*Hevea brasiliensis*) grown at 4.9 x 4.9 m spacing in Kerala. The ^{32}P was applied at lateral distance of 250 cm from the tree and to a soil depth of 90 cm. The extent of absorption of applied ^{32}P by the tree from various placements was assessed by radio assay of leaf and latex serum. The results revealed that rubber is a surface feeder with 55% of the root activity confining to the top 10 cm of soil layer. Root activity declined with increasing depths and the concentration of physiologically active roots at 90 cm depth was only 6%. They also reported that concentration of physiologically active roots in the surface layer suggests the possibility for root competition under intercropped situation.

Kunhamu *et al.* (2010) evaluated the root activity pattern of two-year-old *Acacia mangium* as a function of three population densities (1,250, 2,500 and 5,000 stems ha^{-1}) with and without 50% crown pruning, using ^{32}P soil injection. The label was placed at 25, 50 and 75 cm lateral distances and at 30 and 60 cm depth. Low density stands (1,250 stems ha^{-1}) showed higher ^{32}P recovery, which was exaggerated by pruning. Pruned low density stands had 34% root activity at 25 cm, as against 23% for unpruned. The low density stands also showed higher root activity at 75 cm, signifying greater lateral root spread. High stem densities favour restricted spread of absorbing roots and facilitated competitive downward displacement of roots.

Kumar and Divakara (2001) studied the competitiveness of bamboo (*Bambusa bambos*) for belowground resources in mixed species systems using ^{32}P soil injection. They also reported that ^{32}P uptake by bamboo in binary combination involving *Tectona grandis* and *Vateria indica* was proportional to the bamboo rooting intensity. Therefore they concluded that root competitiveness in polycultural system involving bamboo is a function of the proximity of bamboo to the associated tree/crop, which in turn decides the bamboo rooting intensity.

Isaac and Anglaaere (2013) reported that tree root distribution and activity are determinants of belowground competition. In the study they employed a nondestructive approach to determine tree coarse root architecture as a function of a perennial tree crop, *Theobroma cacao* at two edaphically contrasting sites (sandstone and phyllite-granite derived soils) in Ghana, West Africa. The study detected vertical distribution of coarse roots using ground-penetrating radar and root activity via soil water acquisition using isotopic matching of δ(18)O on plant and soil signatures. Coarse roots were detected to a depth of 50 cm. Soil δ(18)O isotopic signature declined with depth. They also reported that the approach was able to characterize trends between intraspecific root architecture and edaphic dependent resource availability.

2.9 Biomass production and allocation

Biomass production and allocation to various parts is a decisive factor that reflects the success of an organism in an environment (Gadgil and Solbrig, 1972). Measurements of the amount and distribution of biomass and nutrients are important in understanding the structure and function of the ecosystem (Grove and Malajczuk, 1985). Aboveground biomass production and carbon sequestration in bamboo has two components: growth of newly emerging culms and biomass increase in older culms. The culm biomass and relative allocation of various fractions to total biomass varied markedly among the species. Total biomass in an area depends on stocking level. Therefore the stand stocking is one of important measure for site productivity; overstocking and/or understocking may retard the growth and development of the bamboo (Shi *et al.*, 1993). Relative productivity i.e., the ratio of fresh to older shoots and culm quality decreased with an increase in stand density (Liao and Huang, 1984).

In a comparative study on biomass production of two bamboo species in Malaysia, Chinte (1965) found that 3 to 4 year old plantation of *Bambusa vulgaris* recorded 7 Mg ha^{-1} while *Gigantochloa aspera* recorded 1 Mg ha^{-1}. Othman (1992) evaluated the above ground biomass of *Gigantochloa scortechinii* in natural stands and three year old plantations in Malaysia. He found that biomass production was 71.9 Mg ha^{-1} in a plantation and 36.2 Mg ha^{-1} in natural stands. Young (1991) examined dominant understorey bamboo (*Chusquea* spp) at timberline in north-central Peru and found an aboveground biomass yield of 22 Mg ha^{-1}, below-ground biomass yield of 7 Mg ha^{-1} and an average culm density of 26 culms/ha.

Bamboo clump biomass production and its relative allocation to various components was evaluated in *tahun-kebun* (fallow cropping) rotation cycle by Christanty *et al.* (1996) using *Gigantochloa* species. The results revealed that the aboveground biomass of each bamboo component increased with increased culm age from 0.4 Mg ha^{-1} at 16 moths to 2.7, 9.2 and 34.4 Mg ha^{-1} at the ages of 24, 36 and 72 months respectively. In case of culm biomass, 0.1 Mg ha^{-1} at 16 months to 6 Mg ha^{-1} at 72 months in case of branch biomass, 0.1 Mg ha^{-1} at 16 months to 2.6 Mg ha^{-1} and 4.7 Mg ha^{-1} at 36 months and 72 months respectively in case of foliage biomass.

Biomass productivity in *Bambusa bambos* aged at 4, 5 and 6 years were studied by Shanmughavel and Francis (1996) and found that the standing biomass increased with age. Biomass in leaves, branches and culm were 1.9, 27.2 and 92.8 Mg ha^{-1} respectively at age 4 years and 4.0, 39.9 and 242.7 Mg ha^{-1} at 6 years. Culms accumulated a higher proportion of the biomass than the other parts of the bamboo.

Shanmughavel and Francis (2002) estimated the biomass production in an age series of *Bambusa bambos* plantation. They revealed the linear increase of the total biomass with the age of the plantation upto six years and then it decreased. In the above ground biomass, the relative percentage contributions were: culms (81%), branches (14%) and leaves (1%). The below ground rhizome contribution was 4%. The total biomass increased from 2.3 t/ha (1 year) to 298 t/ha (6 year).

The age and stocking density mainly effect the overall biomass production in any forest or plantation. Embaye *et al.* (2004) studied the biomass distribution in a highland bamboo forest in south-west Ethiopia. The age-structure was 13% of <1 year, 24% of 1–3 years and 63% of >3 years. Culm contributed 82%, branch 13% and leaf 5% to the 110 t ha^{-1} total aboveground biomass, while culms mature for harvest (>3 year) made up 73%. The culm component of the mature bamboo was 60% of the aboveground biomass, whereas the biomass of current shoots (<1 year) constituted only 7%. The biomass of live new rhizomes increased with increasing culm age (0.2 Mg ha^{-1} at 16 months and 10.5 Mg ha^{-1} 72 months).

Biomass estimation of *Bambusa nutans* subspecies *cupulata* was done in Eastern Terai, Nepal (Oli and Kandel, 2005). To estimate the biomass, regression model was developed on the basis of oven dry and green weight. The model used was root $W = a + b * (D^2L)$. Based on the oven dry weight, the R^2 values obtained for culm, branch and foliage components were 90, 82 and 73 per cent respectively. Similarly, R^2 values for culm and foliage components on the basis of green weight were 90 and 73 per cent respectively. The R^2 values obtained for branch and foliage components were lesser compared to the culm.

Kumar *et al.* (2005) studied above ground biomass stock of *Bambusa bambos*. The aboveground biomass of bamboo clumps was 2417 kg per clump with average per hectare accumulation of 241 Mg. Highest biomass accumulation was observed in the live culms (82%), followed by thorns + foliage (13%); dead culms accounted for 5% of the biomass accumulation. The fitted allometric equation were $Y= -3225.8 + 1730.4$ DBH ($R^2 = 0.83$) where Y is the total biomass per clump. They reported relatively high R^2 values implying that the equations reasonably give good prediction of culm number per clump and standing stock of clump biomass.

Vyas *et al.* (2010) studied the leaf area index (LAI) of bamboo (*Dendrocalamus strictus*) grown in Gujarat, India. The LAI was obtained by destructive sampling, photo-grid method and by litter trap method. An allometric equation (between leaf area by litter trap method and canopy spread area) was developed for the determination of LAI. Results showed that LAI value calculated by allometric equation was similar to that estimated by destructive sampling and photo-grid method. They also reported the perfect match in both the LAI values (estimated and calculated), indicating the accuracy of the developed equations for the bamboo. They concluded that, canopy spread is a better and sensitive parameter to estimate leaf area of trees and the developed equations can be used for estimating LAI of bamboo in tropics.

Growth and biomass production in bamboo and *Miscanthus sp.* were studied in China by Hong *et al.* (2011). They revealed that matured stand biomass production ranged from 5.9 to 49 t/ha/yr for bamboo and 3.2 to 49 t/ha/yr for *Miscanthus sp.* Rai *et al.* (2013) studied the growth and biomass accumulation in six year old *Meloccana baccifera* plantation in Mizoram, India. The result showed that the number of culms varied from 2165 to 4190 culms/ha.; the biomass ranged between 8.212 to 9.025 kg/culm and 195.391 t/ha to 362.56 t/ha.

Artificial fertilization increases the growth rate and yield of bamboo. Fertilizer trials conducted by Patil and Patil (1990) on *Dendrocalamus strictus* indicated that, the total dry matter production increased from 4 Mg ha^{-1} in control to 12.5 Mg ha^{-1} with an application of 100 + 50 + 50 kg N:P:K kg/ha/year. Suzuki and Narita (1975) reported that the number of sprouts from the fertilized plots was 1.7 to 1.9 times that of the control. Also fertilizer experiments conducted on *Thyrsostachys siamensis, Dendrocalamus asper*, *Bambusa* spp. and *D. strictus* in three-year-old plantation at Dong-larn in Japan showed that the use of 15:15:15 N:P:K fertilizer at 100 kg ha^{-1} is sufficient to increase the yield (Suwannapinuut and Thaiutsa, 1990).

Singh and Kochhar (2005) studied the planting density (278, 204 and 156 clumps/ha) effect in *Bambusa pallida.* They reveal that planting density significantly influenced growth characters i.e., number of internodes, mean height, girth, dry weight of a culm etc. Total biomass productivity decreased from 341 t/ha at 278 clumps/ha to 234 t/ha at 156 clumps/ha.

Fuzhong *et al.* (2009) studied the effects of different stem densities i.e. high density (220 stems/ha), medium density (140 stems/ha), and low density (80 stems/ha)) on biomass accumulation pattern in dwarf bamboo (*Fargesia denudata*) in China. They reveal that leaf, branch, rhizome, root and total biomass of dwarf bamboo increased with the increase of stem density.

Yen *et al.* (2010) estimated biomass of *Phyllostachys makinoi* bamboo in Taiwan planted at a density of 21191 culms/ha. The proportion of foliage, branches and culms to the aboveground biomass were 78%, 17% and 9% respectively. The results revealed that the aboveground biomass was 105.33 Mg/ha. The also revealed that aboveground biomass and DBH and height had a high correlation (R = 0.94 and 0.80).

Rai *et al.* (2013) studied the growth and biomass accumulation of six year old *Meloccana baccifera* plantation in Mizoram, India. The result showed that the number of culms varied from 2165 to 4190 culms/ha. and the biomass ranged between 8.212 to 9.025 kg/culm which on per hectare basis was 195.391 t/ha to 362.56 t/ha.

A study was conducted in two subtropical bamboo ecosystems in South-west China to determine the rate of different litter fraction production (Li-Hua *et al.*, 2014). Mean annual total aboveground litter production ranged from 494 to 434 g m^{-2} in two bamboo stands viz. *Pleioblastus amarus* and *Bambusa pervariabilis*. Bulk (80%) of litter production was contributed by leaf litter in two stands followed by twigs and sheathes. Different litter fractions represented considerable variations in the rates of mass loss and nutrient release.

2.10 Nutrient accumulation

Mailly *et al.* (1997) studied the accumulation and removal of five major nutrients (N, P, K, Ca, and Mg) in plants, at various stages of a bamboo *talun-kebun* agroforestry system in West Java, Indonesia. The accumulation of five major nutrients in live plant biomass during a complete *talun-kebun* rotation cycle was 787, 134, 692, 218, and 248 kg ha^{-1} for N, P, K, Ca, and Mg, respectively. The overall nutrient removals accounted 51, 48, 55, 52 and 56 per cent of N, P, K, Ca, and Mg from the live plant biomass, respectively.

Shanmughavel and Francis (2002) estimated nutrient distribution in different biomass components varied; the order of major element concentrations was K > N > Mg > Ca > P in leaves. The maximum amount of all nutrients accumulated in the culms, followed by branches, rhizomes and leaves.

Lux *et al.* (2003) found that the highest concentration of silicon (7.6%) in the epidermis layer of *Phyllostachys heterocycla* leaves. In the roots, silicon (2.4 %) deposition was found only in endodermal cell walls.

Embaye *et al.* (2004) examined the nutrient distribution in different age classes (<1 year, 1– 3 year and >3 year) in highland bamboo forests of south-west Ethiopia. They revealed that nutrient concentration ratio across all aboveground plant parts and age-classes were 8 kg ha^{-1} N, 1 kg ha^{-1} P, 11 kg ha^{-1} K, 1 kg ha^{-1} Ca. The mean N, P and K concentration in culms were highest in age-class <1 year and lowest in age-class >3 year. The N and P ratio increased with age. The amount of N and P located in the rhizome and root biomass of the upper 10 cm of soil were between 12% and 28%.

Singh and Kochhar (2005) studied the nutrient accumulation (N, P, K, Ca, Mg, Cu, Zn, Mn and Fe) in the aboveground biomass of *Bambusa pallida* which decreased with decreasing stand density (278 to 156 clumps/ha). Total nutrient accumulation 5 t/ha at 278 clumps/ha. The nutrient export through harvest of culms from the plantation site was 469 kg/ha per year. However nutrient addition through litter was 79 kg nutrient/ha per year.

Kumar *et al.* (2005) studied nutrient export in *Bambusa bambos*. The nutrient export through harvest varied among the tissue types with the highest in live culms, followed by leaves + twigs and dead culms. Average N, P and K removals were 9.22, 1.22 and 14.4 kg per clump respectively. Litter accumulation on the forest floor was 909 g m^{-2} accounting for 48.15, 3.67 and 42.98 of N, P and K gm^{-2} respectively.

The effects of different stem densities (high density (220 stems/ha), medium density (140 stems/ha), and low density (80 stems/ha)) on nutrient distribution in the biomass of dwarf bamboo (*Fargesia denudata*) populations of China was studied by Fuzhong *et al.* (2009). Their study reveal that nutrient concentrations in bamboo components decreased with decreasing clump density. Leaf had the highest N, K and Ca concentrations, followed by root, rhizome, branch and culm, while root had the highest C, P and Mg concentrations regardless of stem density.

Nutrient accumulation, distribution and use efficiency in 30 bamboo plant species were studied in a 14 year old bamboosetum in Arunachal Pradesh by Singh and Arvind (2012). The study revealed that concentration of N, P, Ca, Mn and Zn in different components of biomass was in the order of leaves > branches > stems and the concentration of K, Mg and Fe was in the order: leaves > stems > branches. The N: P: K ratios of above ground biomass varied with species (76–706:1:66–930) and they reported that P is the most limiting nutrient. Rai *et al.* (2013) studied the nutrient distribution in six year old *Meloccana baccifera* plantation in Mizoram, India. The result showed that the order of nutrient concentration in biomass components were: K > N > Mg > Ca > P.

The silica deposition is one of the important characteristics of plants in the family Poaceae. Many investigations have been conducted into the distribution, deposition and physiological functions of silica in this family. Bamboos accumulate on the average 0.1-2.8% of their dry weight as silica in the epidermis of the culm and particularly in older leaves, reaching over 40% in some species (Motomura *et al.*, 2008). In contrast, nodes and internodal tissues are free of silicon dioxide (Seethalakshmi and Kumar, 1998), an advantage for processing, since silica enhances ash content and deteriorates performance of cutting tools. With 0.3-5.3%

of ash, bamboos approximate with tropical tree species (Knigge and Schulz, 1966). They contain more ash than temperate woods (0.3-1%), but less than some bioenergy grasses like *Miscanthus giganteus* or *Panicum virgatum*. Among the chemical peculiarities of bamboo, it has low chlorine content which is favourable for industrial bamboo biomass combustion. The moisture content in the air-dry state of 8-15% is lower than that of timber species (Scurlock *et al.*, 2000; Nakagawa *et al.*, 2007).

2.11 Carbon sequestration

In order to exploit the mostly unrealized potential of carbon sequestration through agroforestry research in both subsistence and commercial enterprises, innovative policies are urgently required. Nevertheless in India, average C sequestration potential in agroforestry has been estimated to be 25 t C/ha over 96 million ha (Sathaye and Ravindranath, 1998), but there is substantial variation in different regions depending upon the biomass production. However, compared to degraded areas, agroforestry may hold more carbon. Gratani *et al.* (2008) reported that trees outside forests in India store about 934 Tg C or 4 Mg C ha^{-1}, in addition to the forests. The net annual carbon sequestration rates for fast growing short rotation agroforestry crops such as poplar and eucalyptus have been reported to be 8 Mg C $ha^{-1}yr^{-1}$ and 6 Mg C $ha^{-1}yr^{-1}$ respectively (Kaul *et al.*, 2010). Selection and development of tree species with capacity to fix higher CO_2 is an increasing requirement worldwide. However, literature reviewed below discusses bamboos and bamboo based agroforestry systems that have the potential to sequester large amounts of above and belowground carbon.

Growth pattern and photosynthetic activity of different bamboo species viz., *Phyllostachys pubescens, Phyllostachys bambusoides* and *Bambusa ventricosa* growing at the Botanical Garden, Rome were studied by Gratani *et al.* (2008). Among the species, *P. pubescens* had highest mean culm height (14 m) and diameter (10.77 cm), while *B. ventricosa* recorded lowest mean culm height (6.07 m) and internodes number (35). Owing to the great potential for biomass production, bamboos could be a significant net sink for CO_2; with the highest whole culm photosynthetic rate by *P. pubescens* (272 μmol CO_2 s^{-1}). However, they reported that *P. pubescens* contributed major role for carbon sequestration (14.6 kg CO_2 $year^{-1}$ per culm) compared with the other considered species.

The rates of carbon bio-sequestration within silica phytoliths of the leaf litter in the economically important bamboo species was studied by Parr *et al.* (2010). There is considerable variation in the content of carbon occluded within the phytoliths (PhytOC) of the leaves between different bamboo species. The potential phytolith carbon bio-sequestration rates in the leaf-litter component for the bamboos ranged upto 0.7 tonnes of CO_2 equivalents (t-e-CO_2) ha^{-1} yr^{-1}. Assuming a median phytolith carbon bio-sequestration yield of 0.36 t-e-CO_2 ha^{-1} yr^{-1}, the global potential for bio-sequestration via phytolith carbon (from bamboo and/or other similar grass crops) is estimated to be ~1.5 billion t-e-CO_2 yr^{-1}, equivalent to 11% of the current increase in atmospheric CO_2. They also reported that the management of vegetation such as bamboo forests to maximize the production of PhytOC has the potential to result in considerable quantities of bio-sequestered carbon.

Yen *et al.* (2010) estimated biomass carbon storage in *Phyllostachys makinoi* bamboo Taiwan. The results revealed that the aboveground biomass carbon storage was 49.81 Mg/ha. A comparative study on carbon fixation ability of three forest stands was conducted by Xu *et al.* (2011) at Zhejiang Province, China. The results showed that total carbon storage in the ecosystems of Moso bamboo, Chinese fir, and Masson pine stands were 104.83, 95.66, and 96.49 t C/ha, respectively. The spatial distribution of carbon storage in the three ecosystems were decreased. Carbon storage in the soils under Moso bamboo, Chinese fir, and Masson pine stands accounted for 65.3, 61.4, and 55.6% of the total carbon stocks, respectively. The Moso bamboo forest ecosystem fixed 1.69 and 1.63 times as much C (9.64 t C/ha/year) as the Chinese fir and Masson pine forest ecosystems, respectively.

Nath and Das (2011) studied C sequestration in smallholder bamboo farming system in Barak Valley, Assam. The C estimate in aboveground vegetation ranged from 6.51 (2004) to 8.95 (2007) Mg ha^{-1} with 87%, 9% and 4% of the total C stored in culm, branch and leaf respectively. The mean rate of C sequestration was 1.32 Mg ha^{-1} yr^{-1}.

2.12 Soil nutrient studies

Singh and Singh (1999) studied growth and impact of a solid bamboo (*Dendrocalamus strictus*) plantation on mine spoil in a dry tropical region. They reported that, the amounts of N and P deposition and release increased with the age of the plantation. The rate of N-mineralization increased from 3.3 (3 years) to 6.9 µg g^{-1} $month^{-1}$ (5 years). The proportion of mineralized-N converted into nitrate decreased with age. Soil microbial C increased from 127 to 319, microbial-N from 19 to 38 and microbial-P from 9 to 16 µg g^{-1} soil between 3 to 5 years. With increasing age of plantation, a greater proportion of soil C, N and P was found to be immobilized in soil microbial biomass.

Wang *et al.* (2004) investigated the distribution of microbial biomass carbon, nitrogen and phosphorus in the soil profiles of five different vegetation systems including barren area, Bamboo, Chinese Fir, Citrus orchard and rice field. The microbial carbon B:C levels in the bamboo system were higher than those in the other systems, and it decreased with increasing soil depth in all vegetation systems except the bamboo. The highest microbial biomass nitrogen was detected in the top 20 cm of soil for the bamboo and in the 20-40 cm soil layer for the other vegetation systems. The order of soil microbial biomass Phosphorus levels from highest to lowest was as follows: Bamboo > Chinese fir > Citrus orchard > Rice field > bare area.

Embaye *et al.* (2004) studied the belowground nutrient distribution in a highland bamboo forest in southwest Ethiopia. Their study revealed that soil nutrient concentrations declined sharply with soil depth. Between 50% and 70% of the total nutrient content estimated in one meter soil depth were located in the organic matter layer above the mineral soil and between 80% and 97% were located down to 40 cm soil depth. The nutrient concentrations in the soil were 261 kg ha^{-1} N, 1 kg ha^{-1} P, 6 kg ha^{-1} K, 21 kg ha^{-1} Ca, indicating a soil poor in P and K.

The density of stand have much influence on soil physico-chemical properties. At surface soil (0–20 cm) electrical conductivity and soil pH, organic matter, avail. P, exchangeable K and Fe decreased with decreasing density (278 to 156 clumps/ha) of *Bambusa pallida* plantation (Singh and Kochhar, 2005).

Phyllostachys praecox cultivation with intensive management has high economic profits in China. However, soil acidification is a severe problem (Gui *et al.*, 2013). They reported that soil nutrients accumulated significantly high in the bamboo plantation, but soil p^{H} dropped dramatically.

Tu *et al.* (2013) evaluated the effect of bamboo plantation on rhizosphere soil enzyme and microbial activities and nutrient contents in coastal ecosystem. The content of soil moisture content, soil organic matter, total N, P and K in bamboo forest soils was significantly increased but the soil p^{H} was decreased. Soil enzyme activities and soil microbial population counts were higher in various bamboo species than bare land. They also found that the content of soil chemical, enzyme and microbial properties in *Phyllostachys violascens* and *Dendrocalamus minor* forests were higher than other bamboo species.

2.13 SOC in aggregate fraction

Six *et al.* (2000) found significantly greater soil organic carbon (SOC) in the micro-aggregate (250–53 μm) compared to macro (> 250 μm) and silt and clay (<53 μm) fraction in native grasslands as compared to adjacent tilled sites on four Midwestern American sites. They also reported that long term SOC storage occurs in the silt and clay (<53 μm) aggregate class of soil compared to other fractions. Haile *et al.* (2008) found significantly higher SOC in the macro-aggregate (>250 μm) fraction on a slash pine (*Pinus elliotti*) + Bahiagrass (*Paspalum notatum*) silvopasture as compared to immediately adjacent open treeless pastures sites in Florida.

Emanuela (2010) examined the soil organic carbon (SOC) storage in relation to soil aggregate classes (>250 µm, 250–53 µm, and <53 µm) in cacao (*Theobroma cacao*) based agroforestry systems (AFSs) of Bahia, Brazil. The results reveal that 72% of SOC was in macro-aggregate-size, 20% in micro-aggregate-size, and 8% in silt-and-clay size fractions of soil. Cacao had higher SOC stock than the other two land-use systems in the 0–30-cm soil layer. The C content in soil aggregates of macro-size fraction declined with increase in soil depth in all land-use systems. The C storage in the silt-and-clay size fraction above 30 cm was almost 50% greater under cacao AFSs than under natural forest. However, they also reported that SOC beyond 30 cm depth was not significantly varied among land-use systems.

Saha *et al.* (2010) examined the aggregate (250-2000 µm, 53-250 µm, <53 µm) soil C storage, an indicator of C sequestration potential in homegardens (HGs), natural forests and single species stands of *Cocos nucifera*, *Oryza sativa* and *Hevea brasiliensis* plantation in Kerala. They reported that total C stock was highest in forests (176.6 Mg/ha), followed by managed tree-based systems and lowest in rice-paddy field (55.6 Mg/ha). The higher amount of C in the <53 µm fraction is the most stable form of C in the soil. The SOC in the micro-sized class (53-250 µm) in coconut, rubber and HGs were lower than macro-sized (>250 µm) but higher than the silt and clay sized class. However, they also reported that systems with higher tree-density (forest and rubber plantation) stored higher amount of SOC compared to old treeless systems such as rice-paddy.

Baah-Acheamfour *et al.* (2014) studied the impact of three agroforestry systems (hedgerow, shelterbelt, and silvopasture) on soil organic carbon (SOC) and nitrogen in the 0–10 cm mineral layer by comparing SOC and N distributions in whole soils and three aggregate classes (<53, 53–250, 250–2000 µm) to assess the potential role of physical protection on soil C and N storage. Across all sites, 48.4%, 28.5%, and 23.1% of SOC was found in the fine (<53 µm), medium (53–250 µm) and coarse aggregate (250–2000 µm), respectively. Mean SOC in the whole soil was 62.5, 47.7 and 81.3 g kg^{-1} in hedgerow, shelterbelt and silvopasture systems, respectively. Soil C in the more stable fine aggregate (<53 µm) was 34.3, 28.8 and 29.3 g kg^{-1} in the hedgerow, shelterbelt and silvopasture systems, respectively. They concluded that within each agroforestry system, the forested land-use consistently had greater total SOC and SOC in all size aggregates than the agricultural component.

Shang *et al.* (2014) quantified SOC in aggregates (coarse >250 µm, medium, 250-53 µm and fine <53 µm) and density fractions (light and heavy) under four types of common forest vegetation-land uses: an evergreen broad-leaf forest, a pine forest, a managed chestnut (*Castanea dentate*) forest and an intensively managed bamboo forest in subtropical China. The results reveal that SOC in the 0–20 and 20–40 cm soil layers was the highest in the bamboo forest (31.6–34.8 g C kg^{-1}), followed by the evergreen broad-leaf forest (10.2–19.9 g C kg^{-1}), the pine forest (8.5–13.6 g C kg^{-1}) and the chestnut forest (6.3–12.2 g C kg^{-1}). The SOC was higher in the coarse aggregate under the evergreen broad-leaved, pine and bamboo forests, while it was higher in the fine aggregate in the managed chestnut forest. The SOC in the light fraction under the four forest vegetation-land use types ranged from 1.4 to 13.1 g C kg^{-1} soil, representing 21%–37% of the total organic C. They concluded that forest vegetation-land use type influenced SOC distribution in aggregates and density fractions in the studied subtropical forests.

Materials and Methods

3. MATERIALS AND METHODS

The present study on Bamboo (*Dendrocalamus strictus* (Roxb.) Nees) based agroforestry system: planting density effects on biomass accumulation, carbon sequestration, root distribution pattern and understorey crop productivity was carried out during 2012-2014. The details of the materials used and technique / methodology employed in the experiments during the course of investigation are described in this chapter.

3.1 Experimental site

The study was conducted in a 7 year old bamboo (*Dendrocalamus strictus* (Roxb.) Nees) experimental plot established during 2004 in Vellanikkara, Thrissur, Kerala, India (10^0 13' N latitude and 76^0 13' E longitude and at an elevation of 40.29 m above sea level). The bamboo was planted at 5 different spacings viz. 4x4 m, 6x6 m, 8x8 m, 10x10 m and 12x12 m (densities: 625, 277, 156, 100 and 69 clumps/ha) in a randomized block design replicated thrice at Vellanikkara with one absolute control without any bamboo. The individual plot size was 30 x 30 m.

3.2 Climate and soil

Vellanikkara experiences a tropical warm humid climate, with a mean annual rainfall of 3062 mm, most of which is received during the South-West monsoon (June to September). The mean maximum temperature ranged from 29.10^0 to 35.49^0 C in the months of July and March respectively while the mean minimum temperature varied from 22.19^0 to 24.83^0 C in the months of December and May respectively. The soil of the experimental site was a Typic Plinthustult-Vellanikkara series midland laterite (Thomas *et al.*, 1998).

3.3 Physico-chemical properties of soil under various spacings of bamboo before planting herbaceous understorey crops

For physico-chemical analysis, soil samples were collected before intercropping from a 0-20 cm depth between the bamboo rows in each treatment. Bulk density was estimated by taking out a core of undisturbed soil by using steel cylinder (Jackson, 1958). The soil was oven dried and weight was determined. The volume of soil was calculated by measuring the volume of cylinder ($\pi r^2 h$). The bulk density was calculated by dividing the oven dry weight of soil samples (g) by volume of the soil. The air-dried soil samples ground to pass through a 2 mm sieve. 1:2.5 ratio of soil: water suspension was prepared for pH estimation. The p^H was measured by using p^H meter (Jackson, 1958). The total nitrogen content of soil was determined by Kjeldahl digestion and distillation method (Jackson, 1973). The available phosphorus content of soil was extracted by Bray No.1 and estimated by reduced molybdate blue colour method (Watanabe and Olsen, 1965). The available potassium content of soil was determined by neutral normal ammonium acetate extract using flame photometer (Jackson, 1958).

The data were analysed using the software IBM SPSS Statistics 20 for Windows. It was evaluated with 95% confidence limit for randomized-block experiments with spacings of bamboo as factor. Least significant difference (LSD) tests were used for assessing differences between Means.

3.4 Understorey Photosynthetically Active Radiation (PAR)

A continuous PAR measurement (8 a.m. to 6 p.m.) in all plots from November 14 to December 20, 2012 was carried out using a Line Quantum Indicator (LQI 2404, K131). A battery-powered data logger integrated the mean PAR at hourly intervals from 8 a.m. to 6 p.m. within each plot. PAR above the canopy of each plot was simultaneously recorded by the data logger using a Point Quantum Indicator (LQI 2404, K13-1) mounted on a long pole rising above the canopy. PAR was then converted to canopy

Plate 1. Line Quantum Indicator used for estimating understorey PAR in 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

transmittance-the ratio of light below the canopy to light incidence on the top of the canopy.

3.5 Stand Leaf Area Index (LAI)

LAI is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. This is used to predict understorey crop growth, photosynthetic primary production and evapotranspiration. The bamboo stand LAI was estimated using a Plant Canopy Analyzer (LAI 2000, LI-COR Inc., Lincoln, Nebraska, USA) during December 22, 2012 to January 17, 2013. The instrument can measure LAI of plant canopies 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). The LAI outside the plot was recorded as an "above canopy reading" of sky brightness and then understorey area in each bamboo plot as "below canopy reading" as bamboo LAI. Care was taken to ensure that the unit was facing the same direction both outside and inside the stand. A sun-lit canopy was avoided by taking measurements just after sunrise and just before sunset when the intensity of solar radiations are low. A view restrictor of 90^0 prevented direct sunlight from reaching the sensor and occluded the measuring person from the 'view'.

3.6. Intercropping of herbaceous medicinal plants under bamboo

3.6.1 Treatments and crop cultivation

The understorey crops include turmeric (*Curcuma longa* L. var. Pratibha), ginger (*Zingiber officinale* Roscoe. var. Varade) and chittaratha or lesser galangal (*Alpinia calcarata* Roscoe. var. local) were grown in beds of size 3 m x 1.2 m x 30 cm in between the centrally located hedge-rows of bamboo plot belonging to each spacing treatment (replicated thrice) during 1st May, 2012 (Fig. 1). The beds were laid in East-West direction so as to ensure maximum exposure to available sunlight. The intercrops

Plate 2. Plant Canopy Analyzer used for estimating LAI of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

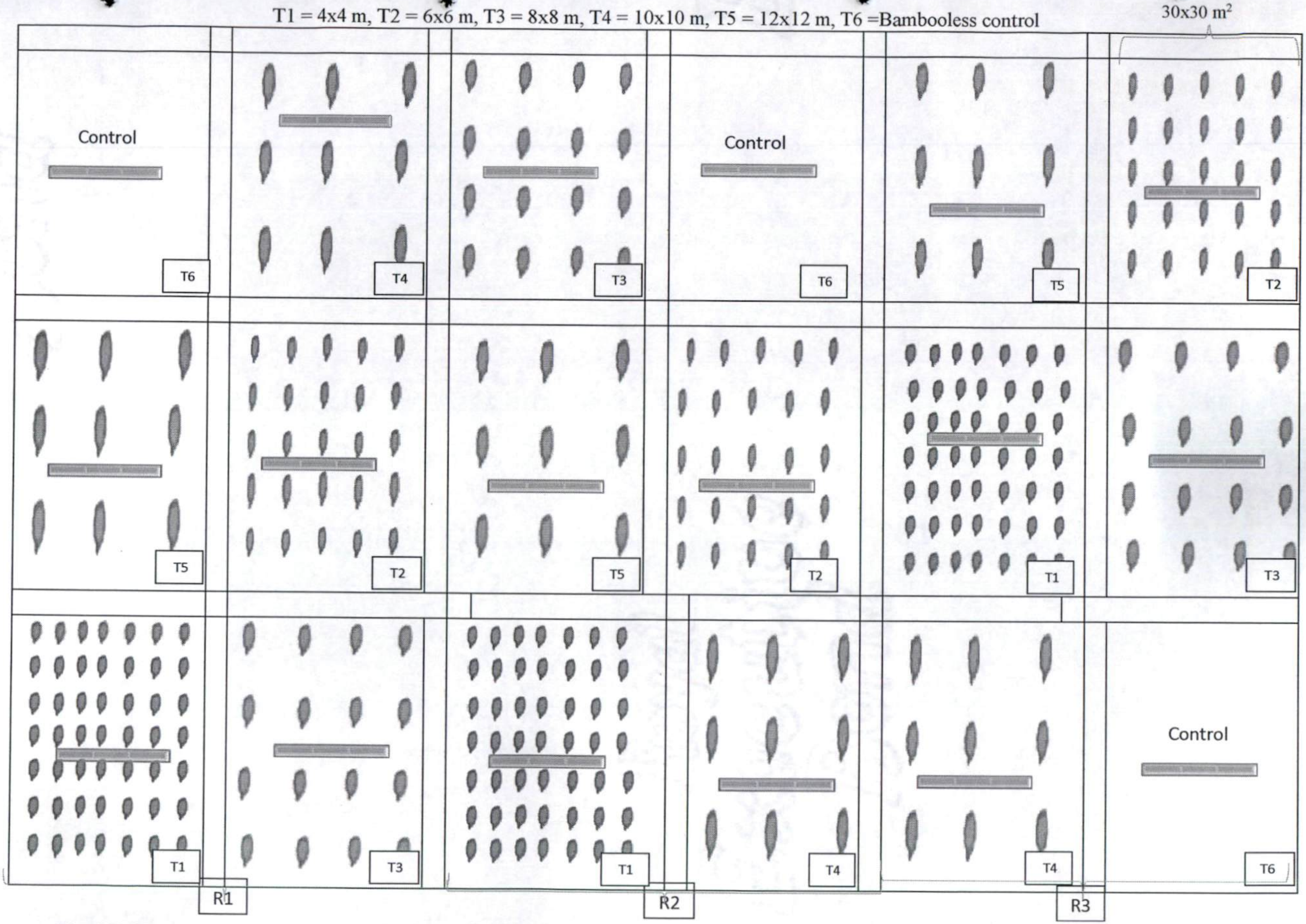


Fig. 1 Schematic presentation of understorey cropping at varying spacings of bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur.

Plate 3. View of seed sowing and mulched beds at varying spacings of bamboo (*Dendrocalamus strictus*)

were planted at 25 x 25 cm spacing following recommended package of practices (KAU, 2011). In addition to these treatments an absolute bambooless control was established where the herbaceous crops were raised in open contiguous plots.

3.6.2 Measurement of crop growth and yield

The turmeric, ginger and chittaratha grown at various spacings of bamboo were destructively sampled at different durations (turmeric, ginger at 90, 180, 230 DAP and chittaratha at 90, 180, 230 and 360 DAP). Size of 0.5x0.5 m^2 (9 plants) were randomly selected from each plot. The plant height, shoot length, number of tillers, number of leaves were recorded. All plants in the sampling units were then uprooted carefully. After cleaning, the aboveground and below ground portions were separated and their fresh weight recorded. The samples were then oven dried at 70^0 C until constant weight was achieved. The component dry matter production and final rhizome yield (230 DAP) for turmeric and ginger and chittaratha (360 DAP) was determined from each treatment. The phytochemical analysis were made at harvest.

3.6.3 Growth attributes of understorey crops

Plant height

The height of the intercrop was measured from the base of the main pseudostem to the tip of the top most leaf and was expressed in cm.

Number of tillers

Number of tillers were determined by counting the number of aerial shoots arising around a single plant (hill).

Number of leaves

Number of leaves were determined by counting the number of leaves of all the tillers of a plant.

3.6.4 Dry matter production

Leaf dry weight

The leaf fresh weight and leaf dry weight (kept in hot air oven at 70° C till constant weight achieved) of the observational plants (9 plants) from each treatments was determined and expressed in grams/plant.

Shoot dry weight

The shoot (including tillers) fresh weight and shoot dry weight from each treatment in each replication was observed and expressed in grams/plant.

Rhizome dry weight

The fresh rhizomes were washed, all roots from the rhizomes were removed and rhizome weight of observational plants from each treatment was determined. The weight was expressed in grams/plant.

Total dry weight

Total dry weight of all the component parts of herbaceous crops were obtained by summing up each component dry weights viz. shoot, leaf, rhizome etc. and expressed in Mg/ha.

3.6.5 Final rhizome yield

The understorey turmeric, ginger (230 DAP) and chittaratha (360 DAP) was harvested (left out crop after sampling) from each experimental plot. The rhizomes were separated from the plant portion and soil clods were detached from the rhizome. After cleaning, the rhizomes were weighed in kg/plot and converted to Mg/ha from each spacings of bamboo and control plot without bamboo.

3.6.6 Phytochemical analyses

3.6.6.1 Composition and uptake of major nutrients (N, P, K)

The leaf tissue of turmeric, ginger and chittaratha at the final harvest were chopped separately and dried in a hot air oven at 70^0 C till constant weights obtained. It was then powdered separately for analysis. The methods for nutrient analysis adapted were:

Nitrogen

Nitrogen was estimated by microkjeldahl method (Jackson, 1973) and expressed in percent

Phosphorus

For the analysis of P, diacid extracts were prepared by digesting 1 g of the sample in 15 ml of 2 : 1 concentrated nitric acid and perchloric acid mixture. Aliquots of digests were taken for the analysis of total P colorimetrically by Vanedomolybdo phosphoric yellow colour method (Koenig and Johnson, 1942). The yellow colour was read in a spectro-photometer at a wavelength of 470 nm.

Potassium

The potassium in leaf was estimated using flame photometer (Piper, 1967). The values expressed in percentage.

The uptake of nitrogen, phosphorus and potassium by the plant was calculated by multiplying the respective nutrient percent of the plant with dry weight of the plant parts and expressed in kg per hectare.

3.6.7 Oleoresin content

Ten grams of finely powdered rhizomes of turmeric, ginger and chittaratha samples in a filter paper pouch were 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 later petroleum ether evaporated out and the difference in weight of flask was recorded for estimating oleoresin content.

$$\text{Percent of oleoresin} = \frac{W_2 - W_1}{S} \times 100$$

Where,

W_1 = weight of empty flask (gms)
W_2 = weight of flask with extractives (gms)
S = weight of sample (gms).

The data were analysed using the software IBM SPSS Statistics 20 for Windows. It was evaluated with 95% confidence limit for randomized-block experiments with spacings of bamboo as factor. Least significant difference (LSD) tests were used for assessing differences between Means.

3.6.8 Incidence of diseases

The occurrence of soft rot (*Pythium aphanidermatum*) on ginger was observed sporadically during heavy rain (August - September). Bavistin (1 g L^{-1}) on affected plants. Neighbouring unaffected plants were soil drenched with Fytolan (3 g L^{-1}) (KAU, 2011).

3.7 Root competition in bamboo-turmeric intercropping system

Soil injection of ^{32}P was carried out on 22nd September, 2012 to evaluate the bamboo and turmeric root competition. A plot size of 1x1 m^2 at the center of each turmeric bed was selected from each bamboo spacing. In the five months old turmeric plants, ^{32}P was applied to the four plants in a row (Fig. 2). For this, two holes were drilled on either side of the selected turmeric plants (10 cm soil depth and 10 cm lateral distance) such that there were eight equidistant holes per experimental unit. The PVC access tubes of 1.25 cm diameter were inserted into these holes by exposing 10 cm above the ground for ease of ^{32}P application. A liquid of 1.176 mCi/plant was transferred to the PVC tube using a special applicator (Wahid *et al.*, 1988).

The most recently matured turmeric leaves from the treated and neighbouring turmeric plants in the two adjacent rows on either side of the treated plants were sampled for radioassay on 15th, 30th and 45th day of application. The leaf samples were air-dried for one day and oven dried at 75°C and radioassayed for ^{32}P at the Radiotracer Laboratory, Kerala Agricultural University, Vellanikkara. The radioassay 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 upto 20 ml volume. Vials containing digest were counted for radioactivity in a liquid scintillation counter (Model: Trialther-Hidex) by the Cerenkov counting technique (Wahid *et al.*, 1985). Count rates (counts per minute, cpm) were corrected for background and decay and subjected to $\log_{10}(x+1)$ transformation. Bamboo clumps adjacent to turmeric beds were also sampled to assess the extent of root competition by bamboo clumps for the ^{32}P applied to turmeric. For this, fresh bamboo leaves were sampled separately at 15th, 30th and 45th days interval and were subjected to radioassay as described above.

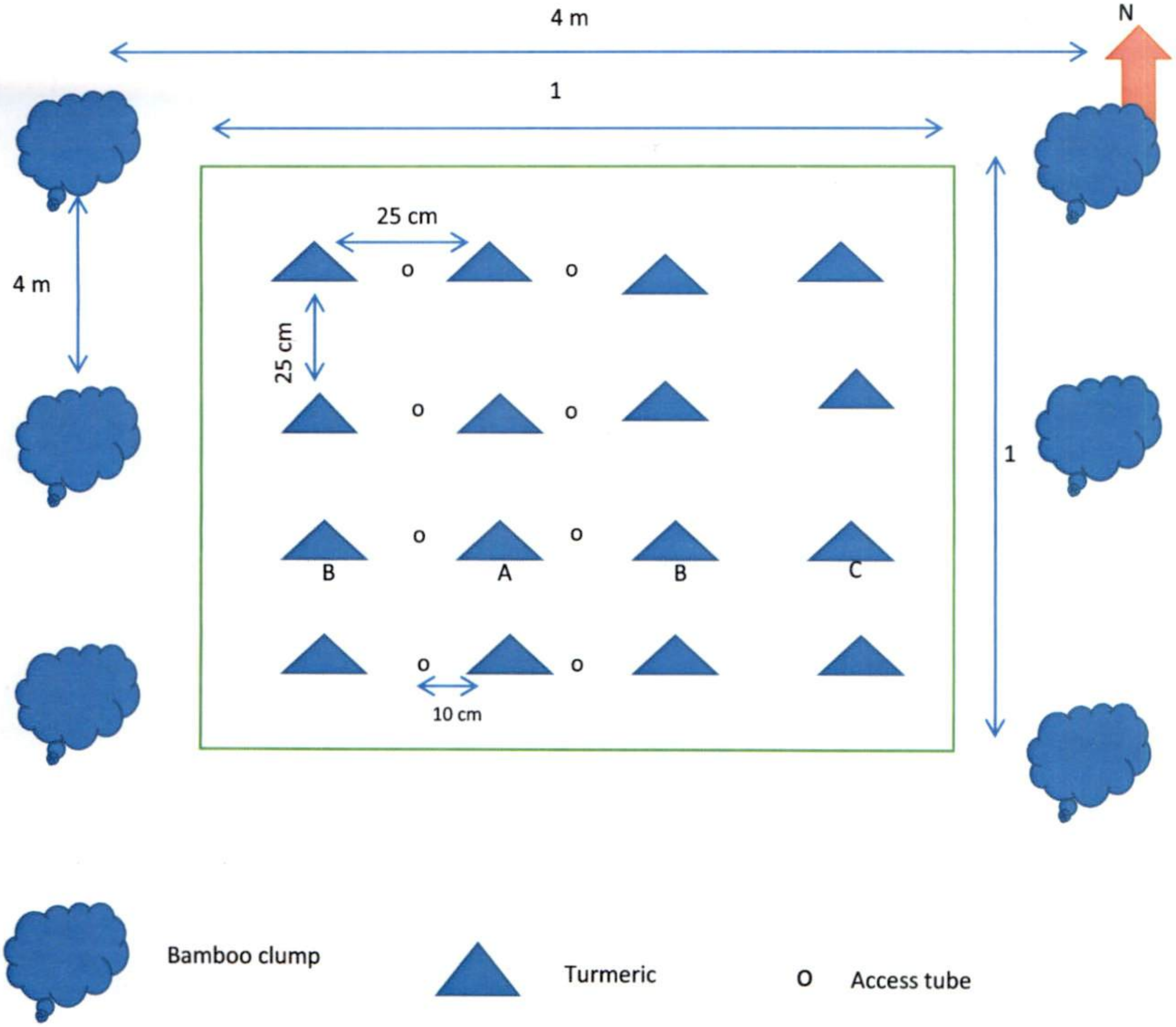


Fig. 2 Schematic sketch showing turmeric plants, bamboo clumps and access tubes for ^{32}P application

Plate 4. ^{32}P Application on understorey turmeric grown at various spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

Plate 5. ^{32}P Application on understorey turmeric grown at various spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

The data on root activity of turmeric were analysed using statistical package SPSS (ver. 20) for evaluating the differences in ^{32}P absorption pattern owing to differences in time intervals of measurement and distance of bamboo clumps from the place of ^{32}P application. It was evaluated with 95% confidence limit for randomized-block experiment. Least significant difference (LSD) tests were used for assessing differences between Means.

3.8 Characterization of root distribution pattern in bamboo using modified logarithmic spiral trenching method

Logarithmic spiral trenches suggested by Huguet (1973) were used to characterise the root systems under different planting densities of bamboo (4x4, 6x6, 8x8, 10x10 and 12x12 m). In order to avoid intertwinement of roots of adjacent bamboos, one clump in the border of each treatment was randomly selected considering the clump diameter and distance between adjacent bamboo clumps. The crown radius of the selected clump was measured by projecting the crown edge to the ground. The distance between each crown edges were summed and mean crown radius (r) calculated.

The root systems of the selected clumps in each treatment (4 x 4 m, 6 x 6 m, 8 x 8 m, 10 x 10 m and 12 x 12 m) were partially excavated using a modified logarithmic spiral trench technique based on the ratio between crown radius and diameter of clump (r/d). The spiral nature of trench enables a large proportion of the root system to be examined with minimal damage to the trees. The dimensions of each trench were determined using the following formulae (Modification of Tomlinson *et al.*, 1998).

$$X = 0.75 \times d \quad \longrightarrow \quad (1)$$

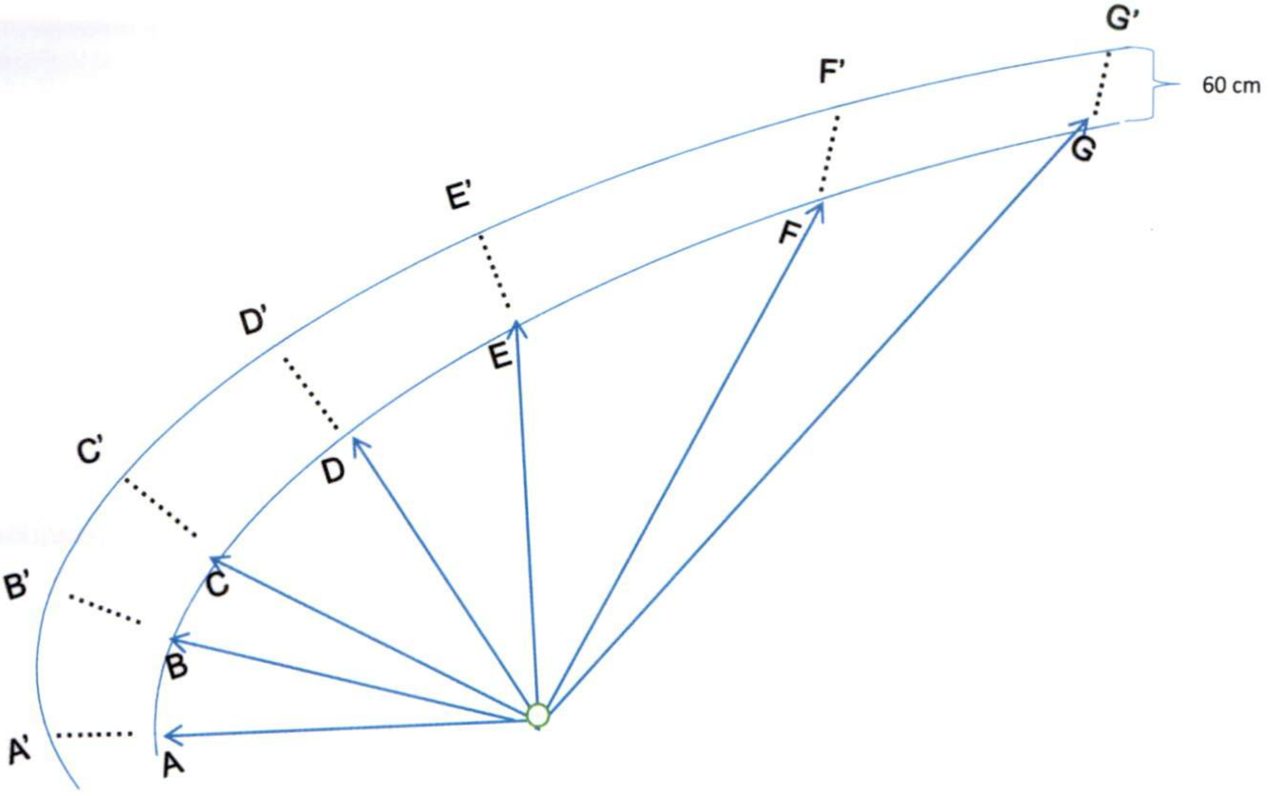
$$Y = [\mathrm{In}\,(r/d)] / \pi/2 \quad \longrightarrow \quad (2)$$

$$Z = Xe^{y\O} \quad \longrightarrow \quad (3)$$

Where,

d = clump diameter in m.

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



○= Origin of the spiral.

OA, OB, OC, OD, OE, OF, OG = co-ordinates of the internal spiral at ϴ= 00, 450, 67.50, 900 and 112.50

OA', OB', OC', OD', OE', OF', OG'= co-ordinates of the external spiral at ϴ= 00, 450, 67.50, 900, and 112.50

Fig. 3 Schematic diagram showing co-ordinates of the modified logarithmic spiral trench.

Plate 6. Semi logarithmic trench for estimating root distribution in different spacings of 7 year old bamboo (*Dendrocalamus strictus*), Vellanikkara, Thrissur

Plate 7. Semi logarithmic trench for estimating root distribution in different spacings of 7 year old bamboo (*Dendrocalamus strictus*), Vellanikkara, Thrissur

X = natural logarithm of the ratio of crown radius to diameter of clump divided by $\pi/2$.
Y= the distance of the starting point of the spiral from the clump in m.
Z = the distance of any point on the spiral from the clump base in m.

The starting point for internal face of each trench (A) was obtained by calculating 'X' from a north facing point on the clump, the origin (O), with the spiral curving in a clockwise direction due south, thus sampling a 135° sector of the root system. Ø was taken as 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 get the seven co-ordinates of the internal trench OA, OB, OC, OD, OE, OF and OG as shown in the fig. 3. The co-ordinates of the external trench were obtained by increasing the length of the internal co-ordinates by 60 cm to give OA', OB', OC'. OD', OE', OF', OG'. Contours of both internal and external spirals were marked on the ground. The trench was then dug to a depth of 60 cm and to a breadth of 60 cm taking care that the sides remain intact. Severed bamboo roots on the internal and external trench walls were counted by placing a 50 cm x 60 cm quadrat (subdivided into 10 cm depth intervals). Roots were classified into less than 2.5 and 5 mm diameter classes at the time of counting. The quadrats were placed along the spiral trench at 2 m interval upto 8.75 m from the origin. Root counts were then converted into rooting intensity (number of roots per meter^2, Bohm, 1979).

Root intensity data from the excavation studies were analysed using statistical package SPSS (ver. 20) for evaluating the vertical and horizontal distribution of bamboo roots along the spiral trench. It was evaluated with 95% confidence limit for randomized-block experiment. Least significant difference (LSD) tests were used for assessing differences between Means.

3.9 Root activity study in bamboo using radio isotope

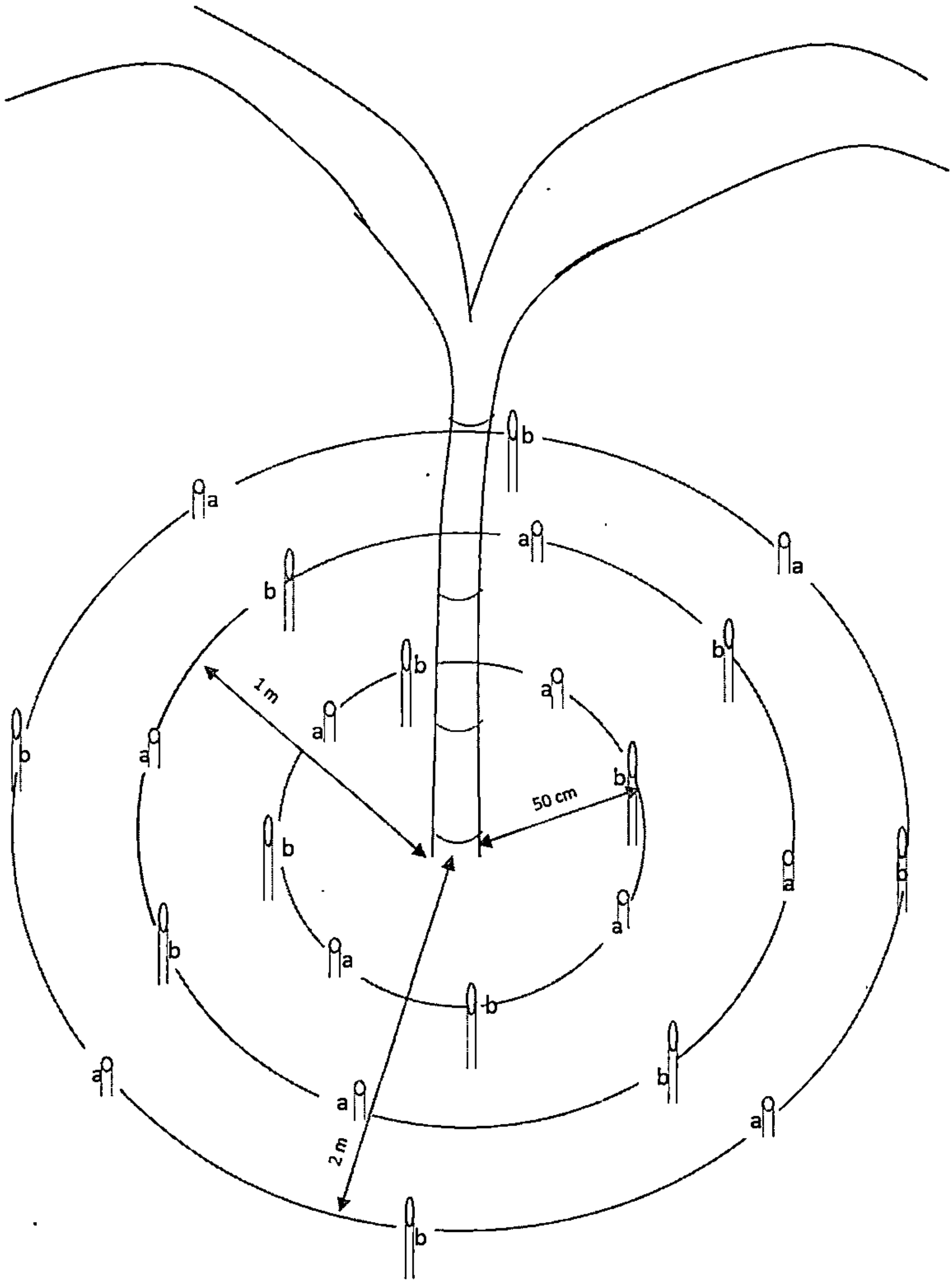
The experiment was laid in a factorial RBD design with lateral distances from different spacings of bamboo and soil depth as factors. The PVC access tubes protruding 10 cm above the soil surface were inserted into the holes at 3 lateral distances *viz.* 50 cm, 1 m and 2 m from the bamboo clump centre and at 2 depths *viz.* 50 cm and 1 m (Fig. 4). The open end of each tube was covered with a plastic cap to prevent entry of rain water. Minimum of 8 m distance was kept between any two treated clumps to eliminate cross feeding. The ^{32}P solution with a carrier P concentration of 1000 mg L^{-1} was applied at the rate of 2.1 mCi per clump on 24th September, 2013, using a device for the purpose (Wahid *et al.*, 1988). The isotope solution was applied into the equally spaced eight tubes around each clump, through equal volumes so as to give 2.1 mCi per clump.

3.9.1 Radioassay of bamboo leaves

The newly formed, young bamboo leaves from the treated clump were sampled separately for radioassay. Sampling was done at 15th and 30th days after application of ^{32}P. The leaf samples were air-dried for one day and oven dried at 75^{0}C and radioassayed for ^{32}P at the Radio-tracer Laboratory, Kerala Agricultural University, Vellanikkara. The method consists of wet digestion of one gram of leaf sample using diacid mixture (HNO_3 and $HCLO_4$ at 2:1 ratio) and the digest was transferred to a counting vial. The final volume of the content in the vial was made-upto 20 mL. The samples were then counted in a liquid scintillation counter (Model: Trialther-Hidex) by Cerenkov counting technique (IAEA, 1975). The ^{32}P counts recorded from the Cerenkov were expressed as counts per gram of leaf per minute (cpm g^{-1}/min). Prior to statistical analysis the cpm values were corrected for back ground as well as for decay and subjected to $\log_{10}(x+1)$ retransformation and statistically analysed. The root activity for ^{32}P at each lateral distance and depth was calculated with following formula.

$$\text{Root activity (\%)} = \frac{{}^{32}\text{P counts (g}^{-1}\text{/min) in a lateral distance and depth x 100}}{\text{Sum of } {}^{32}\text{P counts (g}^{-1}\text{/min) in all the lateral distances of a particular depth}}$$

The data on root activity were analysed using statistical package SPSS (ver. 20). It was evaluated with 95% confidence limit for randomized-block experiments



Depth:

a = 50 cm

b = 100 cm

Fig. 4 Lay out plan for ^{32}P application in the bamboo showing the locations of holes for ^{32}P injection

Plate 8. ^{32}P Application at different depths and lateral distances under various spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

Plate 9. ^{32}P Application at different depths and lateral distances under various spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

with spacings of bamboo as factor. Least significant difference (LSD) tests were used for assessing significant differences between Means.

3.10 Physico-chemical properties of soil under varying spacings of bamboo

3.10.1 Soil sampling

The soil samples was collected from each of the experimental plot involving different spacings of bamboo (4 x 4, 6 x 6, 8 x 8, 10 x 10 and 12 x 12 m) and a bambooless control. For this soil collection pits (1 m^3) were cut and soil samples was drawn for analysis. The soil was collected from four depths (0-20, 20-50, 50-80 and 80-100 cm) in three replications from each spacing of bamboo. There were a total of 72 samples (6 spacings including control x 3 replications x 4 depths). Bulk density was estimated by taking out a core of undisturbed soil using steel cylinder (Jackson, 1958). The soil was oven dried and weight was determined. The volume of soil was calculated by measuring the volume of cylinder ($\pi r^2 h$). The bulk density was calculated by dividing the oven dry weight of soil samples (g) by volume of the soil. The air-dried soil samples were ground to pass through a 2 mm sieve. 1:2.5 ratio of soil: water suspension was prepared for p^H estimation. The p^H was measured by using p^H meter (Jackson, 1958).

3.10.2 Soil nutrients (N P K)

Total nitrogen

Total nitrogen under each treatment at different soil depths was determined by Kjeldahl digestion and distillation method (Jackson, 1973).

Available phosphorus

Available phosphorus under each treatment at each depth of soil was determined by reduced molybdate blue colour method (Watanabe and Olsen, 1965).

Plate 10. View of soil pits for soil collection at different depths in varying spacings of 7 year old bamboo (*Dendrocalamus strictus*), Vellanikkara, Thrissur.

Available potassium

Available K in each treatment at four depths extracted using neutral normal ammonium acetate and was read in Flame photometer (Jackson, 1973).

3.10.3 Soil preparation and analysis for organic carbon

The soil samples were physically fractioned by wet-sieving using disruptive forces of slaking and wet-sieving through a series of two sieve sizes (250 and 53 μm) to obtain three fraction size classes: macro (250-2000 μm), micro (53-250 μm) and silt and clay size fraction (<53 μm). The detailed procedure is as follows.

Yoder's apparatus for soil aggregation

For estimating the soil aggregates, the apparatus consists of a graduated set of sieves arranged in such a manner that top sieve was 250 μm size followed by middle sieve 53 μm and <53 μm sieve were kept one below the other. At the bottom a collecting dish was also attached. A 100 g of composite soil collected from the field was kept on top most sieve and the drum was filled with salt free water upto a level slightly below the top sieve. The apparatus was oscillated for 30 minutes with a frequency of 30-35 cycles/min and also properly checked whether the aggregates on the top sieve was moved through water. After 30 min all the sieves containing soil were taken out for fresh weight and oven dried at 60°C for 72 hrs for dry weight determination and the soil was crushed separately to fine powder for C analysis.

Organic carbon

Soil organic carbon was estimated by Walkley and Black's rapid titration method (Jackson, 1973) under each treatment of bamboo (4x4, 6x6, 8x8, 10x10, 12x12 m and bambooless control) at four depths (0-20, 20-50, 50-80 and 80-100 cm) and three aggregate class (macro >250-2000 μm, micro 53-250 μm and silt and clay <53 μm).

The C storage in the soil was calculated as (Anderson and Ingram, 1989):

C storage (Mg/ha) = C concentration x BD x Depth x Fraction weight

Where,

C storage = C expressed in Mg ha^{-1} in each fraction class for a given depth

C concentration = C in a aggregate, g per kg soil of that fraction

BD = Bulk Density, Mg m^{-3}

Depth = Depth of soil profile, cm and

Fraction weight = % weight of the fraction in the whole soil

The total C stored to a meter depth is the sum of the C stored at each of the depths of the soil.

The soil data were analysed using MSTATC. It was evaluated with 95% confidence limit for randomized-block experiments with bamboo spacings and soil depths as factors. Least significant difference (LSD) tests were used for assessing differences between Means.

3.11 Biomass production, nutrient accumulation and C storage

To estimate the biomass production potential of solid bamboo (*Dendrocalamus strictus*), one clump located at each plot was destructively sampled from each replication belonging to treatment during January, 2014. The clump DBH and crown width of all the selected clumps from the center of each plot was measured. After felling the clumps at ground level, the culm wood (stem), twigs and leaves were separated culm wise, followed by measurement of culm height. Fresh weight of all the above ground components (live culms, twigs, leaves and dried culms) was recorded immediately after felling using appropriate spring scale. Representative culmwood, twig, foliage and driedwood samples (ca 500 gm each) were collected randomly (clump wise in triplicate) for moisture estimation and chemical analysis. Triplicate samples

Plate 11. A closer view of destructive sampling 7 year old bamboo (*Dendrocalamus strictus*)

Plate 12. A closer view of weighing of aboveground biomass components of 7 year old bamboo (*Dendrocalamus strictus*)

transferred immediately to the laboratory in double sealed polythene bag for moisture estimation and N, P, K and C analysis.

After recording the fresh weights, the samples were oven dried to constant weight at 70°C. Estimates of biomass dry weight were obtained from the fresh weight of various tissue types and their corresponding moisture contents. Total aboveground biomass of bamboo was calculated by summing all the aboveground component parts in each clump. It was then multiplied by the number of trees per hectare to obtain stand above ground biomass on hectare basis.

$$\text{Moisture \%} = \frac{\text{Fresh weight (g)} - \text{Dry weight (g)}}{\text{Fresh weight (g)}} \times 100$$

$$\text{Dry matter (kg)} = \frac{\text{Dry weight of the sample (g)}}{\text{Fresh weight of the sample (g)}} \times \text{Fresh weight of the clump (kg)}$$

Elemental carbon in aboveground biomass parts in bamboo were analysed using CHNS analyser. The component parts viz. culm wood, twig, leaf and driedwood from each spacings of bamboo were analysed for total carbon. Carbon concentration (%) in different components in each spacings of bamboo were calculated. Biomass C stocks in the different clump component parts were calculated by multiplying their oven dry biomass with the corresponding carbon concentration. Total C for the whole clump of bamboo from each spacings were obtained by summing results of each component parts of the respective clump. Stand level aboveground biomass C stock in the varying spacings of bamboo were estimated by multiplying the average C stock per clump with number of clumps per hectare.

3.11.1 Phytochemical analysis

In order to estimate the nutrient accumulation in the aboveground biomass, triplicate samples of aboveground components (culm wood, twigs, leaf and driedwood) were analysed for N, P and K. The sub samples were drawn from the composite samples for phytochemical analysis. The total Nitrogen was estimated following the Kjeldahl digestion and distillation method. Phosphorus was determined following the Vanado-molybdo phosphoric yellow colour method (Koenig and Johnson, 1942) and Potassium was estimated using flame photometer (Piper, 1967). Nutrient accumulation in the culm component parts from each spacings of bamboo were calculated by multiplying their oven dry biomass with the corresponding nutrient concentrations. Total for whole clump from each spacings of bamboo were obtained by summing results of component parts from the respective spacings.

3.11.2 Biomass prediction

The biomass and carbon content data of all the components from each treatment were used to compute the component biomass and biomass carbon sequestration on clump basis. Simple linear and quadratic equations were developed for predicting above ground biomass and biomass carbon using number of culms, clump DBH and clump height as predictor variables.

Statistical analysis was done with the help of statistical software SPSS V.20. Biomass prediction equations were developed using regression analysis. Biomass production potential and nutrient accumulation of bamboo was evaluated with 95% confidence limit for randomized-block experiments with spacings of bamboo as factor. Least significant difference (LSD) tests were used for assessing differences between Means.

Results

4. RESULTS

4.1 Intercropping with bamboo

4.1.1 Growth parameters of bamboo before understorey planting

The growth parameters of bamboo at various spacings (4x4, 6x6, 8x8, 10x10 and 12x12 m) were determined and presented in the table 1 and fig. 5. The results reveal that, as spacings of bamboo increased the clump height significantly decreased. The closest spacing of 4x4 m recorded clump height of 9.11 m; this decreased to 7.31 m in widest spacing of 12x12 m. The decrease of clump height in widest spacing was 19.75 per cent compared to closest spacing (4x4 m).

The clump DBH in 4x4 m spacing recorded lowest (1.03 m). This was significantly increased with increasing spacing of bamboo. Widest spacing of 12x12 m recorded 1.58 m; this was 53.39 per cent more compared to 4x4 m spacing. The crown width and clump diameter in general increased with increase in spacings. At 12x12 m spacing it was 8.13 m, which decreased to 4.69 m when the spacings between the bamboo decreased to 4x4 m. As compared to closest spacing about 73.34 per cent higher crown width was recorded by widest spacing (12x12 m).

4.1.2 Physico-chemical properties of soil before intercropping

The soil was collected from 0-20 cm depth from the centre of each plot in the various spacings of bamboo (4x4, 6x6, 8x8, 10x10 and 12x12 m) and a bambooless control. The samples were then analysed for bulk density, p^H, total N, avail. P and avail. K. Among the spacings of bamboo, the bulk density increased significantly with spacings from 1.11 Mg m^{-3} in 4x4 m to 1.54 Mg m^{-3} in 12x12 m, implying that, changes in spacings of bamboo have significant influence on bulk density of soil (Table 2). Soil p^H was not significantly affected by varying spacings of bamboo. The p^H in bambooless control was 5.96; this was comparatively higher than 4x4 (5.83), 6x6 (5.80) and 8x8 m (5.93) spacings and lesser than 12x12 m spacing of bamboo.

Table 1. Growth parameters of 7 year old bamboo (*Dendrocalamus strictus*) grown at different spacings before understorey planting.

Spacings (m)	Height (m)	Clump DBH (m)	Crown width (m)
4x4	9.11(0.10)^{d}	1.03(0.01)^{a}	4.69(0.17)^{a}
6x6	8.18(0.20)^{c}	1.28(0.02)^{b}	6.61(0.22)^{b}
8x8	8.03(0.05)^{c}	1.44(0.02)^{c}	7.36(0.16)^{c}
10x10	7.6(0.18)^{b}	1.55(0.007)^{d}	7.79(0.15)^{d}
12x12	7.31(0.09)^{a}	1.58(0.006)^{d}	8.13(0.14)^{e}

Values in the parenthesis are Standard Deviation of the Mean

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

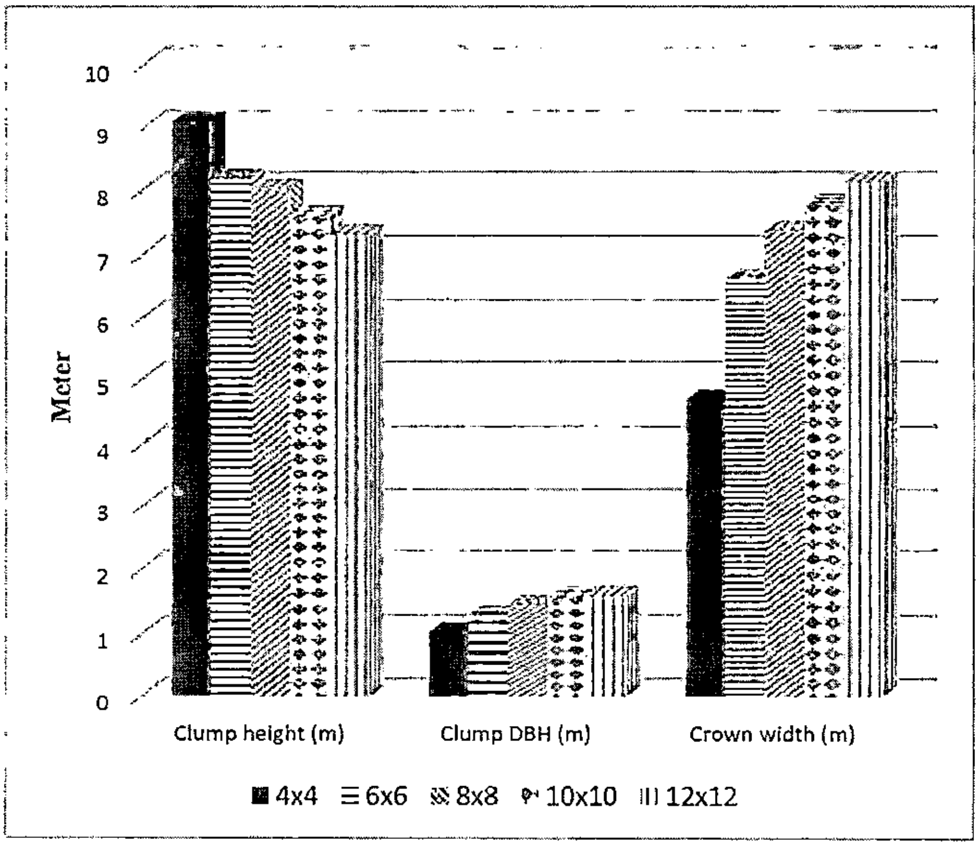


Fig. 5 Growth parameters of 7 year old bamboo (*Dendrocalamus strictus*) grown at different spacings before understorey planting.

The chemical (total N, available P and avail. K) properties of soil from each spacing of bamboo was analysed and compared with bambooless control (Table 2 and Fig. 6). The results depict that spacings of bamboo significantly affected the soil total N. As spacings of bamboo decreased, the total N gradually and significantly increased. The closest spacing (4x4 m) recorded highest total N (2197.7 kg/ha) and the lowest (1404.97 kg/ha) was recorded by widest spacing (12x12 m), which was at par with (1396.41 kg/ha) bambooless control plot. About 57.31 per cent increase in total N when bamboo grown in closest spacings compared to bambooless control plot. The avail. P was significantly affected by spacings of bamboo, for instance, the closest spacing of 4x4 m recorded maximum (21.32 kg/ha); this was decreased to 14.73 kg/ha in widest spacing of 12x12 m. Further decrease (14.43 kg/ha) was observed in bambooless control plot.

Table 2. Physico-chemical properties of soil before understorey planting in bamboo (*Dendrocalamus strictus*) grown at various spacings

Spacings (m)	Bulk Density (Mg m^{-3})	p^H	Total N kg/ha	Avail. P kg/ha	Avail. K kg/ha
4x4	1.11(0.15)^a	5.83(0.25)^a	2197.70(170.52)^e	21.32(0.49)^e	203.49(2.82)^d
6x6	1.18(0.01)^b	5.8(0.1)^a	1807(103.76)^d	19.02(0.45)^d	202.39(1.35)^d
8x8	1.24(0.015)^c	5.93(0.20)^a	1556.50(90.52)^c	17.20(0.28)^c	192.77(3.10)^c
10x10	1.31(0.01)^d	6.0(0.1)^a	1466.71(103.76)^b	15.99(0.37)^b	164.26(3.53)^b
12x12	1.44(0.015)^e	6.1(0.17)^a	1404.97(112.53)^a	14.73(0.33)^a	153.26(3.45)^a
Bambooless control	1.54(0.017)^f	5.96(0.15)^a	1396.41(99.99)^a	14.43(0.08)^a	152.86(1.33)^a

Values in the parenthesis are Standard Deviation of the Mean

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

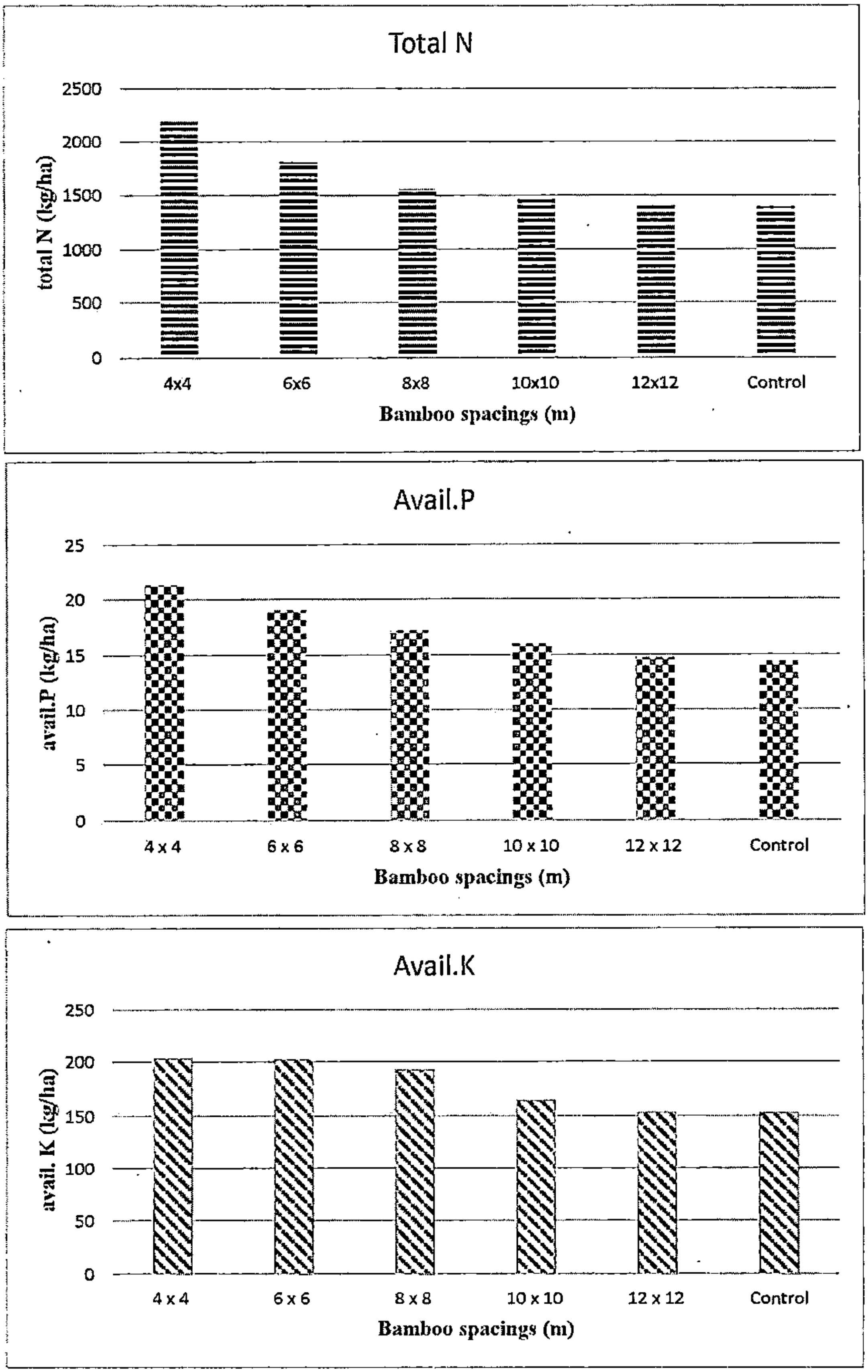


Fig. 6 N, P and K content in soil (0-20 cm) before understorey herbaceous planting in a 7 year old bamboo (*Dendrocalamus strictus*)

The avail. P in closest spacing (4x4 m) was about 47.74 per cent higher compared to bambooless control plot. The widest spacing (12x12 m) recorded 14.73 kg/ha available P; this was at par with bambooless control plot (14.43 kg/ha). Similar pattern of decrease was also observed for avail. K. As compared to bambooless control (152.86 kg/ha), the 4x4 m (203.49 kg/ha) and 6x6 m (202.39 kg/ha) spacings, the widest spacing of bamboo (12x12 m) and control plot have recorded significantly lesser K value. The closest spacing of 4x4 m recorded 203.49 kg/ha of K; this was significantly higher than widest spacing (153.26 kg/ha) and bambooless control plot (152.86 kg/ha). However, the avail. K in widest spacing (12x12 m) of bamboo was at par with bambooless control plot.

4.3 Photosynthetically Active Radiation (PAR)

The influence of different spacings of bamboo on understorey photosynthetically active radiations was studied by installing photon-flux meter at above and below the canopy of bamboo at the center of each plot. The observations taken from 8 to 18 hours are presented in the table 3 and fig. 7. As the spacings of bamboo increased from 4x4, the understorey PAR values were increased. At 8.00 hours the minimum (6 μmol/sec./m^2) understorey PAR was recorded by 4x4 m spacing of bamboo and the maximum (76.66 μmol/sec./m^2) in widest spacing of 12x12 m. At 12 hours noon the understorey PAR increased from 107.33 μmol/sec./m^2 in 4x4 m to 1019 μmol/sec./m^2 under 12x12 m in the overstorey PAR was 1033 μmol/sec./m^2. Among the spacings, the widest spacing (12x12 m) recorded maximum (42%) understorey PAR and minimum (4.44%) recorded by closest spacing of 4x4 m (Table 4 and Fig. 8). The PAR in the overstorey (1033 μmol/sec./m^2) did not vary with that of understorey PAR in wide spacings like 10x10 m (767 μmol/sec./m^2) and 12x12 m (1019 μmol/sec./m^2) which imply that, nearly same amount of PAR reached the ground in wide spacings as the amount of PAR reached in overstorey. When the sun overhead (14 hours), the overstorey recorded maximum PAR (1220 μmol/sec./m^2); at this time, the understorey PAR was 132 μmol/sec./m^2 due to closest spacing (4x4 m) and 1210 μmol/sec./m^2 due to widest spacing (12x12 m).

Table 3. Understorey PAR (μmol. per sec/m^2) at different time intervals as influenced by varying spacings of 7 year bamboo (*Dendrocalamus strictus*)

Spacings (m)	Time in hours					
	8	10	12	14	16	18
4x4	6(1.00)^{a}	19.33(4.04)^{a}	107.33(19.21)^{a}	132(21.00)^{a}	20(5.00)^{a}	3.33(0.57)^{a}
6x6	15.33(1.52)^{ab}	46.33(3.51)^{a}	163.33(9.45)^{a}	242.66(21)^{b}	22.33(22.33)^{a}	4.66(0.57)^{a}
8x8	25.66(4.04)^{b}	224.33(33.85)^{b}	360.66(27.57)^{b}	321(7.00)^{c}	30.33(4.50)^{a}	6.66(0.57)^{ab}
10x10	60.00(5.00)^{c}	423.33(25.16)^{c}	767(48.77)^{c}	1059.66(42)^{d}	295(15.00)^{b}	9(0.15)^{b}
12x12	76.66(11.54)^{d}	799.66(9.50)^{d}	1019(43.27)^{d}	1210(9.00)^{e}	288.33(17.55)^{bc}	10(1.00)^{c}
Above canopy	500.66(17.78)^{e}	838(42.00)^{d}	1033(54.00)^{d}	1220(5.00)^{e}	315(19.00)^{c}	20.66(5.0)^{d}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P < 0.05$)

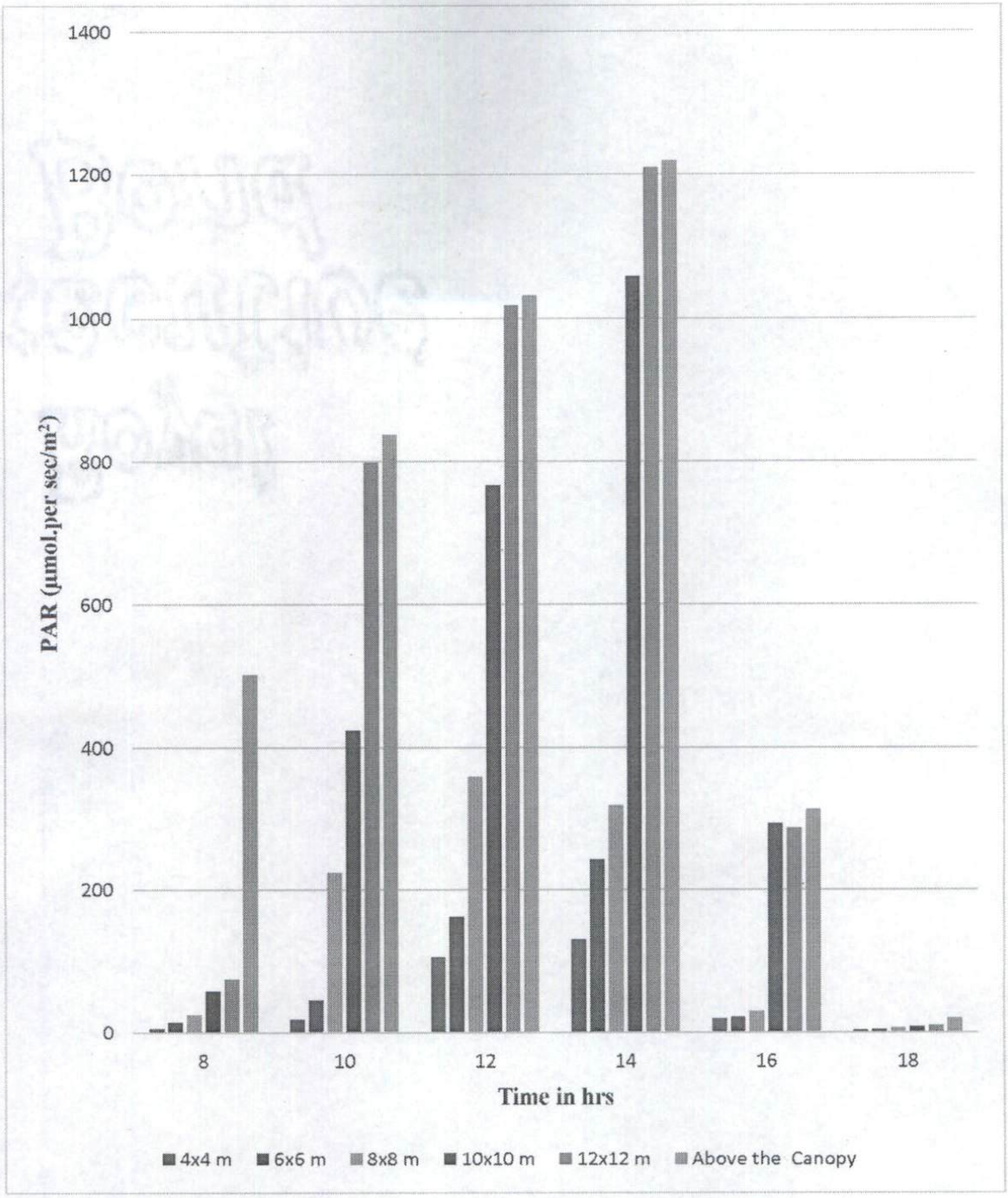
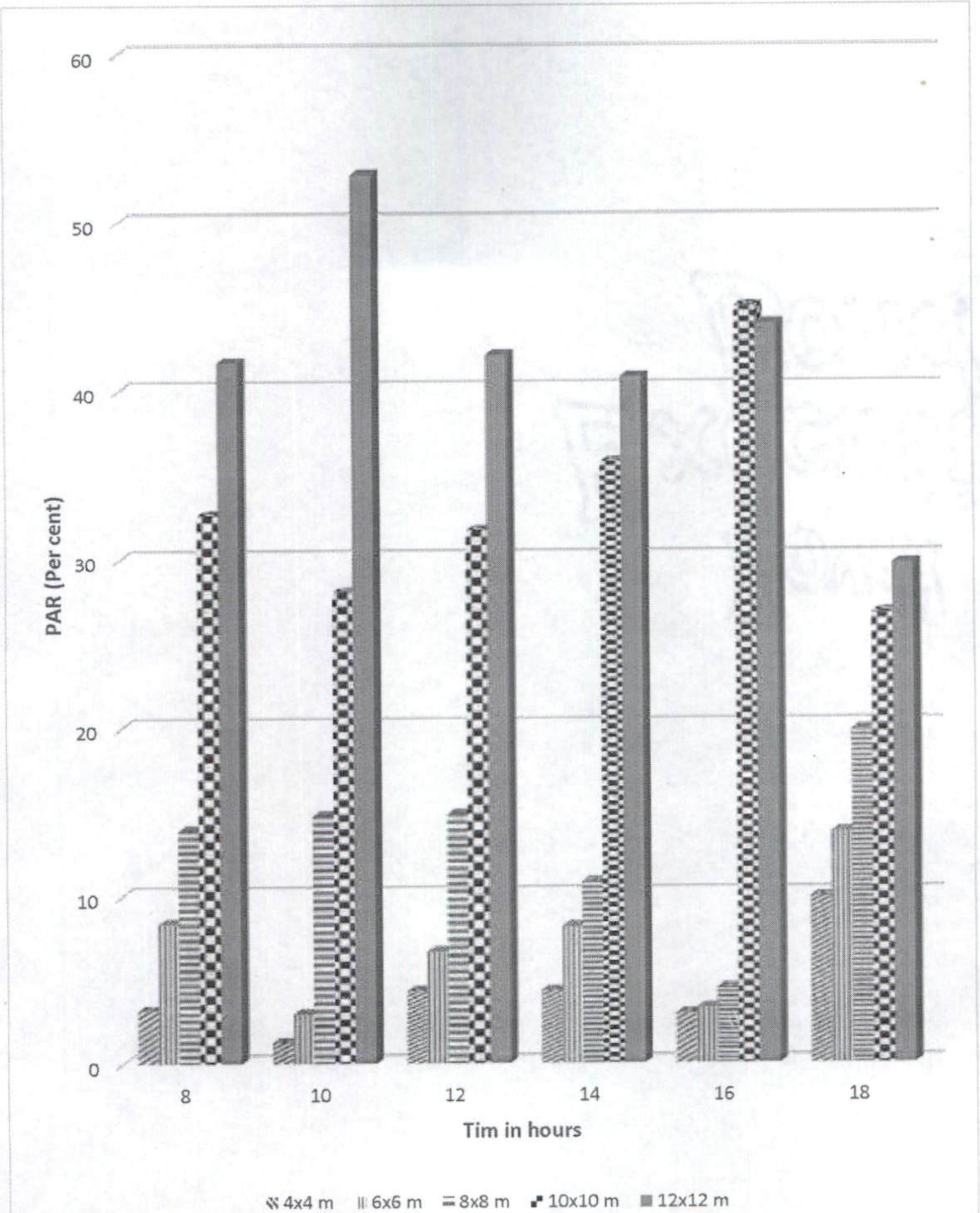


Fig. 7 Understorey PAR (μmol. per sec/m^2) at different time intervals as influenced by varying spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Table. 4 Understorey photosynthetically active radiations (per cent among spacings) at different time intervals as influenced by varying spacings of 7 year bamboo (*Dendrocalamus strictus*)

Bamboo spacings	**Time in hours**					
	8	**10**	**12**	**14**	**16**	**18**
4x4	3.27	1.28	4.44	4.45	3.05	9.90
6x6	8.35	3.06	6.76	8.18	3.40	13.86
8x8	13.97	14.83	14.92	10.83	4.62	19.80
10x10	32.67	27.98	31.73	35.74	44.97	26.73
12x12	41.74	52.85	42.15	40.80	43.95	29.70
Above canopy	100	100	100	100	100	100



ig.8. Understorey photosynthetically active radiations (per cent among spacings) at different time ntervals as influenced by varying spacings of 7 year bamboo (*Dendrocalamus strictus*)

As interspace between the bamboo increased, less interception of PAR by bamboo was observed.

4.4 Leaf Area Index (LAI)

The leaf area index of bamboo was determined under varying spacings of bamboo (Fig. 9). As the spacings of bamboo increased the LAI significantly decreased. The LAI and bamboo spacings are inversely related to each other. The closest spacing (4x4 m) recorded maximum LAI (6.78) as compared to widest spacing (12x12 m, 0). The LAI in 4x4 m spacing was 678 per cent higher compared to 12x12 m spacing. The order of decrease of LAI in bamboo was 4x4 >6x6>8x8>10x10>12x12 m spacings.

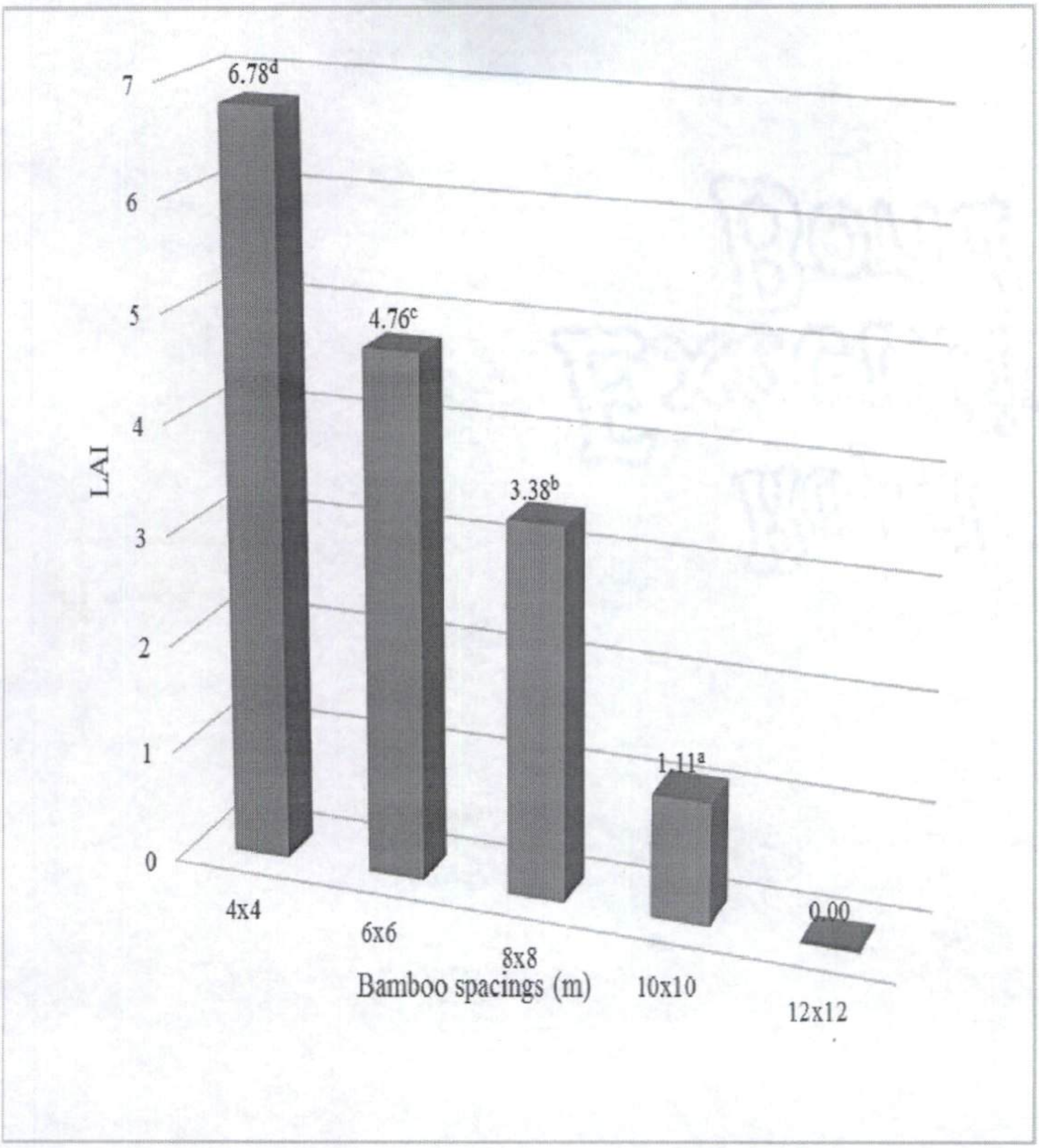
4.5.1 Growth attributes of turmeric, ginger and chittaratha grown at varying spacings of bamboo

Plant height

The turmeric, ginger and chittaratha grown at various spacings of bamboo were destructively sampled at different durations (turmeric, ginger at 90, 180, 230 DAP and chittaratha at 90, 180, 230 and 360 DAP). After sampling, plant height, shoot length, fresh weight and dry weight of shoots, leaves and rhizomes and final rhizome yield were determined.

The data show that the plant height of all the three understorey crops were significantly influenced by varying spacings of bamboo (Table 5 and Fig. 10). The plant height of turmeric at 90 DAP was increased from 10.96 cm when grown at bamboo spacing of 4x4 m to 40.88 cm at 12x12 m; this increase was 273 per cent compared to closest spacing (4x4 m) of bamboo. At 230 DAP, the plant height increased by 143 per cent at open plot (bambooless control) compared to closest spacing of 4x4 m.

In case of ginger the trend of significant increase in plant height at various growth stages with increasing spacings of bamboo was observed. At 90 DAP, the



Values followed by same superscript do not differ significantly (LSD, $P < 0.05$)

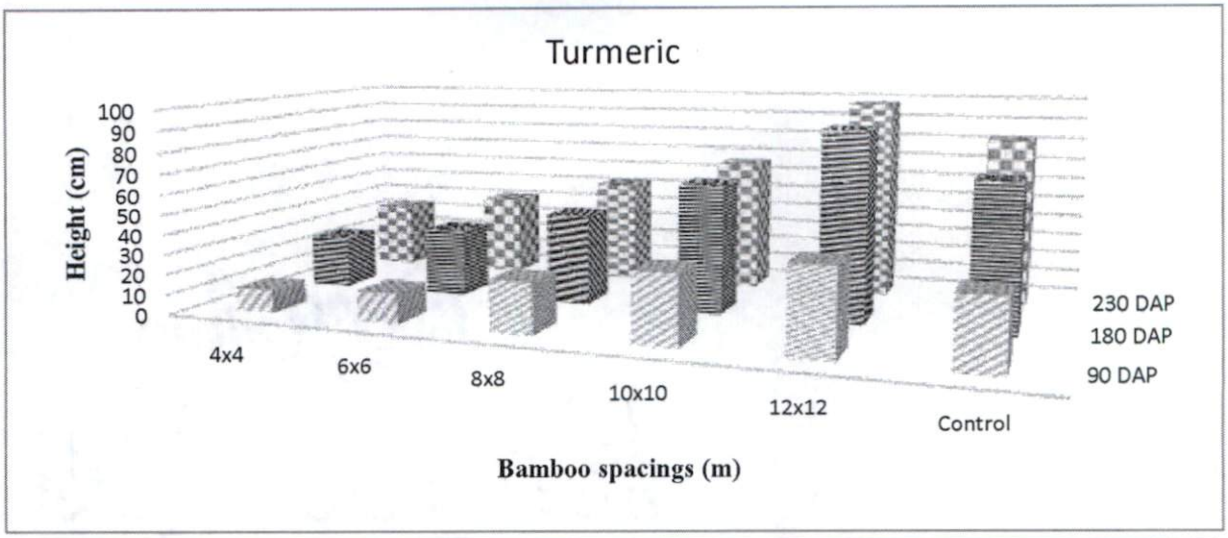
Fig. 9 Leaf area index of bamboo (*Dendrocalamus strictus*) as influenced by its spacings

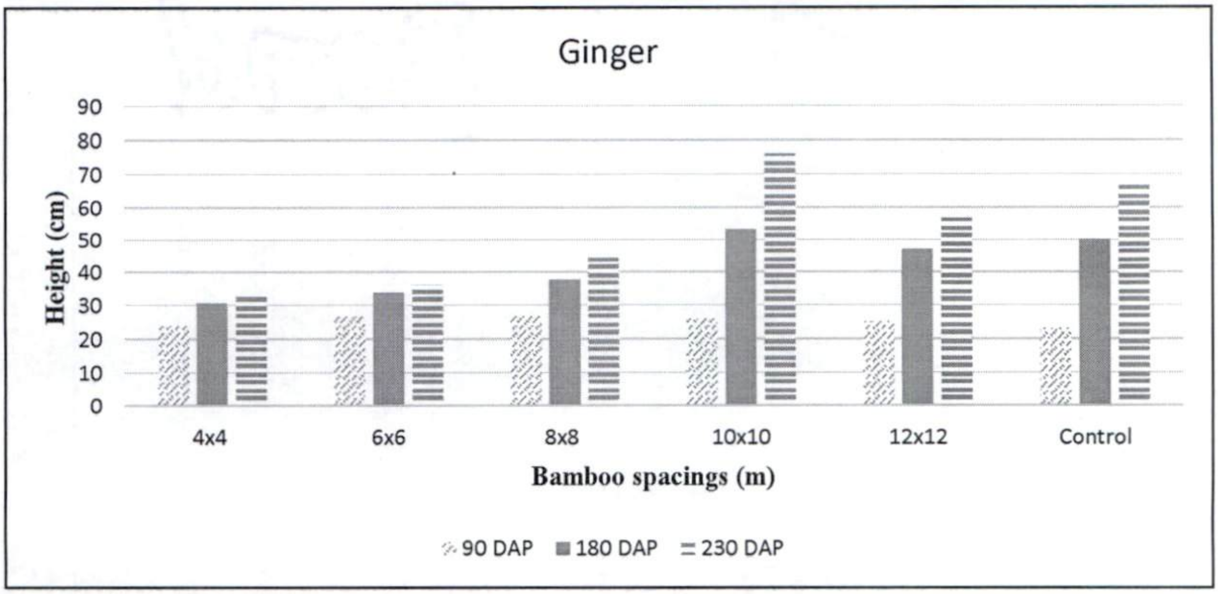
Table 5. Plant height (cm) of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Turmeric			Ginger		
	90 DAP	180 DAP	230 DAP	90 DAP	180 DAP	230 DAP
4x4	10.96(0.99)^{a}	26.38(4.26)^{a}	33.83(5.29)^{a}	23.92(1.10)^{ab}	30.82(0.71)^{a}	32.89(2.08)^{a}
6x6	14.28(0.30)^{b}	33.9(5.36)^{b}	41.24(5.26)^{b}	26.65(1.74)^{c}	34.03(0.61)^{b}	36.26(1)^{b}
8x8	24.26(0.80)^{c}	45.14(6.59)^{c}	52.43(8.23)^{c}	26.99(0.64)^{c}	37.71(0.48)^{c}	45.2(1.01)^{c}
10x10	33.05(0.59)^{d}	63.46(7.59)^{d}	66.13(7.15)^{d}	26.05(0.59)^{c}	53.3(1.06)^{f}	76.23(2.07)^{f}
12x12	40.88(1.95)^{e}	91.17(10.26)^{f}	98.12(12.23$^{)e}$	25.35(0.73)^{bc}	47.24(1.00)^{d}	56.91(0.57)^{d}
Control	32.83(2.17)^{d}	70.89(9.29)^{e}	82.12(11.28)^{f}	23.32(1.03)^{a}	50.49(0.90)^{e}	67.75(1.94)^{e}

Spacings (m)	Chittaratha			
	90 DAP	180 DAP	230 DAP	360 DAP
4x4	7.01(0.83)^{a}	11.85(0.60)^{a}	12.98(0.82)^{a}	15.27(0.54)^{a}
6x6	9.05(0.19)^{b}	13.64(0.52)^{b}	14.88(0.23)^{b}	17.66(0.16)^{b}
8x8	9.51(0.58)^{b}	19.47(0.63)^{c}	25.90(0.22)^{c}	29.35(0.52)^{c}
10x10	10.44(0.45)^{c}	35.57(0.11)^{d}	45.89(1.20)^{d}	47.53(0.86)^{d}
12x12	11.02(0.33)^{c}	45.77(1.20)^{e}	57.03(1.31)^{e}	57.46(0.50)^{e}
Control	11.30(1.54)^{c}	53.54(0.33)^{f}	59.72(0.50)^{f}	64.43(0.17)^{f}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).





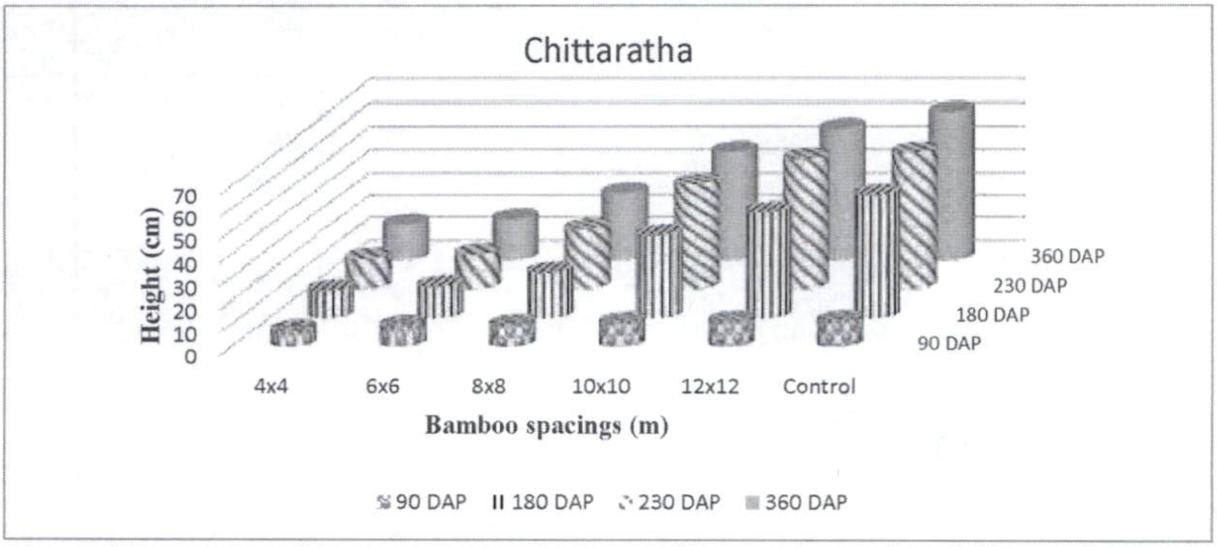


Fig. 10 Plant height (cm) of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

plant height of ginger was at closest spacing was 23.92 cm; this height was significantly lesser than widest spacing (12x12 m). At 180 and 230 DAP, the height was significantly increased to 53.30 cm (180 DAP) and 76.23 cm (360 DAP) in 10x10 m spacing as compared to 30.82 cm and 32.89 cm in closest spacing of bamboo (4x4 m). Under 10x10 m spacing of bamboo the ginger height was increased by 131.77 per cent compared to 4x4 m spacing of bamboo.

The chittaratha plant height in sole crop was compared with bamboo+chittaratha intercrop. The results found that, close spacings (4x4 and 6x6 m) of bamboo negatively affected the height of chittaratha. At early stages of plant growth (90 DAP), the plant height was 7.01 cm and in the bambooless control plot it was 11.30 cm. This show about 61 per cent increase in plant height in the control as compared to closest spacing of 4x4 m. The plant height of chittaratha under 10x10 m spacing of bamboo was at par with 12x12 m and control plot (90 DAP). At later stages (180 and 230 DAP) the plant height in all the spacings of bamboo show significant difference. At 230 DAP closest spacing (4x4 m) recorded 12.98 cm, this height increased by 360 per cent in control plot (59.72 cm). However, chittaratha performed better for plant height in 10x10 and 12x12 m than close spacings of bamboo of 4x4 and 6x6 m. Meanwhile, at 360 DAP, the sole chittaratha performed best for height (64.43 cm) as compared to chittaratha under all the spacings of bamboo.

Shoot length

The data on shoot length of turmeric, ginger and chittaratha at different growth stages as influenced by varying spacings of bamboo are furnished in the table 6 and fig. 11. In all the three crops, the shoot length was found to increase at various growth stages with increasing spacings of bamboo. In case of turmeric, the shoot length increased from 13.96 cm at 90 DAP when grown at 4x4 m spacing of bamboo to 43.88 cm in the widest spacing (12x12 m); this increase was about 214 per cent. At 230 DAP, shoot length recorded minimum (38.83 cm) in closest spacing and maximum (103.12 cm) in widest spacing of bamboo. The shoot length was increased by 165 per cent when grown in widest spacing of bamboo compared to

Table 6. Shoot length (cm) of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Turmeric			Ginger		
	90 DAP	**180 DAP**	**230 DAP**	**90 DAP**	**180 DAP**	**230 DAP**
4x4	13.96(0.99)^{a}	29.38(3.36)^{a}	38.83(7.26)^{a}	26.92(4.21)^{ab}	34.82(5.23)^{a}	37.89(5.36)^{a}
6x6	17.28(2.23)^{b}	36.9(8.39)^{b}	46.24(16.23)^{b}	29.65(4.19)^{c}	38.03(4.26)^{b}	41.26(5)^{b}
8x8	27.26(5.32)^{c}	48.14(7.42)^{c}	57.43(13.36)^{c}	29.99(5.17)^{c}	41.71(7.85)^{c}	50.2(14.29)^{c}
10x10	36.05(4.32)^{d}	66.46(5.75)^{d}	71.13(19.23)^{d}	29.05(7.05)^{c}	51.24(17.28)^{d}	81.23(15.27)^{e}
12x12	43.88(4.39)^{e}	94.17(7.39)^{f}	103.12(12.27)^{f}	28.35(5.29)^{bc}	54.49(19.26)^{e}	72.75(14.47)^{d}
Control	35.83(4.39)^{d}	73.89(4.10)^{e}	87.12(14.07)^{e}	26.32(9.17)^{a}	57.3(13.39)^{f}	71.25(12.28)^{d}

Spacings (m)	Chittaratha			
	90 DAP	**180 DAP**	**230 DAP**	**360 DAP**
4x4	8.44(0.82)^{a}	13.05(0.55)^{a}	17.07(0.33)^{a}	18.99(0.93)^{a}
6x6	10.51(0.29)^{b}	14.85(0.32)^{b}	16.56(0.25)^{a}	18.91(0.29)^{b}
8x8	11.20(0.28)^{b}	20.22(0.49)^{c}	27.83(0.35)^{b}	30.86(0.57)^{c}
10x10	12.12(0.22)^{c}	37.50(0.31)^{d}	47.42(1.39)^{c}	48.75(0.73)^{d}
12x12	12.65(0.40)^{c}	47.69(1.11)^{e}	58.92(1.16)^{d}	58.86(0.49)^{e}
Control	12.66(0.19)^{c}	55.76(0.47)^{f}	61.48(0.58)^{e}	65.48(0.25)^{f}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).

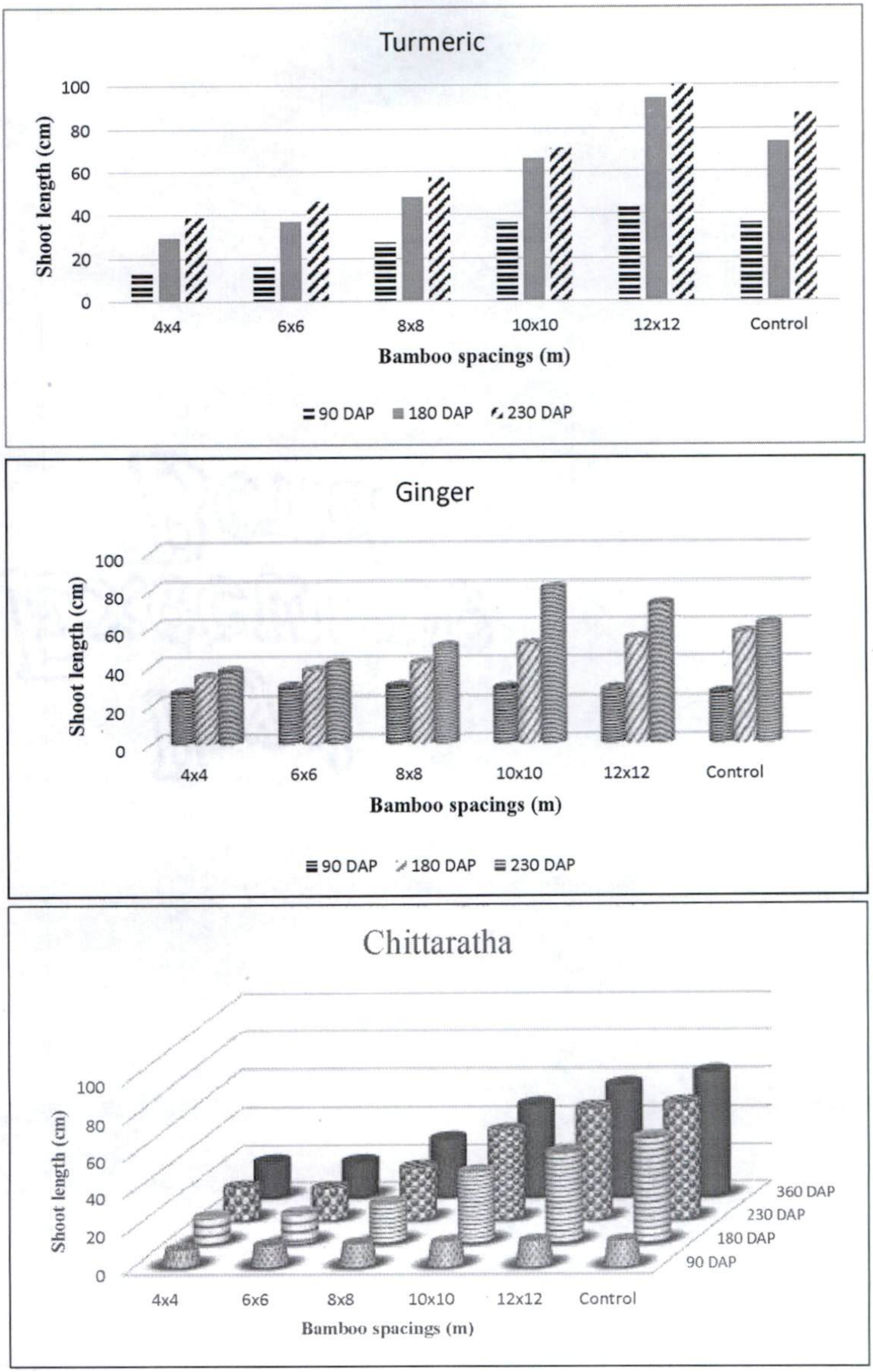


Fig. 11 Shoot length of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Plate 13. Understorey turmeric grown at 4x4 and 6x6 m spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

Plate 14. Understorey turmeric grown at 8x8 and 10x10 m spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

Plate 15. Understorey turmeric grown at 12x12 m spacing and bambooless control of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

closest spacing of 4x4 m. In case of ginger, at 90 DAP the shoot length increased by 5.31 per cent when grown in widest spacing (12x12 m) as compared to close spacing (4x4 m). At 230 DAP the shoot length of ginger at 4x4 m spacing was increased from 37.89 cm to 81.23 cm due to 10x10 m spacing of bamboo; this height was significantly greater than control plot.

In case of chittaratha at 90 DAP the shoot length in closest spacing recorded minimum (8.44 cm) and maximum (12.66 cm) was recorded in bambooless control plot, the increase of shoot length was upto the tune of 50 per cent compared to closest spacing of 4x4 m. The shoot length in 10x10 m spacing was at par with 12x12 m and control plot. At 230 DAP the shoot length was significantly increased with increasing spacings of bamboo. The increasing trend of minimum height (17.07 cm) in closest spacings and maximum height (61.48 cm) in control plot of bamboo was found. At harvest stage (360 DAP) the shoot length of chittaratha was 25 per cent higher under open plot compared to closest spacing of bamboo (4x4 m).

Number of tillers

The data on tillers/hill in turmeric, ginger and chittaratha at various growth stages under varying spacings of bamboo are presented in the table 7 and fig. 12. The results show that at 90 DAP the number of tillers in turmeric were 1.22/hill which increased to 2.488/hill in 10x10 m spacing. This reveal that about 103.27 per cent increase in number of tillers was observed in wider spacing (10x10 m) compared to closest spacing (4x4 m) of bamboo. At 180 DAP the number of tillers/hill were 140.4 per cent more under 12x12 m spacing while at 230 DAP the tillers increased by 136 per cent compared to closest spacing of 4x4 m. The wide spacings (10x10 m and 12x12 m) of bamboo favored more number of tillers in turmeric as compared to close spacings (4x4 m and 6x6 m). Therefore, the results reveal that turmeric requires partial shade for tiller development during its early life and in later stages (230 DAP) the shade may not be necessary once the crop reaches to its maturity.

In case of ginger the number of tillers/hill increased with growth stages. Results clearly found that influence of spacings of bamboo on tillers was

Table 7. Number of tillers/hill of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Turmeric			Ginger		
	90 DAP	180 DAP	230 DAP	90 DAP	180 DAP	230 DAP
4x4	1.22(0.01)^{a}	1.41(0.25)^{a}	1.78(0.22)^{a}	1.03(0.06)^{a}	1.29(0.17)^{a}	1.81(0.13)^{a}
6x6	1.78(0.22)^{a}	2.07(0.06)^{b}	2.59(0.34)^{b}	1.78(0.22)^{b}	1.14(0.14)^{a}	1.63(0.23)^{a}
8x8	2.26(1.24)^{a}	2.74(0.42)^{c}	2.98(0.07)^{bc}	2.03(0.72)^{bc}	3.74(0.15)^{b}	4.63(0.75)^{b}
10x10	2.48(1.12)^{a}	3.05(0.14)^{cd}	3.38(0.15)^{c}	2.14(0.22)^{bc}	6.55(0.99)^{d}	9.62(0.71)^{d}
12x12	1.63(0.39)^{a}	3.39(0.33)^{d}	4.20(0.34)^{d}	2.74(0.54)^{c}	6.26(0.68)^{d}	8.77(0.49)^{cd}
Control	1.74(0.16)^{a}	2.92(0.38)^{cd}	4(0.22)^{d}	3.89(0.11)^{d}	4.92(0.35)^{c}	8.03(0.76)^{c}

Spacings (m)	Chittaratha			
	90 DAP	**180 DAP**	**230 DAP**	**360 DAP**
4x4	3.07(0.12)^{a}	3.37(0.23)^{a}	3.59(0.17)^{a}	5.40(0.42)^{a}
6x6	3.66(0.50)^{ab}	4.51(0.23)^{a}	6.33(0.57)^{b}	6.92(0.06)^{b}
8x8	4.11(0.29)^{b}	9.59(0.17)^{b}	11.18(1.40)^{c}	13.81(0.73)^{c}
10x10	3.96(0.56)^{b}	14.81(0.16)^{c}	16.89(1.60)^{d}	17.14(0.61)^{d}
12x12	4.99(0.57)^{c}	18.55(1.73)^{d}	20.89(0.80)^{e}	21.44(1.30)^{e}
Control	5.33(0.22)^{c}	18.77(0.68)^{d}	21.03(0.90)^{e}	21.81(0.97)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).

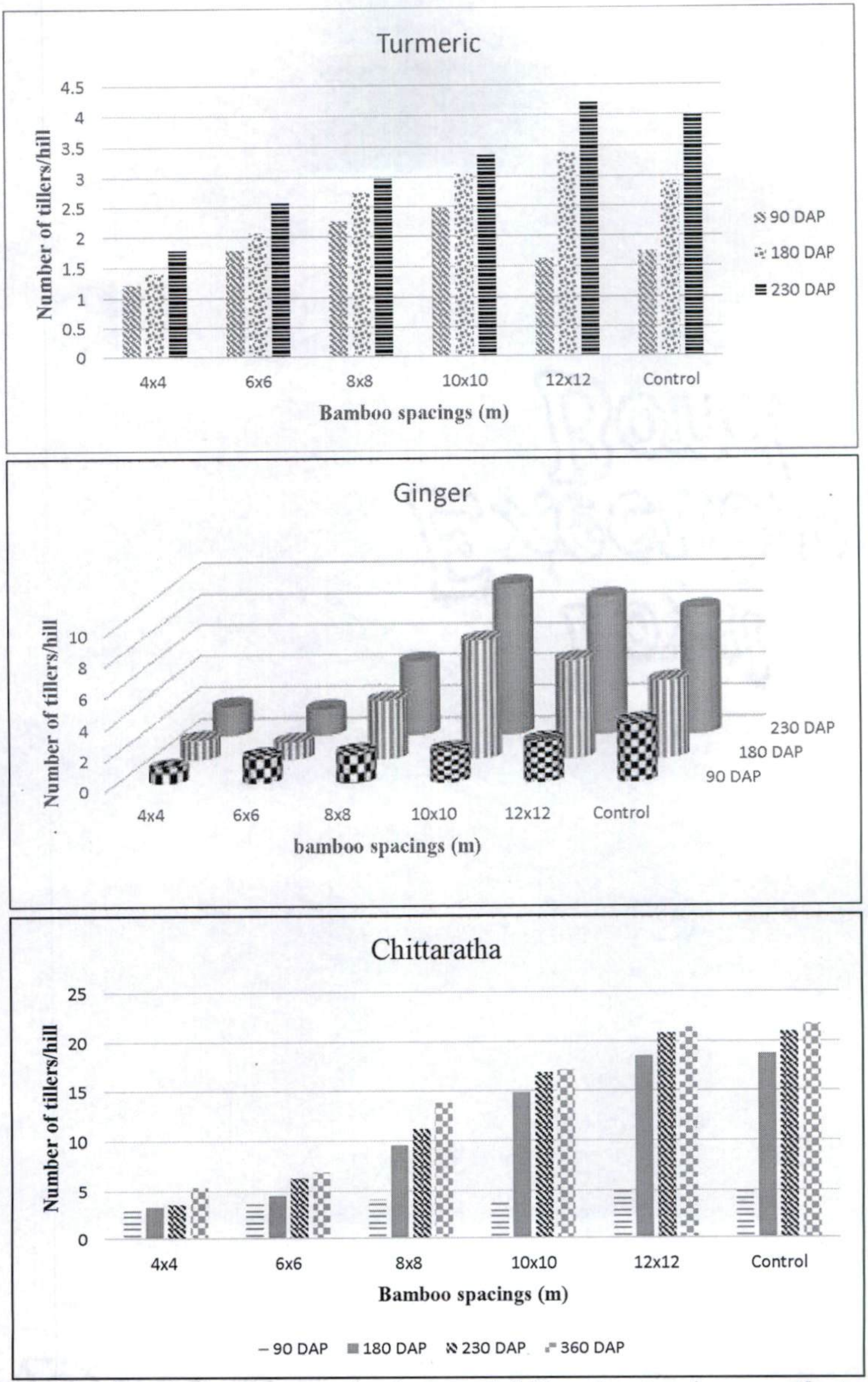


Fig. 12 Number of tillers in turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

significant. At 90 DAP minimum number of tillers (1.03/hill) in closest spacing of 4x4 m and maximum (3.89/hill) was observed in open plot. The trend of gradual increase in tiller number with increasing spacings of bamboo was observed. At 4x4 m spacing the tillers (90 DAP) were 1.03/hill; this was increased by 277 per cent at open plot (control). However, at 180 and 230 DAP significantly higher (6.55/hill and 9.62/hill) number of tillers were observed in the 10x10 m spacing compared to remaining spacings of bamboo and open plot (control).

For chittaratha at 90 DAP, number of tillers was 3.07/hill in the closest spacing of bamboo (4x4 m) and in the control plot it was 5.33/hill, i.e. 74 per cent more in control plot compared to closest spacing (4x4 m). At 180 DAP the number of tillers in 12x12 m spacings was at par with open plot (control). The number of tillers in chittaratha at 12x12 m spacing of bamboo was increased by 481.89 per cent at 230 DAP and 295 per cent at 360 DAP compared to closest spacing of bamboo (4x4 m). But sole chittaratha recorded comparatively more tiller number than bamboo+chittaratha intercrops. The control recorded about 304 times more number of tillers as compared to closest spacing of bamboo (4x4 m). In open plot about 58 per cent more number of tillers was recorded compared to intermediate spacing (8x8 m). However, the control plot and wide spacings of bamboo (12x12 m) were found to be better for chittaratha.

Number of leaves

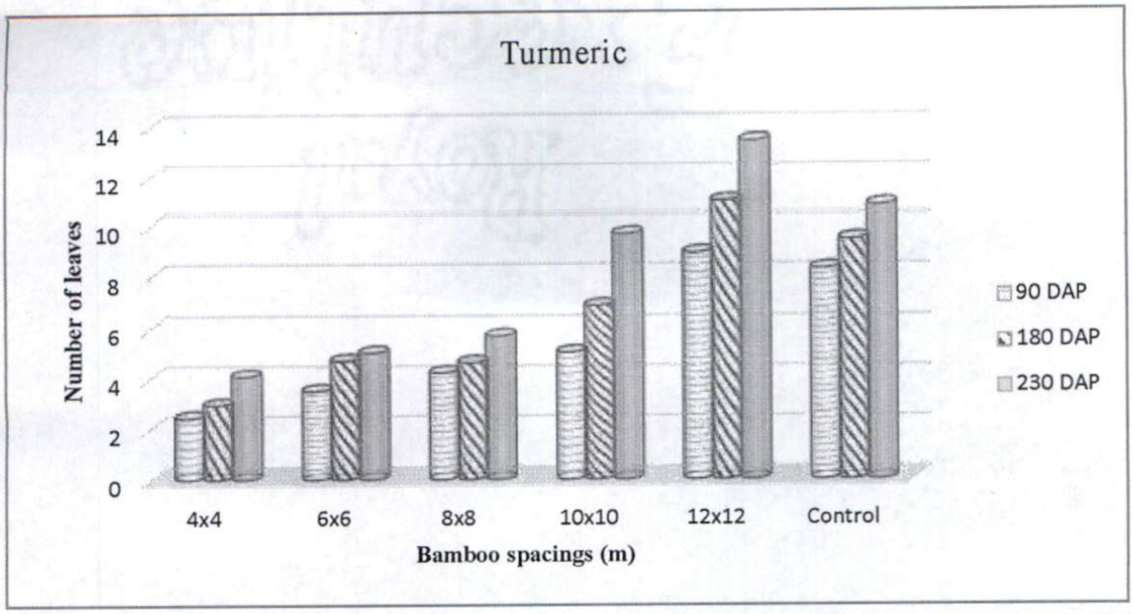
The leaves of turmeric, ginger and chittaratha at different growth stages are varyingly influenced by spacings of bamboo. The data are furnished in the table 8 and fig. 13. In the case of turmeric, number of leaves were lowest (2.40/ plant) at closest spacing (4x4 m) of bamboo which increased gradually with increasing spacings of bamboo. When the turmeric was intercropped at widest spacing of 12x12 m, highest number of leaves (8.92/plant) were observed; this was at par with open plot (control). With increasing days from 180 to 230 DAP the number of leaves were also increased from 11/plant to 13.44/plant at widest spacing (12x12 m) of bamboo. About 276.71 per cent more number of leaves in 12x12 m spacing

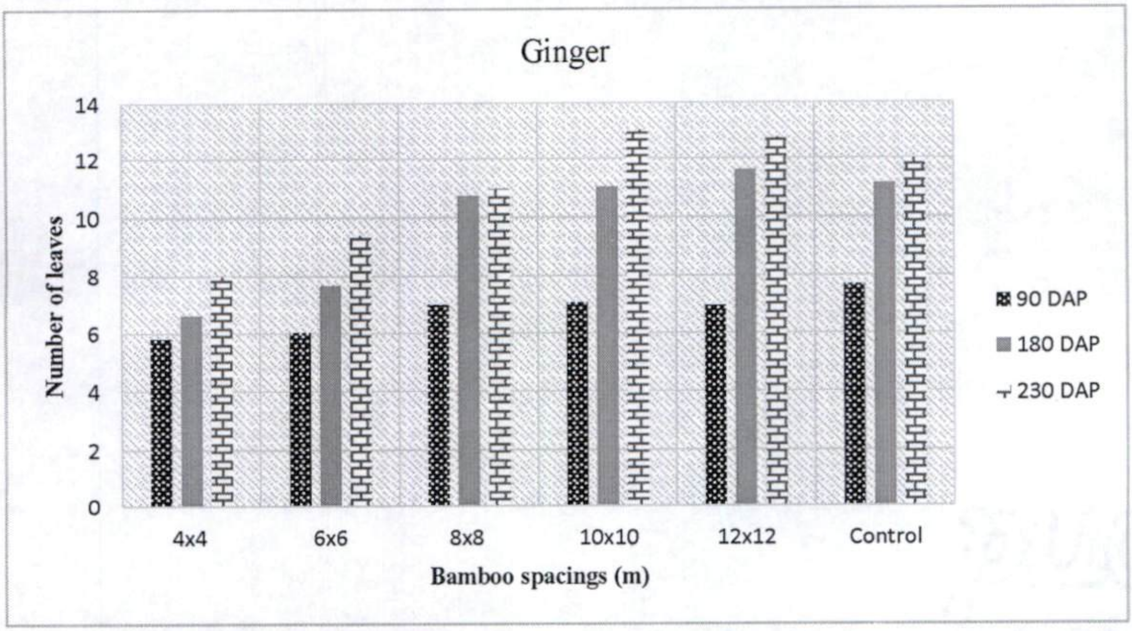
Table 8. Number of leaves in turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Turmeric			Ginger		
	90 DAP	**180 DAP**	**230 DAP**	**90 DAP**	**180 DAP**	**230 DAP**
4x4	2.40(0.13)^{a}	2.92(0.38)^{a}	4.07(0.16)^{a}	5.81(0.39)^{a}	6.63(0.17)^{a}	7.99(0.67)^{a}
6x6	3.48(0.35)^{b}	4.70(0.77)^{b}	5.03(0.27)^{b}	6.03(0.56)^{a}	7.69(0.07)^{b}	9.40(0.39)^{ab}
8x8	4.22(0.29)^{bc}	4.63(0.61)^{b}	5.70(0.34)^{b}	7(0.38)^{b}	10.74(0.28)^{c}	10.96(0.67)^{bc}
10x10	5.03(0.16)^{c}	6.88(0.55)^{c}	9.66(0.29)^{c}	7.07(0.44)^{b}	11.03(0.22)^{cd}	13.03(0.72)^{d}
12x12	8.92(1.07)^{d}	11(1.12)^{e}	13.44(0.61)^{e}	6.96(0.65)^{b}	11.63(0.75)^{d}	12.78(2.1)^{cd}
Control	8.29(0.80)^{d}	9.44(0.88)^{d}	10.81(0.39)^{d}	7.70(0.44)^{b}	11.14(0.27)^{cd}	12.00(1.50)^{cd}

Spacings (m)	Chittaratha			
	90 DAP	**180 DAP**	**230 DAP**	**360 DAP**
4x4	4.74(1.40)^{a}	7.96(0.86)^{a}	10.18(0.39)^{a}	13.55(0.38)^{a}
6x6	5.59(0.46)^{abc}	8.63(0.06)^{a}	11.67(0.61)^{b}	15.88(1.05)^{b}
8x8	6.37(1.40)^{abc}	12.40(0.06)^{b}	15.29(0.23)^{c}	17.07(0.32)^{b}
10x10	8.11(0.40)^{d}	17.81(0.42)^{c}	22.29(0.23)^{d}	26.29(0.23)^{c}
12x12	7.07(0.55)^{bcd}	19.62(1.57)^{d}	24.70(0.16)^{e}	27.03(0.84)^{c}
Control	6.58(1.41)^{cd}	21.59(0.34)^{e}	26.33(0.22)^{f}	29.62(1.57)^{d}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).





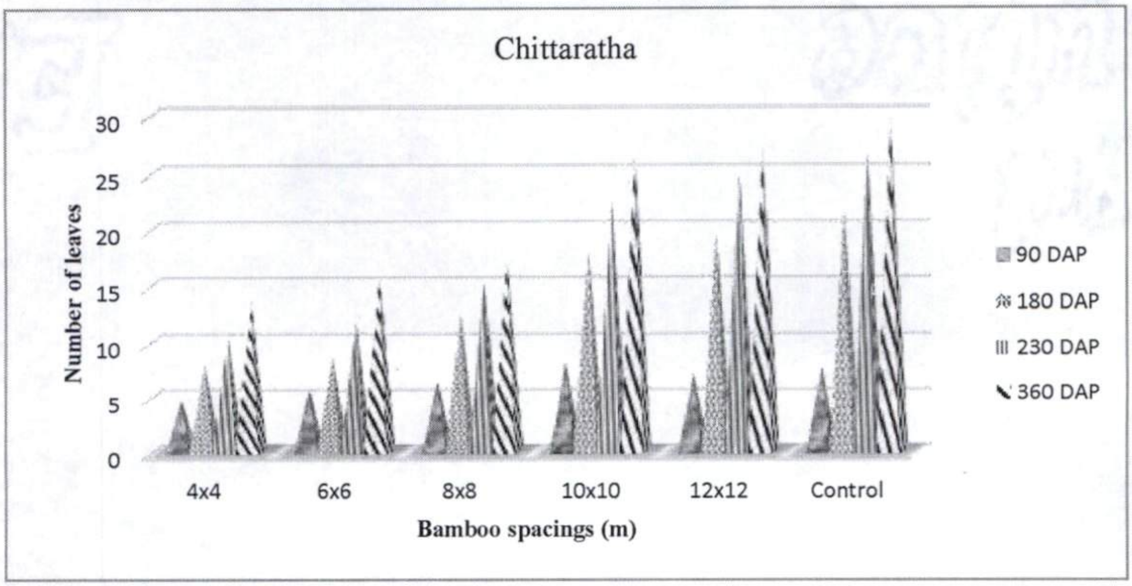


Fig. 13 Number of leaves in turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

compared (180 DAP) to closest spacing of 4x4 m was observed. Further, about 230 per cent higher number of leaves (230 DAP) were recorded in widest spacing (12x12 m) compared to 4x4 m spacing. This clearly show that turmeric intercropped in widest spacing (12x12 m) of bamboo performed better followed by open plot.

In the case of understorey ginger at 90 DAP, the number of leaves in intermediate (8x8 m), wider (10x10 m) and widest (12x12 m) spacings of bamboo was at par with bambooless control. The number of leaves in ginger at 12x12 m was 20 per cent more as compared to closest (4x4 m) spacing of bamboo. The trend of gradual increase in number of leaves with increasing spacings of bamboo was found except at 12x12 m spacing. The number of leaves at 180 DAP were minimum (6.63/plant) in closest (4x4 m) spacing and maximum (11.63/plant) at widest (12x12 m). However, at harvest (230 DAP) the ginger leaves in control plot was at par with12x12 m spacing of bamboo. Though number of leaves increased with increasing spacings of bamboo, highest number (13.03) of leaves were recorded by 10x10 m spacing followed by 12x12 m and bambooless control plot.

The chittaratha planted at closest spacing (4x4 m) recorded lowest number (4.74) of leaves, which increased with increasing spacings of bamboo and recorded maximum number of leaves (7.07) was recorded in widest spacings of bamboo (12x12 m). The number of leaves under widest spacing (7.07) were at par with chittaratha (6.58) grown at bambooless plot. As compared to bambooless control, the closest spacing recorded about 39 per cent lesser number of leaves. At 230 DAP also trend of gradual increase of number of leaves with increasing spacings of bamboo was observed. The closest spacing recorded 10.18 number of leaves; this was 159 per cent less compared to control plot. At 360 DAP, closest spacing (4x4 m) recorded 13.55 leaves which was 1.99 times lesser than widest spacing (12x12 m). In intermediate spacing (8x8 m) about 54.01 per cent lesser number of leaves recorded compared to wider spacing of bamboo (10x10 m) was observed.

4.5.2 Understorey dry matter production

After destructive sampling of turmeric, ginger and chittaratha, the fresh weight of shoots, leaves and rhizomes were determined and the samples were oven dried at 60^0 C and the dry weight of all the component biomass parts were determined.

Shoot dry weight

The data presented in the table 9 and fig. 14 depict that shoot dry weight of all the three intercrops at various growth stages significantly increased with the increasing spacings of bamboo. In the case of turmeric, at 90 days after planting the shoot dry weight was 0.21 gm/plant in bamboo grown at 4x4 m spacing and in the open (control) plot it was 7.92 gm/plant. This shows that there was 3671 per cent increase in the shoot dry weight in the open plot as compared to 4x4 m spacing of bamboo. At 180 and 230 DAP, even though shoot dry weight significantly increased with increasing spacings of bamboo, largest shoot dry weight of turmeric was observed when grown at widest spacing of bamboo (12x12 m). At 180 DAP in widest spacing (12x12 m) the shoot dry weight was 1079 per cent higher compared to closest spacing (4x4 m) which was statically significant. More shoot dry weight in wide spacings (10x10 and 12x12 m) reveal that turmeric requires partial shade at growth stages beyond 90 DAP. However, the shoot dry weight of turmeric at 12x12 m spacing of bamboo was 1067 per cent more at 230 DAP compared to closest spacings of 4x4 m.

In the case of ginger also, the shoot dry weight increased at various growth stages with increasing spacings of bamboo. At 90 DAP, largest dry weight (3.25 gm/plant) of ginger was observed at the widest spacing (12x12 m) of bamboo. However, at 230 DAP the shoot dry weight of ginger increased significantly with increasing spacing of bamboo from 4x4 m to 10x10 m spacing of bamboo. The increase in 10x10 m spacing was 681 per cent compared to closest spacing (4x4 m). However, the shoot dry weight in bambooless control plot was at par with 12x12 m and 10x10 m spacings of bamboo.

Table 9. **Shoot dry weight (gm/plant) of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)**

Spacings (m)	Turmeric			Ginger		
	90 DAP	**180 DAP**	**230 DAP**	**90 DAP**	**180 DAP**	**230 DAP**
4x4	0.21(0.07)^{a}	1.09(0.31)^{a}	1.20(0.27)^{a}	0.36(0.08)^{a}	0.42(0.08)^{a}	1.01(0.17)^{a}
6x6	0.79(0.37)^{ab}	0.95(0.03)^{a}	1.33(0.26)^{a}	0.53(0.30)^{a}	0.79(0.11)^{a}	2.87(0.33)^{b}
8x8	2.95(1.60)^{b}	6.53(0.16)^{b}	8.68(0.30)^{b}	2.09(1.06)^{b}	3.20(0.21)^{b}	5.63(0.60)^{c}
10x10	6.98(2.13)^{c}	8.68(0.23)^{c}	10.14(0.45)^{c}	2.18(0.67)^{bc}	7.15(0.32)^{e}	7.89(0.34)^{d}
12x12	6.67(0.52)^{c}	12.86(1.16)^{e}	14.01(1.27)^{d}	3.25(0.61)^{c}	5.48(0.34)^{c}	7.72(0.09)^{d}
Control	7.92(0.89)^{c}	11.40(0.84)^{d}	10.41(1.28)^{c}	3.16(0.28)^{bc}	6.07(0.38)^{d}	7.51(1.46)^{d}

Spacings (m)	Chittaratha			
	90 DAP	**180 DAP**	**230 DAP**	**360 DAP**
4x4	0.12(0.05)^{a}	0.33(0.07)^{a}	0.95(0.16)^{a}	2.63(0.23)^{a}
6x6	0.20(0.01)^{a}	0.61(0.16)^{a}	1.00(0.07)^{a}	2.57(0.22)^{a}
8x8	0.31(0.17)^{a}	3.84(0.41)^{b}	3.37(0.17)^{b}	5.21(0.48)^{b}
10x10	1.17(0.58)^{b}	4.00(0.09)^{b}	4.63(0.52)^{c}	5.88(0.45)^{c}
12x12	1.63(0.26)^{b}	4.21(0.21)^{b}	5.07(0.22)^{c}	6.39(0.09)^{cd}
Control	2.61(0.12)^{c}	5.45(0.63)^{c}	5.70(0.28)^{d}	6.91(0.44)^{d}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).

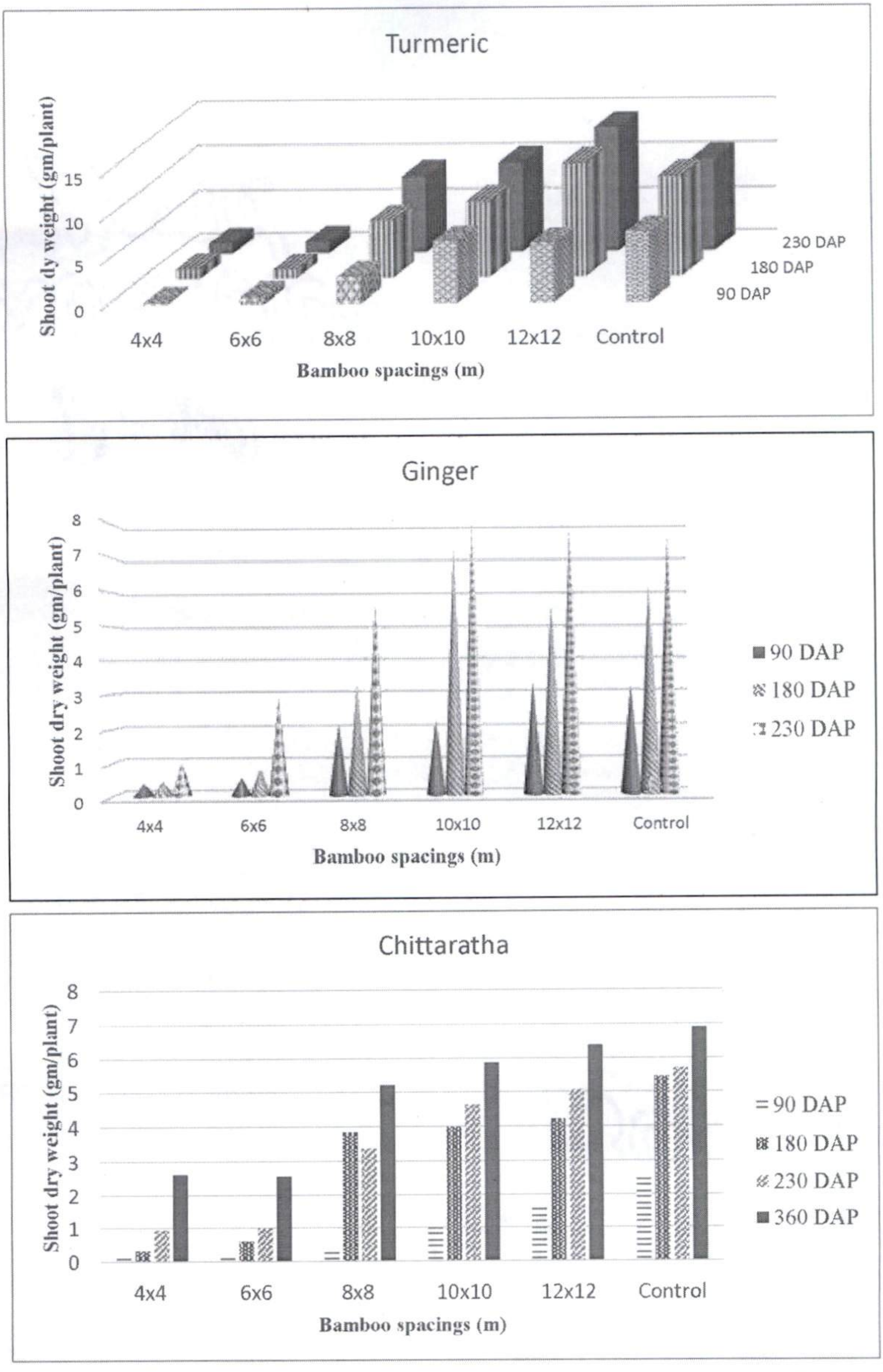


Fig. 14 Shoot dry weight of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Plate 16. Understorey ginger grown at 4x4 and 6x6 m spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

Plate 17. Understorey ginger grown at 8x8 and 10x10 m spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

Plate 18. Understorey ginger grown at 12x12 m spacing and bambooless control of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

Shoot dry matter production in understorey chittaratha significantly increased at various growths stages with increasing spacings of bamboo. The trend of gradual increase of shoot dry matter production with increasing spacings of bamboo was observed. At 90 DAP, shoot dry weight of chittaratha was 0.12 gm/plant at 4x4 m spacing of bamboo and in the open (control) plot shoot dry weight increased to 2.61 gm/plant; this increase in control plot was 2075 per cent. At harvest (360 DAP) shoot dry weight of chittaratha in closest spacings (4x4 m) was 2.63 gm/plant, which increased significantly to 6.39 gm/plant under widest spacings bamboo (12x12 m).

Leaf dry weight

Data on leaf dry weight of turmeric, ginger and chittaratha at different growth stages as influenced by spacings of bamboo are given in the table 10 and fig. 15. In all the three crops leaf dry weight was found to increase at various growth stages with increasing spacings of bamboo. In general, the largest leaf dry weight was observed in open plot under all the intercrops. In the case of turmeric, leaf dry weight increased from 0.3 gm/plant at 90 DAP when grown at bamboo spacing of 4x4 m and in the open plot this was increased by 2393 per cent. At 230 DAP, leaf dry weight increased by 1032 per cent when grown at widest spacing (12x12 m) of bamboo compared to closest spacing of 4x4 m. The trend of significant increase in leaf dry weight with increasing spacings of bamboo was observed.

In the case of ginger at 90 DAP, leaf dry weight was increased by 2037.14 per cent when grown in the open plot compared to closest of spacing of bamboo (4x4 m). At 230 DAP, shoot dry weight of ginger was 1.23 gm/plant at 4x4 m spacing, which increased significantly to 6.78 gm/plant when grown at 10x10 m spacing of bamboo. With further increase of spacings of bamboo to 12x12 m and open plot no trend of increase in leaf dry weight of ginger was observed. However, the leaf dry weight in 12x12 m spacing was at par with control plot. The results reveal that ginger grows better in partial shade (10x10 m) compared to open plot.

Table 10. Leaf dry weight (gm/plant) of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Turmeric			Ginger		
	90 DAP	**180 DAP**	**230 DAP**	**90 DAP**	**180 DAP**	**230 DAP**
4x4	0.30(0.09)^{a}	0.97(0.17)^{a}	1.04(0.08)^{a}	0.35(0.08)^{a}	0.79(0.001)^{a}	1.23(0.11)^{a}
6x6	1.23(0.65)^{a}	1.55(0.19)^{a}	2.34(0.68)^{b}	0.59(0.33)^{a}	1.32(0.21)^{a}	2.02(0.19)^{b}
8x8	4.87(0.82)^{b}	4.32(0.18)^{b}	6.39(0.08)^{c}	1.92(0.99)^{ab}	4.15(0.50)^{b}	4.88(0.12)^{c}
10x10	5.26(0.27)^{bc}	6.64(0.38)^{c}	7.039(0.54)^{c}	2.80(0.60)^{bc}	7.18(0.71)^{d}	6.78(0.97)^{e}
12x12	5.93(0.16)^{bc}	8.97(0.52)^{d}	11.78(0.68)^{e}	4.44(0.73)^{c}	4.90(0.08)^{c}	5.76(0.11)^{d}
Control	7.48(0.80)^{c}	11.20(0.63)^{e}	10.38(0.05)^{d}	7.48(0.80)^{d}	5.31(0.17)^{c}	5.70(0.18)^{d}

Spacings (m)	Chittaratha			
	90 DAP	**180 DAP**	**230 DAP**	**360 DAP**
4x4	0.09(0.02)^{a}	0.43(0.05)^{a}	0.88(0.05)^{a}	1.33(0.16)^{a}
6x6	0.25(0.03)^{a}	0.46(0.10)^{a}	0.99(0.01)^{a}	1.45(0.25)^{a}
8x8	0.47(0.32)^{a}	2.54(0.15)^{b}	2.60(0.06)^{b}	3.45(0.07)^{b}
10x10	1.68(0.42)^{b}	3.93(0.19)^{c}	3.95(0.27)^{c}	4.91(0.11)^{c}
12x12	2.04(0.59)^{b}	4.57(0.08)^{d}	5.03(0.23)^{d}	5.54(0.16)^{d}
Control	2.96(0.21)^{c}	5.82(0.07)^{e}	5.00(0.12)^{d}	6.37(0.03)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

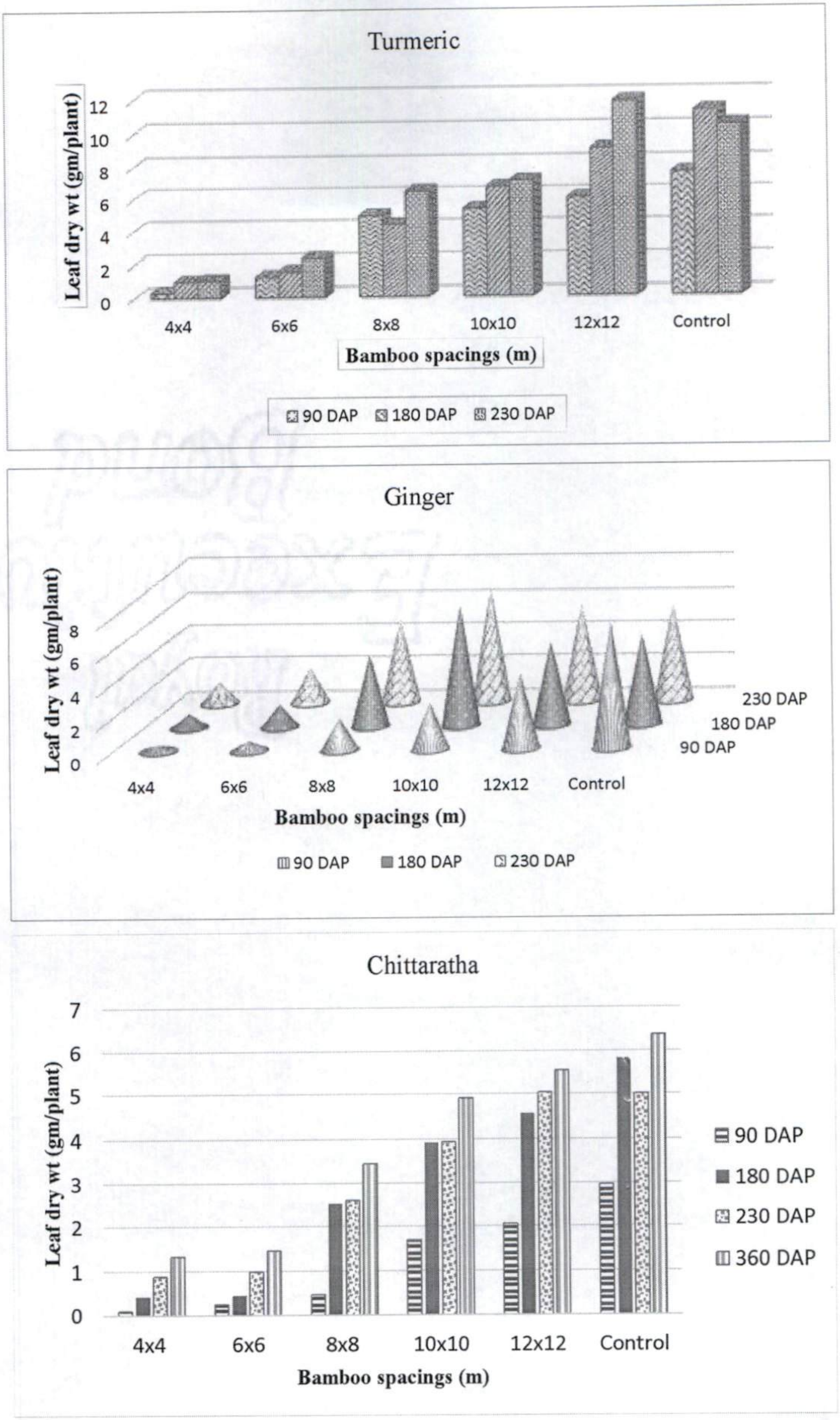


Fig. 15 Leaf dry weight (gm/plant) of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

The chittaratha performed better in control plot compared to bamboo+chittaratha intercrop. At 90 DAP, leaf dry weight increased by 3188 per cent when grown in the open compared to closest spacing (4x4 m) of bamboo. At 360 DAP chittaratha leaf dry weight was 1.33 gm/plant in the closest spacing of bamboo (4x4 m); this increased significantly with increasing spacings of bamboo. In the open plots 378.94 per cent increase in leaf dry weight was observed as compared to closest spacings of 4x4 m. The trend of gradual increase in leaf dry weight with increasing spacing of bamboo was observed.

Rhizome dry weight

At 90 DAP, turmeric rhizome dry weight was 0.39 gm/plant in 4x4 m spacing and this was increased to 9.07 gm/plant when grown at wide spacings of bamboo (10x10 m). This reveal that there was 2225 per cent increase in rhizome dry weight when the spacings of bamboo increased from 4x4 m to 10x10 m (Table 11 and Fig. 16). However, with further increase in spacings (12x12 m) of bamboo and in open plot the shoot dry weight was comparatively decreased. At 180 and 230 DAP, even though the rhizome dry weight significantly increased with increasing of spacing of bamboo, largest rhizome dry weight of turmeric was observed when grown at widest (12x12 m) spacings of bamboo as compared to control (open) plot. Turmeric being a partial shade loving crop recorded maximum rhizome dry weight at 12x12 m spacing of bamboo and this was 382 per cent at 180 DAP and 344.40 per cent at 230 DAP higher as compared to closest spacing (4x4 m) of bamboo.

In case of ginger also rhizome dry weight increased at various growth stages with increasing spacing of bamboo. At 90 DAP, largest dry weight (6.61gm/plant) was observed under open plot. At later stages i. e. 180 DAP, the 10x10 m spacing was found to have largest rhizome dry weight (15.10 gm/plant). With further increase of spacings beyond 10x10 m and open plot the rhizome dry weight significantly decreased. At 230 DAP, although increase in rhizome dry weight was observed with increasing spacings of bamboo, about 850 per cent increase in

Table 11. Rhizome dry weight (gm/plant) of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Turmeric			Ginger		
	90 DAP	**180 DAP**	**230 DAP**	**90 DAP**	**180 DAP**	**230 DAP**
4x4	0.39(0.04)^{a}	6.19(0)^{a}	7.95(1.58)^{a}	0.62(0.19)^{a}	0.89(0.05)^{a}	1.76(0.16)^{a}
6x6	1.20(0.46)^{a}	10.11(1)^{b}	12.54(1.16)^{b}	0.72(0.34)^{a}	1.22(0.09)^{a}	2.75(0.35)^{b}
8x8	1.98(1.39)^{a}	16.37(1)^{c}	20.24(0.62)^{c}	1.80(0.66)^{a}	6.11(0.25)^{b}	13.10(0.28)^{c}
10x10	9.07(1.75)^{b}	24.81(0.61)^{d}	25.92(0.48)^{d}	2.53(0.52)^{a}	15.10(0.32)^{e}	16.71(1.13)^{e}
12x12	5.53(0.70)^{b}	29.85(1.64)^{e}	35.33(0.46)^{f}	4.99(1.52)^{b}	13.63(0.99)^{d}	14.66(0.12)^{d}
Control	6.61(1.25)^{b}	26.72(0.33)^{f}	32.22(0.71)^{e}	6.61(2.48)^{b}	12.81(0.12)^{c}	13.61(0.37)^{c}

Spacings (m)	Chittaratha			
	90 DAP	**180 DAP**	**230 DAP**	**360 DAP**
4x4	0.27(0.21)^{a}	1.01(0.09)^{a}	1.12(0.08)^{a}	4.41(0.06)^{a}
6x6	0.25(0.07)^{a}	1.20(0.18)^{a}	2.78(0.33)^{b}	6.90(0.66)^{b}
8x8	0.99(0.76)^{ab}	4.33(0.31)^{b}	7.51(0.47)^{c}	9.46(0.15)^{c}
10x10	1.50(0.90)^{bc}	5.89(0.13)^{c}	10.23(0.05)^{d}	15.64(1.01)^{d}
12x12	2.30(0.49)^{cd}	10.51(0.21)^{d}	11.92(0.33)^{e}	17.97(0.50)^{e}
Control	2.90(0.18)^{d}	12.40(0.34)^{e}	13.25(0.43)^{f}	24.85(1.55)^{f}

Values in the parenthesis are Standard Deviation of the mean

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).

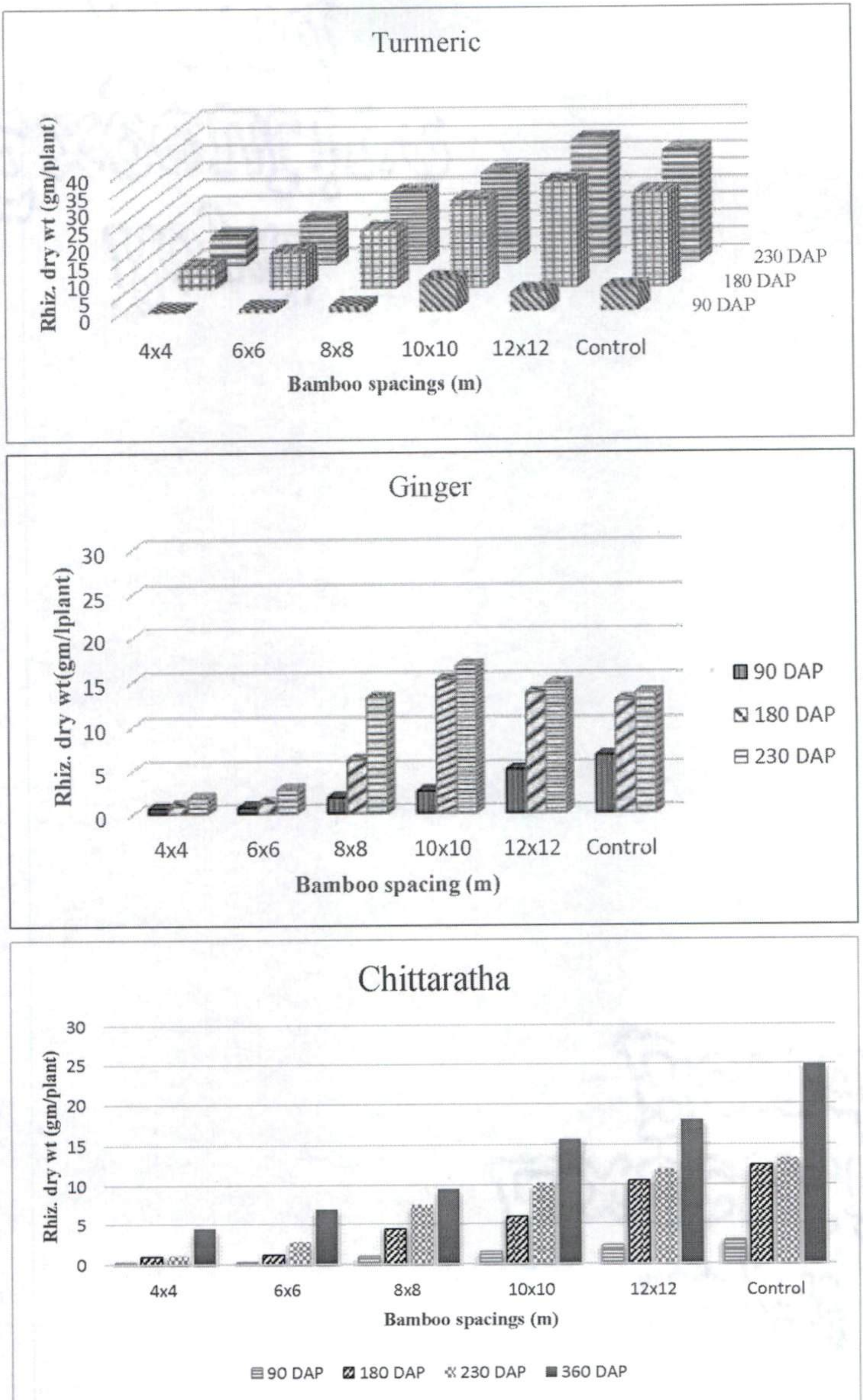


Fig. 16 Rhizome dry weight of turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Plate 19. Understorey Chittaratha grown at 4x4 and 6x6 m spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

Plate 20. Understorey Chittaratha grown at 8x8 and 10x10 m spacings of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

Plate 21. Understorey Chittaratha grown at 12x12 m spacing and bambooless control of 7 year old bamboo (*Dendrocalamus strictus*) in Vellanikkara, Thrissur

rhizome dry weight was observed under 10x10 m spacing as compared to closest spacing (4x4 m).

In chittaratha the trend of gradual increase in rhizome dry matter production with increasing spacings of bamboo was observed. During 90 DAP, rhizome dry weight of chittaratha was 0.27 gm/plant at 4x4 m spacing of bamboo and when the chittaratha was grown under open plot the rhizome dry weight was increased by 974 per cent. At 180 and 230 DAP the control plot was clearly found to have largest dry weight followed by 12x12 m and 10x10 m spacings of bamboo and the similar trend was also observed at 360 DAP. About 463 per cent higher rhizome dry weight in bambooless control plot as compared to closest spacing (4x4 m) of bamboo was found. This reveal that chittaratha although require partial shade for growth, can also perform better in the open plot.

Total dry matter production

The total dry matter production in all the intercrops was significantly affected by the spacing of bamboo (Table 12 and Fig. 17). The total dry matter production of turmeric at 90 DAP recorded minimum (0.14 Mg/ha) in closest spacing (4x4 m) and maximum (3.4 Mg/ha) at wider spacing (10x10 m) of bamboo. The trend of significant increase in dry matter production with increase in spacings of bamboo was observed. In widest spacing (12x12 m) about 1964 per cent increase in dry matter production as compared to closest spacing (4x4 m) was found. However, the dry matter of turmeric under 10x10 m spacings of bamboo was at par with 12x12 m spacing. At 230 DAP, the total dry matter production in turmeric significantly increased with increasing spacings of bamboo. The closest spacing (4x4 m) recorded 1.62 Mg/ha of dry matter; this was increased to 9.75 Mg/ha due to widest spacing (12x12 m). The increase was upto the tune of 501.85 per cent more as compared to closest spacing (4x4 m).

For ginger, the trend of gradual increase in dry matter with increasing spacing of bamboo was observed. At early stage (90 DAP) of ginger in 12x12 m

Table 12. Total dry matter production (Mg/ha) of turmeric, ginger and chittaratha at various growth stages as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Turmeric			Ginger		
	90 DAP	180 DAP	230 DAP	90 DAP	180 DAP	230 DAP
4x4	0.14(0.02)^{a}	1.31(0.005)^{a}	1.62(0.28)^{a}	0.21(0.05)^{a}	0.33(0.01)^{a}	0.63(0.02)^{a}
6x6	0.51(0.22)^{a}	2.01(0.12)^{b}	2.58(0.32)^{b}	0.29(0.15)^{a}	0.53(0.06)^{b}	1.22(0.05)^{b}
8x8	1.56(0.81)^{b}	4.34(0.19)^{c}	5.63(0.12)^{c}	0.92(0.43)^{b}	2.14(0.13)^{c}	3.76(0.12)^{d}
10x10	3.4(0.94)^{c}	6.40(0.10)^{e}	6.87(0.22)^{d}	1.19(0.26)^{b}	4.69(0.02)^{f}	5.00(0.15)^{f}
12x12	2.89(0.19)^{c}	8.24(0.41)^{f}	9.75(0.21)^{e}	2.02(0.42)^{c}	3.83(0.17)^{e}	4.49(0.01)^{e}
Control	2.35(0.65)^{bc}	5.26(0.01)^{d}	5.65(0.09)^{c}	1.84(0.46)^{c}	2.58(0.05)^{d}	2.86(0.15)^{c}

Spacing (m)	Chittaratha			
	90 DAP	180 DAP	230 DAP	360 DAP
4x4	0.07(0.046)^{a}	0.12(0.019)^{a}	0.47(0.03)^{a}	1.33(0.05)^{a}
6x6	0.11(0.005)^{a}	0.17(0.03)^{a}	0.76(0.05)^{b}	1.74(0.06)^{b}
8x8	0.28(0.033)^{a}	1.01(0.05)^{b}	2.15(0.10)^{c}	2.89(0.11)^{c}
10x10	0.69(0.02)^{b}	1.20(0.06)^{c}	2.55(0.08)^{d}	4.06(0.12)^{d}
12x12	0.95(0.08)^{b}	1.26(0.04)^{c}	3.00(0.11)^{e}	4.21(0.24)^{d}
Control	0.90(0.04)^{b}	1.40(0.02)^{d}	3.51(0.09)^{f}	4.77(0.11)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

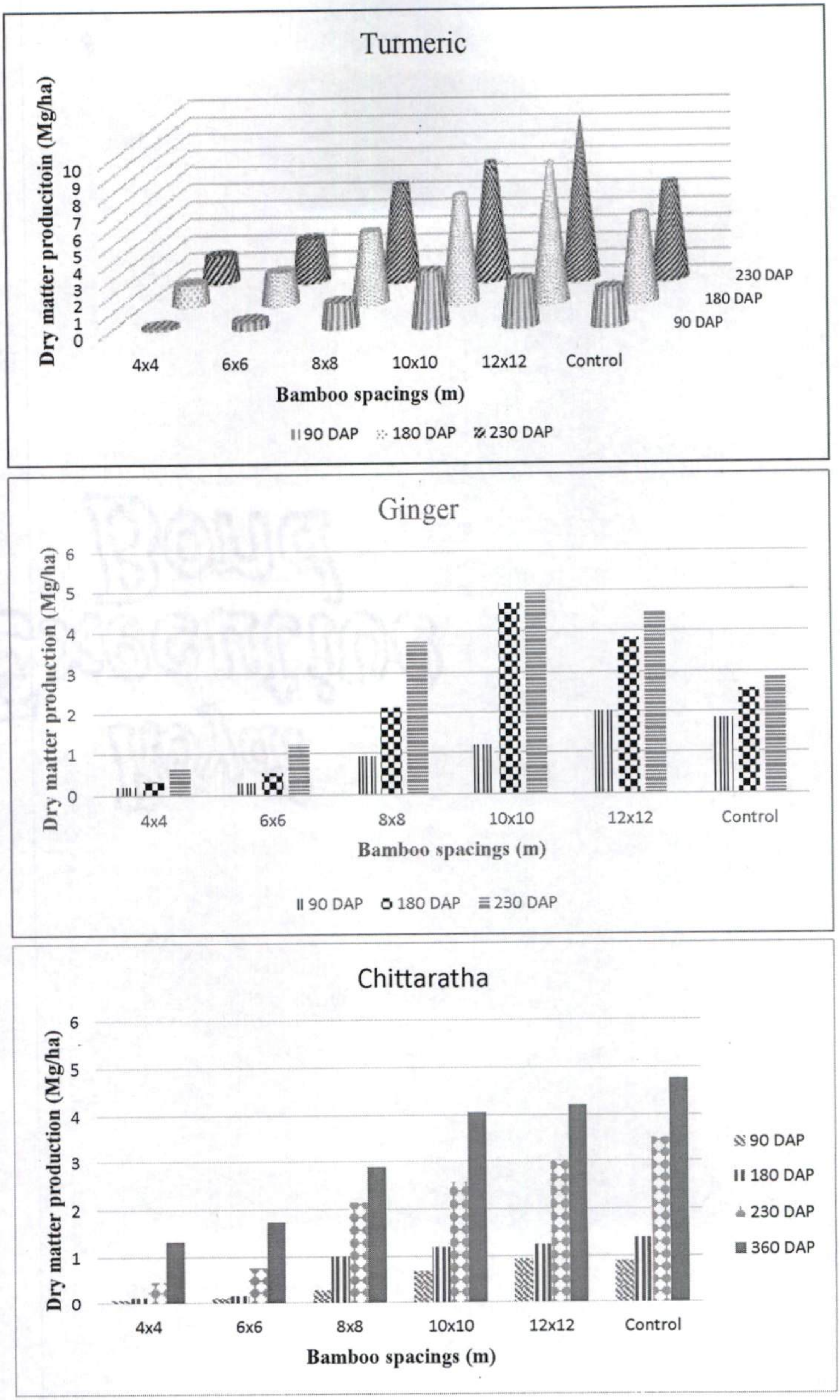


Fig. 17 Total dry matter production in turmeric, ginger and chittaratha at various growth stages as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

spacing of bamboo recorded largest (2.02 Mg/ha) dry matter production, but in subsequent growth stages (180 and 230 DAP) the dry matter production recorded largest in wider spacing of 10x10 m; increase in dry mater production at 10x10 m spacing was about 1321 per cent at 180 DAP and 693 per cent at 230 DAP compared to closest spacing (4x4 m).

In case of chittaratha at 90 DAP lowest dry matter production (0.07 Mg/ha) in closest spacing (4x4 m) and highest (0.95 Mg/ha) in widest spacing (12x12 m) of bamboo was observed; this was increased by 1257 per cent compared to closest spacing. At 180 and 230 DAP the dry matter production at widest spacings (12x12 m) was 1.26 Mg/ha and 3 Mg/ha respectively; this dry weight was significantly lesser than open plot (control). While at harvest (360 DAP) the highest (4.77 Mg/ha) dry matter production was at bambooless plot (control); this was about 258 per cent more compared to closest spacing (4x4 m).

4.5.3 Rhizome yield

The rhizome yield of all the intercrops was significantly influenced by spacings of bamboo. The rhizome yield in turmeric gradually and significantly increased with increasing spacings of bamboo (Table 13 and Fig. 18). Closest (4x4 m) spacing of bamboo plot recorded least rhizome yield of 8 Mg/ha; this was 58 per cent less compared to widest spacing of 12x12 m (19.32 Mg/ha).

The rhizome yield of ginger was significantly high (19.55 Mg/ha) at 10x10 m spacings of bamboo which decreased to 3.19 Mg/ha when the spacings of bamboo decreased to 4x4 m. This decrease was about 513 per cent compared to a 10x10 m spacing of bamboo. However, in case of chittaratha rhizome yield was maximum (18.28 Mg/ha) in control plot; this decreased with decreasing spacings of bamboo and recorded minimum (7.10 Mg/ha) under closest spacings of bamboo. About 157 per cent decrease in rhizome yield of chittaratha was observed when grown under closest spacing (4x4 m) of bamboo. The chittaratha yield under 10x10 m spacing of bamboo was at par with 12x12 m spacing. Therefore results reveal that the turmeric and ginger requires partial shade for its better growth and

Table 13. Rhizome yield (Mg/ha) of turmeric, ginger and chittaratha at various growth stages as influenced by different density (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m) (Density/ha)	Turmeric	Ginger	Chittaratha
4x4(625)	8.00(0.07)^{a}	3.19(0.04)^{a}	7.10(0.94)^{a}
6x6(277)	10.59(0.44)^{b}	3.59(0.09)^{a}	9.82(0.58)^{b}
8x8(156)	13.07(1.02)^{c}	8.29(2.17)^{b}	11.6(0.56)^{c}
10x10(100)	15.72(0.14)^{d}	19.55(2.47)^{d}	15.78(0.58)^{d}
12x12(69)	19.32(0.61)^{f}	18.02(0.15)^{cd}	16.34(0.90)^{d}
Control	17.48(0.69)^{e}	16.69(1.51)^{c}	18.28(0.96)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

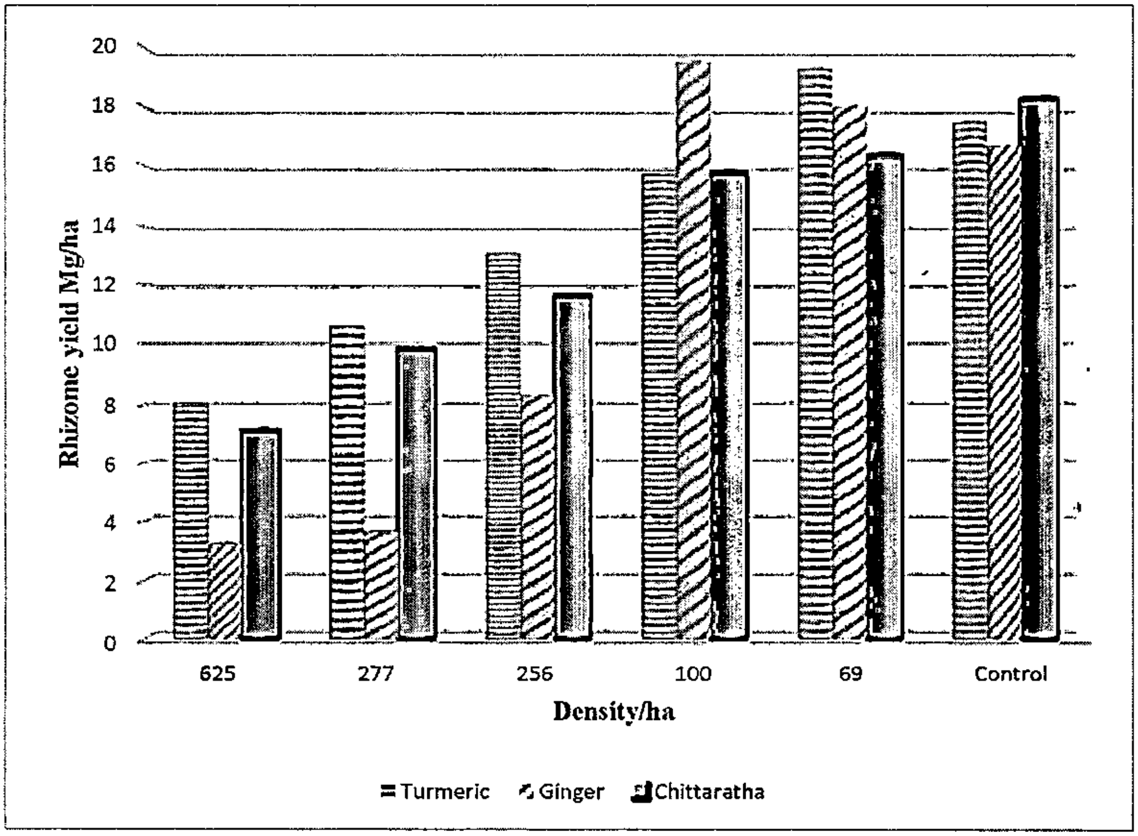


Fig. 18 Rhizome yield (Mg/ha) of turmeric, ginger and chittaratha at various growth stages as influenced by density (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

development. For chittaratha although open plot is found to be best for rhizome production wider spacing (12x12 m) was also better for chittaratha rhizome yield compared to other spacings of bamboo.

4.5.4 Oleoresin content (%) in understorey crops

The spacings of bamboo significantly affected the oleoresin content (%) of understorey crops (turmeric, ginger and chittaratha). In general with decreasing spacings of bamboo the oleoresin content in understorey turmeric, ginger and chittaratha were gradually decreased (Table 14 and Fig. 19). The oleoresin content in understorey turmeric was minimum (8.27%) in 4x4 m and recorded maximum in bambooless control plot (11.68%). The oleoresin in control plot was at par with 12x12 m spacing of bamboo. However, the oleoresin content in turmeric at closest spacing (4x4 m) was decreased by 37 per cent compared to widest spacing of 12x12 m. The oleoresin content in ginger at 4x4 spacings of bamboo was 3.24 per cent, this increased to 5.57 % when the spacings of overstorey bamboo was increased to 12x12 m. However, with increasing spacings of bamboo beyond 8x8 m, the oleoresin content decreased moderately. Among the spacings of bamboo, comparatively higher (5.90 %) oleoresin content was recorded in intermediate spacing (8x8 m) followed by 10x10 m spacing (5.74 %).

The oleoresin content in understorey chittaratha among the spacings of bamboo recorded highest (8.74%) at widest spacing of 12x12 m; this was significantly decreased to 5.75 % when chittaratha grown at closest spacing (4x4 m) of bamboo. The maximum oleoresin content was recorded by bambooless control plot (8.77%), which was 0.65 times higher than closest spacing.

4.5.5 Nutrient concentration (%) and uptake (kg/ha) by understorey crops

The data presented in the table 15 reveal that the N, P and K concentration in leaf tissue of turmeric, ginger and chittaratha was significantly affected by bamboo. The N concentration in turmeric recorded lowest (1.19%) in 4x4 m spacing and highest (1.91%) at 12x12 m spacing of bamboo. The N concentration in turmeric gradually

Table 14. Oleoresin content (per cent) in turmeric, ginger and chittaratha as influenced by varying spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Turmeric	Ginger	Chittaratha
4x4	8.27(0.23)^{a}	3.24(0.31)^{a}	5.75(0.26)^{a}
6x6	8.52(0.26)^{a}	3.60(0.30)^{a}	6.56(0.09)^{b}
8x8	8.48(0.46)^{a}	5.90(0.93)^{b}	7.84(0.80)^{c}
10x10	10.42(0.63)^{b}	5.74(0.36)^{b}	8.32(0.16)^{cd}
12x12	11.32(0.08)^{c}	5.57(0.65)^{b}	8.74(0.14)^{d}
Control	11.68(0.30)^{c}	5.71(0.62)^{b}	8.77(0.03)^{d}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, P<0.05).

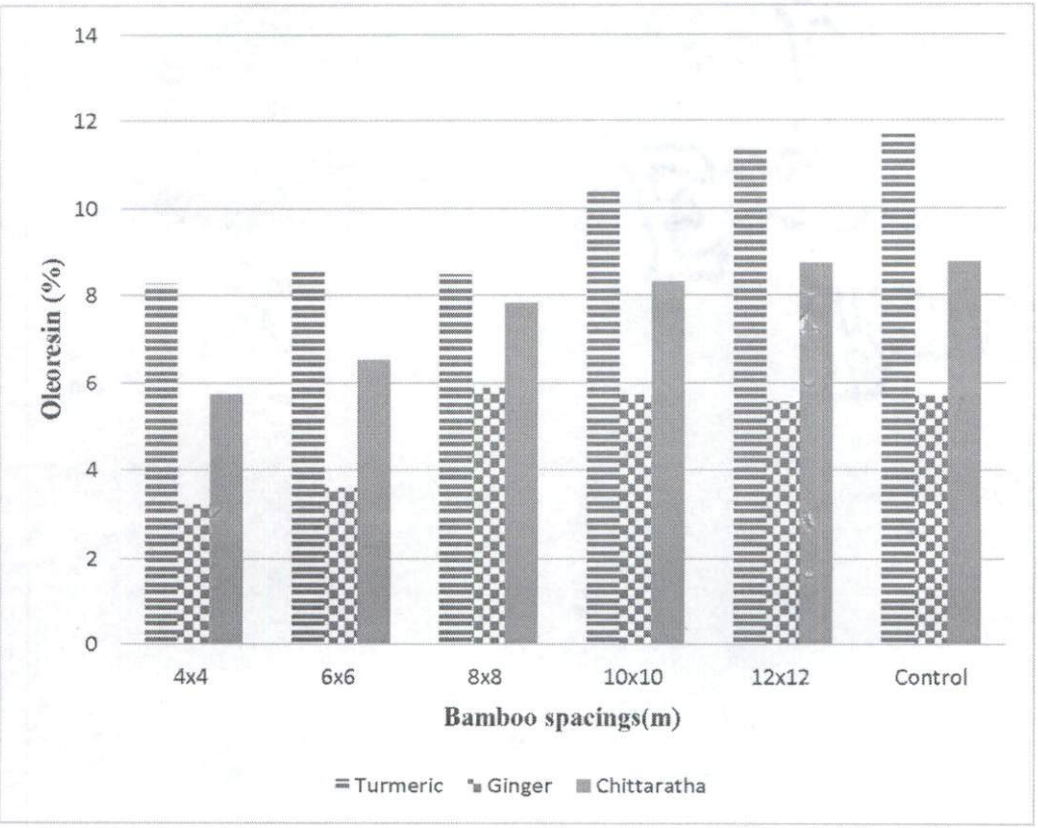


Fig. 19 Oleoresin content (per cent) in turmeric, ginger and chittaratha as influenced by varying spacings of 7 year old bamboo (*Dendrocalamus strictus*)

increased with increasing spacings of bamboo. Similar trend of increase was also observed for P and K. The P concentration in ginger at closest spacing (4x4 m) was 0.08 percent; this was increased to 0.19 percent at 12x12 m spacing. Although the K percent increased with increasing spacings of bamboo, the highest (0.19 %) was recorded under widest spacing (12x12 m).

The uptake (Table 15) of N by turmeric was significantly increased with increasing spacings of bamboo. The lowest (12.15 kg/ha) uptake was at closest spacing (4x4 m) while highest (66.99 kg/ha) was under widest spacing of 12x12 m; this increase was 451 percent compared to closest spacing (4x4 m). Similar trend also observed for P and K. The P uptake by turmeric ranged between 2.41 kg/ha in 4x4 m to 9.52 kg/ha in 12x12 m spacing of bamboo (Fig. 17). The P concentration of turmeric in intermediate spacing (8x8 m) of bamboo was at par with 10x10 m spacing and control plot. However, maximum (67.62 kg/ha) K uptake by turmeric was recorded in widest spacing (12x12 m). The closest spacing (4x4 m) recorded minimum (31.38 kg/ha); this decrease was 53.59 per cent compared to widest spacing (12x12 m).

The N, P and K concentration in understorey ginger decreased drastically with decreasing spacings of bamboo. The N concentration was maximum (2.16 %) at 10x10 m spacing whereas minimum (1.45 %) under closest spacing of bamboo (4x4 m). However, the N concentration in ginger of control plot was at par with 12x12 m and 10x10 m spacings. The P concentration at 10x10 m spacings was 1.58 times higher compared to 4x4 m. However, K concentration in ginger recorded maximum (1.31 %) in control plot and minimum (1.04 %) at closest spacings (4x4 m). The uptake of N, P and K by intercropped ginger significantly increased with increasing in spacings of bamboo upto 10x10 m spacing of bamboo. The maximum uptake of N: P: K by ginger was recorded by 10x10 m spacing of bamboo. About 172.87, 112.97 per cent and 131.77 per cent higher N, P and K uptake was recorded when ginger grown at 10x10 m spacing compared to closest spacing (4x4 m).

In chittaratha, the trend of significant increase of N, P and K concentration with increasing spacing of bamboo was recorded. In general the higher N, P and

Table 15. Concentration (%) and uptake (kg/ha) of N, P and K by understorey crops as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Turmeric						
Spacings (m) (Density/ha)	N P K (%)			Uptake of N P K (kg/ha)		
	N	**P**	**K**	**N**	**P**	**K**
4x4 (625)	1.19(0.02)^{a}	0.08(0.002)^{a}	1.12(0.01)^{a}	12.15(0.78)^{a}	2.41(0.09)^{a}	31.38(0.56)^{a}
6x6 (277)	1.36(0.02)^{b}	0.11(0.01)^{b}	1.20(0.001)^{b}	20.90(1.38)^{b}	3.98(0.38)^{b}	40.43(1.77)^{b}
8x8 (156)	1.56(0.06)^{c}	0.16(0.01)^{c}	1.26(0.09)^{c}	33.35(1.42)^{c}	5.98(0.71)^{c}	47.08(1.57)^{c}
10x10 (100)	1.69(0.07)^{cd}	0.17(0.009)^{c}	1.34(0.01)^{d}	50.84(0.94)^{e}	7.38(0.53)^{d}	57.33(0.98)^{d}
12x12 (69)	1.82(0.04)^{de}	0.19(0.009)^{d}	1.39(0.01)^{e}	66.99(1.16)^{f}	9.52(0.20)^{e}	67.62(4.82)^{e}
Control	1.91(0.14)^{e}	0.17(0.009)^{c}	1.34(0.009)^{d}	43.87(4.48)^{d}	6.00(0.32)^{c}	47.51(0.92)^{c}
Ginger						
Spacings (m) (Density/ha)	**N**	**P**	**K**	**N**	**P**	**K**
4x4 (625)	1.45(0.06)^{a}	0.17(0.005)^{a}	1.04(0.02)^{a}	14.23(0.51)^{a}	7.32(0.42)^{a}	15.01(1.64)^{a}
6x6 (277)	1.7(0.12)^{b}	0.19(0.005)^{b}	1.15(0.03)^{b}	19.38(1.34)^{ab}	9.52(0.12)^{b}	20.62(2.07)^{b}
8x8 (156)	1.79(0.07)^{b}	0.23(0.005)^{c}	1.25(0.02)^{c}	25.85(2.83)^{b}	12.26(0.33)^{d}	27.52(1.38)^{c}
10x10 (100)	2.16(0.15)^{c}	0.27(0.005)^{e}	1.24(0.07)^{c}	38.83(6.99)^{c}	15.59(0.108)^{f}	34.79(2.61)^{d}
12x12 (69)	2.08(0.04)^{c}	0.26(0.005)^{d}	1.29(0.01)^{c}	34.00(5.54)^{c}	14.17(0.18)^{e}	30.40(0.88)^{c}
Control	2.13(0.15)^{c}	0.27(0.001)^{de}	1.31(0.01)^{c}	24.32(1.16)^{b}	11.28(0.04)^{c}	23.49(1.85)^{b}
Chittaratha						
Spacings (m) (Density/ha)	**N**	**P**	**K**	**N**	**P**	**K**
4x4 (625)	1.51(0.07)^{a}	0.07(0.007)^{a}	1.07(0.11)^{a}	32.35(5.66)^{a}	14.30(1.08)^{a}	23.20(2.01)^{a}
6x6 (277)	1.60(0.098)^{ab}	0.10(0.01)^{b}	1.14(0.13)^{ab}	41.07(4.00)^{b}	16.60(0.49)^{ab}	28.87(4.43)^{b}
8x8 (156)	1.70(0.06)^{bc}	0.13(0.006)^{c}	1.25(0.08)^{abc}	50.07(4.48)^{c}	17.27(0.26)^{ab}	38.18(2.30)^{c}
10x10 (100)	1.75(0.05)^{bc}	0.16(0.007)^{d}	1.32(0.08)^{bc}	67.36(6.76)^{d}	18.22(0.85)^{ab}	50.10(1.06)^{d}
12x12 (69)	1.83(0.04)^{cd}	0.19(0.007)^{e}	1.37(0.10)^{c}	77.27(7.65)^{e}	19.30(0.81)^{ab}	56.26(0.81)^{e}
Control	1.93(0.12)^{cd}	0.22(0.005)^{f}	1.44(0.08)^{c}	78.64(6.55)^{e}	18.92(1.26)^{b}	57.95(0.93)^{e}

Values in the parenthesis are Standard Deviation of the Mean

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

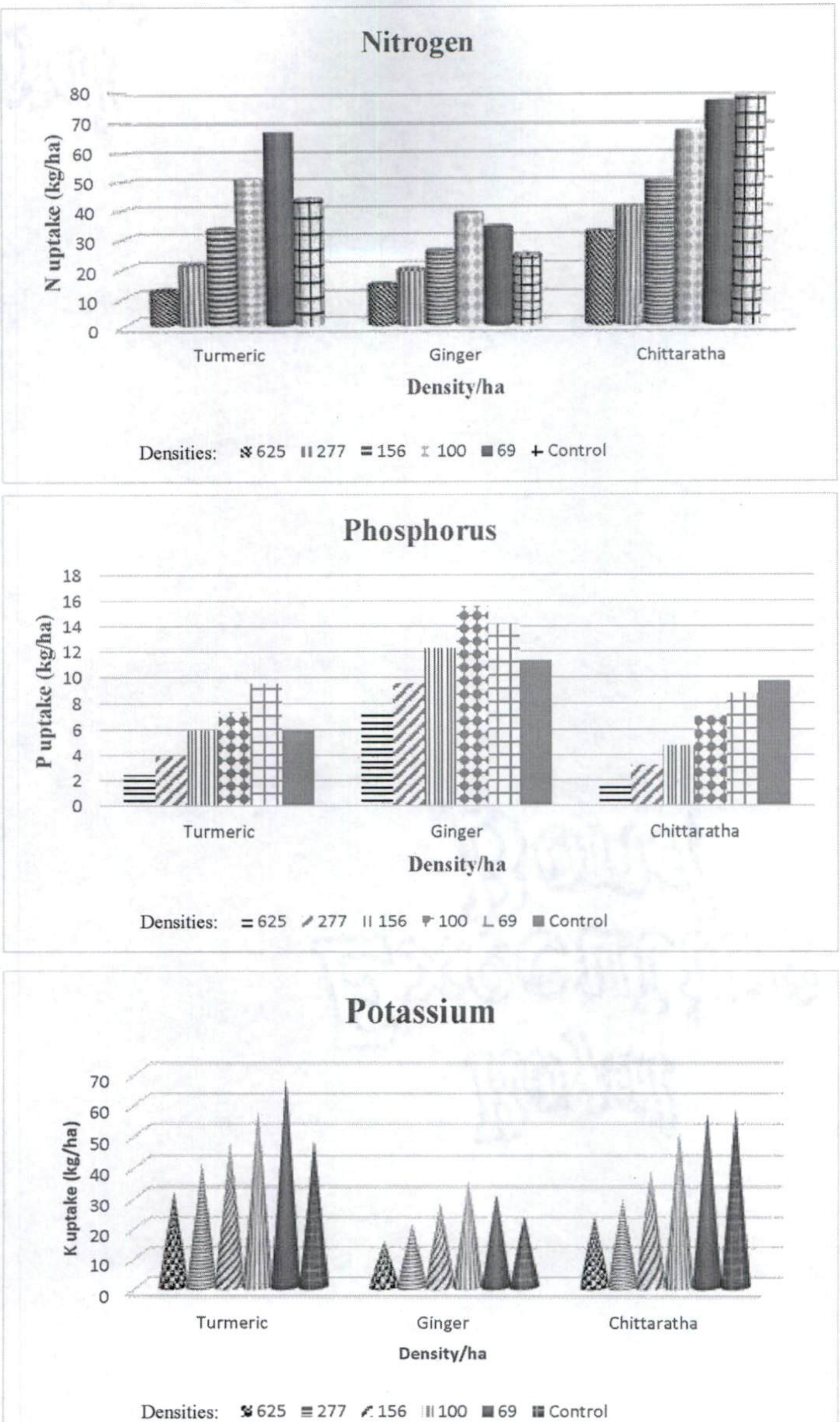


Fig. 20 Uptake (kg/ha) of N P K by understorey crops as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

K concentration was recorded in bambooless control plot. The N concentration in chittaratha at 4x4 m spacing was 1.51 %; this was increased to 1.93 % when chittaratha was grown in open plot. However, N concentration in chittaratha at widest spacing (12x12 m) was 0.78 times higher than closest spacing (4x4 m). Minimum concentration of P (0.07 %) in chittaratha was observed at closest spacing (4x4 m) and maximum (0.22 %) in widest spacing of bamboo. The K concentration in chittaratha gradually increased with increasing spacing of bamboo and the maximum concentration (1.44 %) of K was recorded in bambooless control plot. Among the various spacings of bamboo+chittaratha intercrop, the highest K concentration (1.37%) in chittaratha was recorded in 12x12 m spacings of bamboo and lowest (1.07 %) under closest spacing of bamboo.

The N, P and K uptake by understorey chittaratha was significantly higher when it was grown in wider spacings of bamboo (10x10 and 12x12 m). However, the maximum uptake of N, and K was recorded in open plot (Table 12 and Fig. 20). The N uptake by chittaratha recorded lowest (32.35 kg/ha) in closest spacing (4x4 m); this uptake increased by 139 per cent when chittaratha was grown under widest spacing of bamboo (12x12 m) compared to chittaratha grown under closest spacing (4x4 m). Maximum (19.30 kg/ha) P uptake by chittaratha was found in widest spacing of 12x12 m which decreased with decreasing spacings of bamboo and recorded minimum (14.30 kg/ha) in closest spacing of 4x4 m. Similarly, the K uptake by understorey chittaratha recorded maximum (57.95 kg/ha) in open plot followed by widest spacing (56.26 kg/ha) and minimum (23.20 kg/ha) in closest spacing of 4x4 m.

4.6.1 Applied ^{32}P tracer for rhizosphere competition

Soil injection of ^{32}P solution was done to evaluate the turmeric+bamboo rhizosphere competition. A plot size of 1x1 m^2 at the center of each turmeric bed was selected from each treatment. The ^{32}P solution was applied to the four turmeric plants in a row. The most recently matured turmeric leaves from the treated and neighboring turmeric plants in the two adjacent rows on either side of the treated plants were sampled for radioassay at 15th, 30th and 45th day after application (DAA). The bamboo clumps located at varying lateral distances from the turmeric bed were also monitored by sampling the bamboo leaves along with turmeric leaves simultaneously. The data are furnished in the tables 16, 17 and 18.

Table 16. Absorption of applied ^{32}P by turmeric grown under different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	15 DAA			30 DAA			45 DAA		
	treated plant	N25[*]	N50[#]	treated plant	N25	N50	treated plant	N25	N50
4x4	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)
6x6	4868^{ab} (3.64)	1089^{a} (3.03)	928^{ab} (2.94)	1220^{a} (3.07)	1026^{a} (3.01)	925^{ab} (2.41)	1260^{a} (2.97)	1063^{ab} (2.46)	520^{ab} (2.69)
8x8	7579^{bc} (3.86)	4482^{b} (3.62)	892^{ab} (2.93)	5449^{ab} (3.71)	3921^{ab} (3.30)	2333^{ab} (3.22)	5513^{b} (3.73)	1981^{b} (3.04)	1865^{ab} (3.14)
10x10	9778^{c} (3.98)	6904^{b} (3.73)	2929^{bc} (3.45)	7242^{b} (3.85)	4652^{ab} (3.59)	2746^{ab} (3.37)	5433^{b} (3.73)	2719^{b} (3.41)	2222^{ab} (3.27)
12x12	11003^{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^{ab} (3.26)
Control	10911^{c} (4.03)	7437^{b} (3.85)	4973^{c} (3.43)	7302^{b} (3.79)	5738^{ab} (3.71)	4618^{b} (3.60)	4581^{b} (3.65)	3283^{abc} (3.38)	1624^{b} (3.12)

[*] N25 = untreated turmeric plant at 25 cm away from the treated plant

[#] N50 = untreated turmeric plant at 50 cm away from the treated plant

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

Values followed by same superscript in a column do not differ significantly (LSD, $P < 0.05$)

Invariably the ^{32}P absorption by turmeric was highest in the control plots. At 15th day after application (DAA) ^{32}P absorption by treated plants in the control plot was widest spacings (10911 cpm). This ^{32}P absorption by turmeric decreased with decreasing spacing of bamboo (Table 16 and Fig. 21). The ^{32}P absorption by treated turmeric plants under closest spacing (4x4 m) of bamboo was 75.19 per cent less compared to control plot (Table 17). As the distance of the untreated turmeric plants increased from the treated turmeric plants the ^{32}P absorption decreased

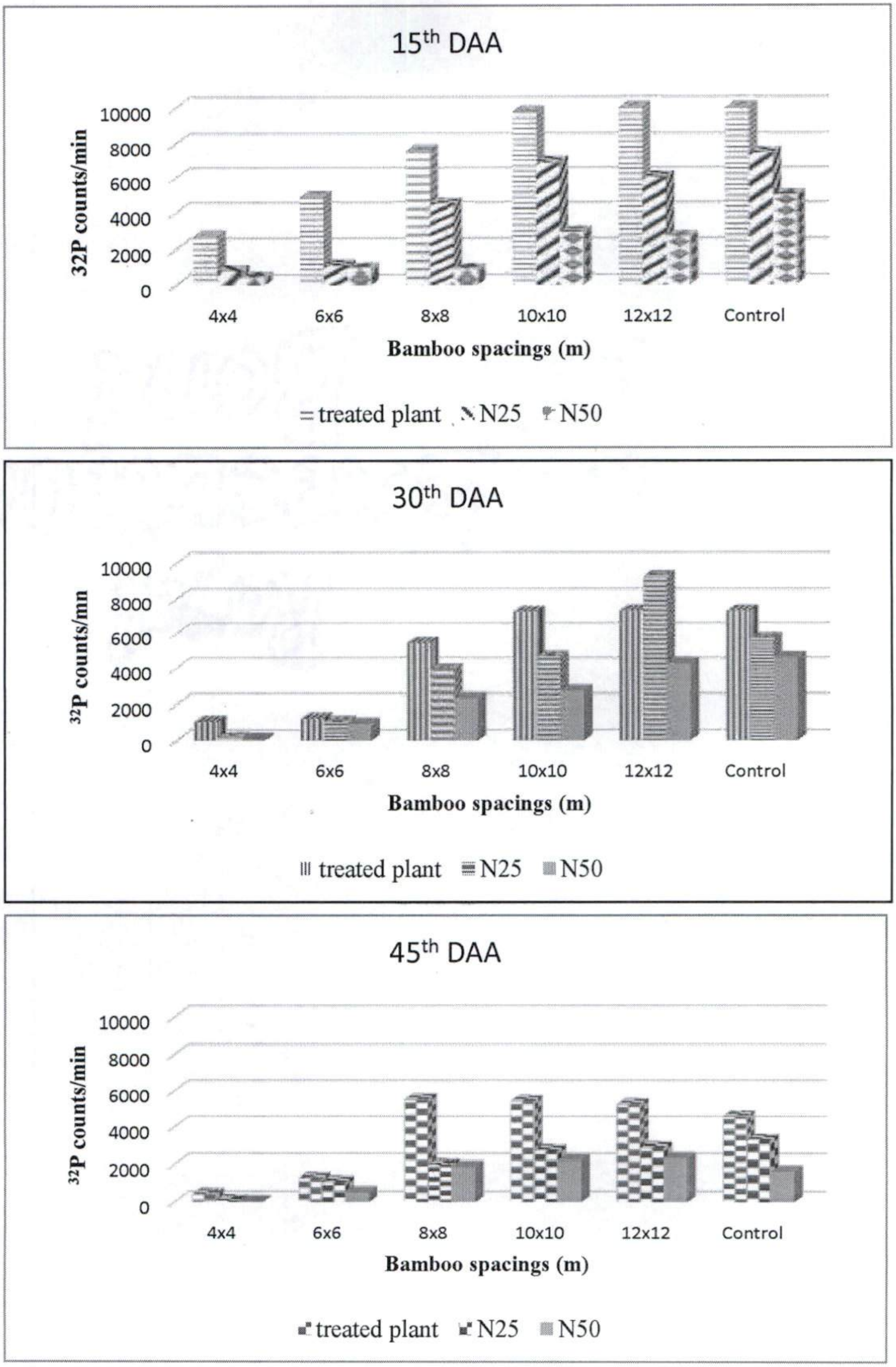


Fig. 21 Absorption of applied ^{32}P (cpm g^{-1}/min) activity by turmeric grown under different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

drastically. ^{32}P absorption by turmeric plants at 25 cm away from the treated plants was 7437cpm in the control plot. When turmeric was grown as intercrop with bamboo the ^{32}P absorption decreased significantly with decreasing spacing of bamboo. As compared to control plot, about 89 per cent decline in ^{32}P absorption was observed in turmeric when grown at closest spacing of bamboo (4x4 m). At a distance of 50 cm away from the treated plants also similar trend was observed. In case of control plot (open), the ^{32}P absorption by turmeric was 4973 cpm. When grown as intercrop in bamboo ^{32}P absorption decreased significantly with the increasing spacings of bamboo. In the case of turmeric at closest spacing (4x4 m), this decrease was 91 per cent compared to bambooless control plot. ^{32}P absorption also decreased with increasing days after application (Fig. 21).

Table 17. Absorption of applied ^{32}P (per cent) by turmeric grown under different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	**15th DAA**			**30th DAA**			**45th DAA**		
	treated plant	**N25[*]**	**N50[#]**	**treated plant**	**N25**	**N50**	**treated plant**	**N25**	**N50**
4x4	69.35	19.94	10.70	79.63	12.52	7.83	77.80	15.73	6.45
6x6	70.70	15.81	13.47	38.45	32.36	29.18	49.10	36.36	14.53
8x8	58.51	34.59	6.89	46.55	33.50	19.93	58.90	21.17	19.92
10x10	49.85	35.20	14.93	49.46	31.77	18.75	52.36	26.20	21.42
12x12	55.78	30.61	13.59	35.05	44.47	20.47	50.16	27.54	22.29
Control	46.78	31.89	21.32	41.34	32.49	26.15	48.27	34.60	17.12

[*] N25 = untreated turmeric plant at 25 cm away from the treated plan
[#] N50 = untreated turmeric plant at 50 cm away from the treated plant

At 30 DAA, the ^{32}P absorption by treated turmeric plants in the control plot was 7302 cpm which was at par with the ^{32}P absorption by turmeric plants grown under bamboo at 12x12, 10x10 and 8x8 m spacings of bamboo. However at 6x6 and 8x8 m spacings of bamboo the ^{32}P absorption by treated turmeric plants declined significantly compared to control plot (open). The ^{32}P absorption by treated turmeric plants under 4x4 m spacing of bamboo declined by 85 per cent. At distance of 25 cm away from the treated plants the ^{32}P absorption by turmeric in the control plot was 5738 cpm, this was on par with ^{32}P absorption by turmeric when grown under bamboo spacing of 12x12, 10x10 and 8x8 m. At closest spacing of bamboo (4x4 m) the ^{32}P absorption by turmeric plants at distance of 2.5 cm away from the treated plants was 97.14 per cent lower compared to control. Similarly at distance of 50 cm away from the treated plants ^{32}P absorption was 97.79 per cent lower compared to the control (open) plot.

The per cent ^{32}P absorption by treated turmeric and also untreated turmeric at a distance of 25 cm and 50 cm away from the treated turmeric at 15, 30, and 45 DAA are given in the table 15. The data clearly show that, as the distance of untreated turmeric plants increased its ^{32}P absorption significantly decreased. In the control plot ^{32}P absorption decreased from 46.78 per cent in treated turmeric plants to 21.32 per cent in the case of untreated turmeric plant at distance of 50 cm away from the treated turmeric. At widest spacing of bamboo (12x12 m), ^{32}P absorption declined from 57.78 to 13.59 per cent and at the closest bamboo spacing of 4x4 m the ^{32}P absorption declined from 69.35 to 10.7 per cent.

4.6.2 ^{32}P recovery by bamboo

The recovery of ^{32}P by bamboo at varying distances from the turmeric bed was significant (Table 18 and Fig. 22). The uptake of ^{32}P at closest spacing (4x4 m) was 28.86 cpm; which decreased significantly when the spacings was increased to 8x8 m. In the case of bamboo beyond 8x8 m spacing, the recovery of ^{32}P from the treated turmeric was nil. This reveal that bamboo roots could not reach upto treated turmeric beds in wider spacings (10x10 and 12x12 m). The percent ^{32}P recovery by bamboo at 30th and 45th days after application were drastically declined. The percent absorption of ^{32}P by bamboo under closest spacing was highest (48.61 per cent) at 30th DAA and 58.21 percent at 45th DAA while at 6x6 and 8x8 m spacings, bamboo have lesser recovery.

Table 18. Recovery of ^{32}P (cpm g^{-1}/min) by 7 year old bamboo (*Dendrocalamus strictus*) under varying spacings

Spacings (m)	^{32}P counts/min			^{32}P counts/min (per cent)		
	Days After Application					
	15th	**30th**	**45th**	**15th**	**30th**	**45th**
4x4	154.27^{c} (2.18)	28.86^{c} (1.52)	4.30^{c} (0.79)	51.25	48.61	58.21
6x6	106.15^{b} (2.06)	17.78^{b} (1.34)	2.25^{b} (0.35)	35.26	29.95	30.13
8x8	40.65^{a} (1.67)	12.72^{a} (1.22)	0.88^{a} (0.30)	13.50	21.42	12.47
10x10	0	0	0	0	0	0
12x12	0	0	0	0	0	0

Values in the parenthesis are $\log_{10}(x+1)$ retransformed values of cpm
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).

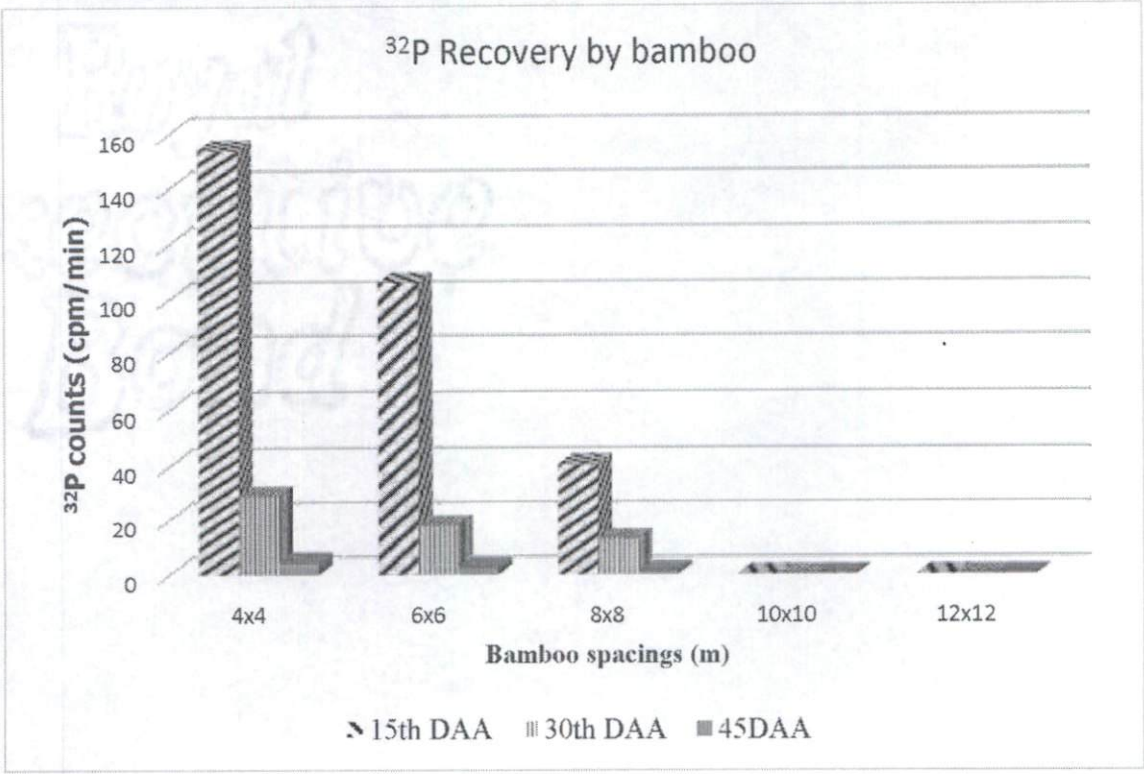


Fig. 22 Recovery of ^{32}P (cpm g^{-1}/min) by 7 year old bamboo (*Dendrocalamus strictus*) under varying spacings

4.7 Logarithmic spiral trenching for bamboo root distribution

The spiral nature of trench enables a large portion of the root system to be physically examined with minimal damage to the standing bamboo. For the study, the trench was dug to a depth of 60 cm and 60 cm breadth. Quadrats of 60 cm x 50 cm were placed at 2 m interval upto 9 m away from the base of the clump. The quadrats were sub-divided into 10 cm depth intervals. The roots were classified into <2.5 mm and >2.5 mm diameter classes. Severed bamboo roots on the internal and external trench walls were manually counted. The root counts were then converted into rooting intensity (number of roots per m^2).

The detailed information on rooting intensity of <2.5 mm size diameter class roots at varying distances along the spiral trench are presented in the table 19 and fig. 23. The data depict that, as the distance from bamboo clump increased the rooting intensity steadily decreased. As the spacings of bamboo increased the lateral spread of bamboo roots (<2.5 mm) increased. For instance, at 4x4 and 6x6 m spacing, the roots were not observed beyond 4.45 m from the bamboo, whereas 12x12 m spacing under same lateral distance recorded total of 28.99 roots/m^2 at all depths. In general with increasing soil depth, the rooting intensity (<2.5 mm) significantly decreased. Under closest spacing (4x4 m) at 0-10 cm and 10-20 cm depth recorded 151.66 and 37.66 roots m^{-2} while at 40-50 and 50-60 cm depth, the roots were decreased to 9 and 10 roots m^{-2} (0.75 m away). Widest spacing (12x12 m) of bamboo recorded 62.66 and 121 roots m^{-2} at 0-10 and 10-20 cm depth which was decreased to 28 and 6.66 roots m^{-2} when the depth increased to beyond 40 cm.

The spacings of bamboo significantly affected the size of the roots. The <2.5 mm diameter size class roots are significantly higher than > 2.5 mm size class under all the spacings of bamboo. Under 6x6 m spacing total roots of smaller diameter class roots (<2.5 mm) at 0-10 cm depth were 133 m^{-2} while in case of larger size class (>2.5 mm) it was 22 roots/m^2 (Table 20 and Fig. 24). Under close spacings (4x4 and 6x6 m), the roots >2.5 mm size class increased upto 20 cm soil

Table 19. Rooting intensity (m^{-2}) of <2.5 mm roots at different depth and lateral distances as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	**Soil depth (cm)**	Lateral distance (m) from the clump				
		0.75	**2.75**	**4.45**	**6.75**	**8.75**
4x4	0-10	151.66^{d}	100.66^{d}	78^{e}	--	--
	10--20	37.66^{c}	36.33^{c}	13^{c}	--	--
	20-30	23.66^{b}	14.66^{b}	20.66^{d}	--	--
	30-40	15.67^{a}	8.66^{a}	9.33^{b}	--	--
	40-50	9^{a}	5^{a}	5.33^{a}	--	--
	50-60	10^{a}	4^{a}	4^{a}	--	--
6x6	0-10	133.66^{d}	116^{e}	97^{d}	--	--
	10--20	38.33^{c}	43^{d}	32.33^{c}	--	--
	20-30	18.67^{b}	33^{c}	23.66^{b}	--	--
	30-40	18.33^{b}	21.33^{b}	15.33^{a}	--	--
	40-50	6.33^{a}	5.33^{a}	14^{a}	--	--
	50-60	5^{a}	4.66^{a}	18.33^{ab}	--	--
8x8	0-10	119^{d}	76^{e}	33.33^{c}	--	--
	10--20	47.66^{c}	32.66^{d}	55^{d}	--	--
	20-30	23.66^{b}	21^{c}	13.33^{b}	5.66^{a}	2.66^{a}
	30-40	45.33^{c}	15.33^{bc}	11^{ab}	10.33^{b}	7^{bc}
	40-50	20.66^{b}	11^{ab}	10^{ab}	8^{ab}	7.33^{c}
	50-60	12^{a}	7.33^{a}	7.33^{a}	6.66^{a}	6^{b}
10x10	0-10	95.33^{e}	87^{d}	25.66^{c}	--	--
	10--20	72^{d}	54.66^{c}	49.66^{d}	--	--
	20-30	30.33^{c}	32^{b}	33^{c}	--	--
	30-40	18.33^{b}	14.66^{a}	12.66^{b}	2.66^{a}	1.33^{a}
	40-50	10.33^{a}	12^{a}	10.33^{ab}	7.66^{b}	3.66^{b}
	50-60	12^{ab}	9.33^{a}	4.33^{a}	8^{b}	1.66^{a}
12x12	0-10	62.66^{e}	65^{d}	21^{bc}	--	--
	10--20	121^{f}	109.33^{f}	23^{bc}	--	--
	20-30	46.66^{d}	89.66^{e}	24.33^{bc}	--	--
	30-40	35.67^{c}	47.33^{c}	26.66^{c}	11.33^{a}	9^{a}
	40-50	28^{b}	33.33^{b}	18.33^{b}	12.33^{a}	10.33^{b}
	50-60	6.66^{a}	5.33^{a}	5^{a}	13.33^{a}	9.66^{ab}

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

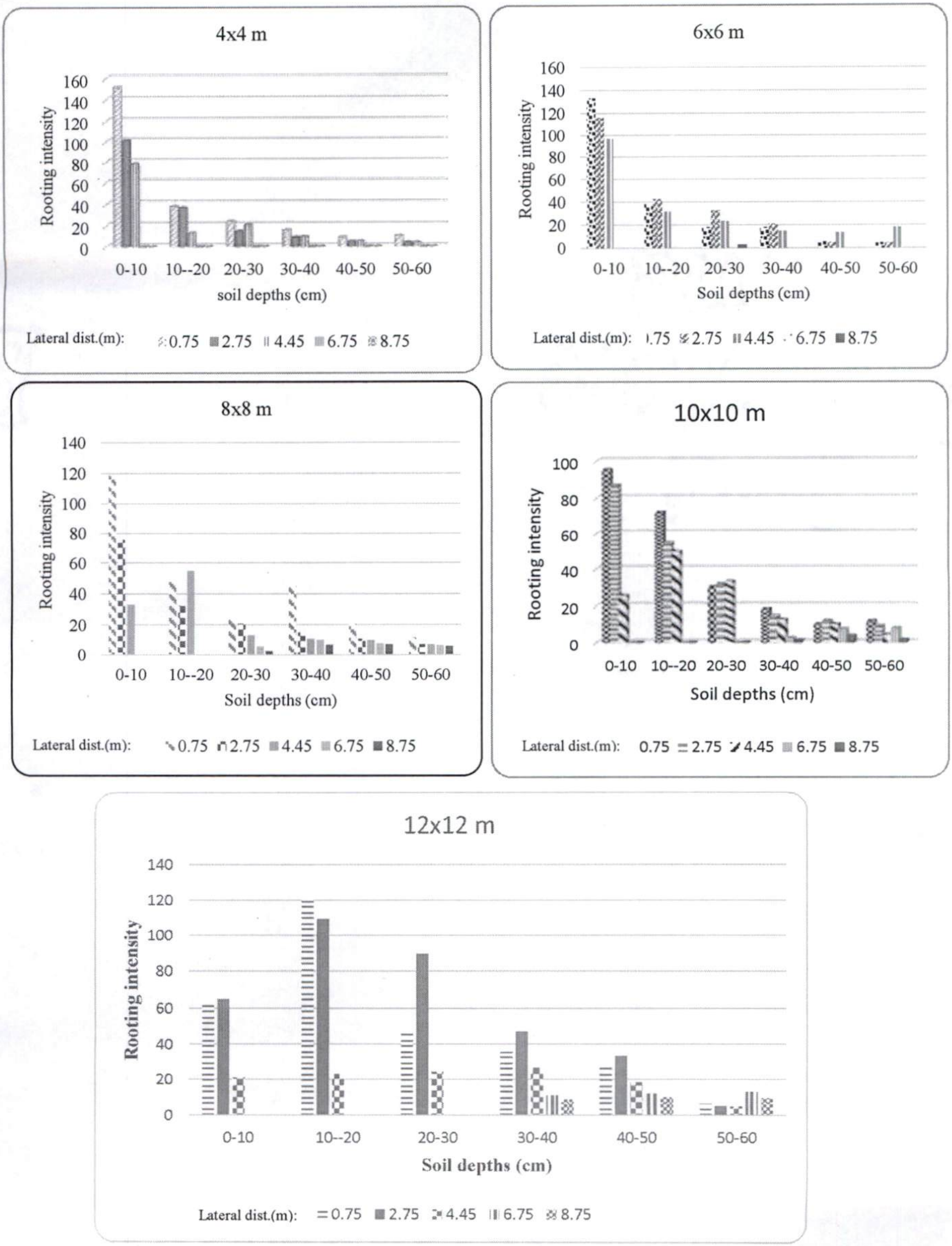


Fig. 23 Rooting intensity (m^{-2}) of <2.5 mm roots at different depth and lateral distances as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Table 20. Rooting intensity (m^{-2}) of >2.5 mm roots at different depth and lateral distances as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)		Lateral distance (m) from the clump				
	Soil depth (cm)	**0.75**	**2.75**	**4.45**	**6.75**	**8.75**
4x4	**0-10**	20.66^{bc}	20^{b}	18^{c}	--	--
	10--20	37.66^{d}	29.66^{c}	12.33^{a}	--	--
	20-30	28.33^{c}	19^{c}	24.33^{d}	--	--
	30-40	22.66^{c}	15^{ab}	16.66^{bc}	--	--
	40-50	17.33^{b}	16.66^{ab}	13^{ab}	--	--
	50-60	12.66^{a}	12.66^{a}	12^{a}	--	--
6x6	**0-10**	22^{bc}	20.66^{bc}	17.33^{ab}	--	--
	10--20	52.66^{d}	43^{e}	33^{c}	--	--
	20-30	24.33^{c}	24.66^{cd}	15.33^{ab}	--	--
	30-40	18.67^{b}	27^{d}	14.33^{ab}	18.33^{c}	1.67^{a}
	40-50	2^{a}	18.33^{b}	13.33^{a}	8^{a}	3.66^{c}
	50-60	5.33^{a}	6.33^{a}	18.33^{b}	13.66^{b}	2.66^{b}
8x8	**0-10**	62.33^{d}	42.33^{e}	3^{a}	--	--
	10--20	58^{d}	35.66^{d}	26.33^{d}	--	--
	20-30	46.66^{c}	24.33^{bc}	18.66^{c}	--	--
	30-40	37^{b}	19.66^{b}	12.66^{b}	18.33^{c}	1.66^{a}
	40-50	32.66^{b}	29^{c}	19.66^{c}	8^{a}	3.66^{c}
	50-60	15^{a}	12.33^{a}	12^{b}	13.66^{b}	2.66^{b}
10x10	**0-10**	107.33^{d}	122^{e}	81^{f}	--	--
	10--20	76.33^{c}	80.66^{d}	52.33^{d}	--	--
	20-30	19^{b}	75.33^{d}	60.66^{e}	10.33^{b}	7^{ab}
	30-40	20^{b}	58^{c}	24.67^{b}	8^{ab}	8.33^{b}
	40-50	13.66^{ab}	30.33^{b}	31.66^{c}	7.66^{a}	6^{a}
	50-60	6^{a}	18.67^{a}	12^{a}	8.66^{ab}	6.33^{a}
12x12	**0-10**	39^{c}	62.66^{d}	50.33^{d}	--	--
	10--20	38.33^{c}	45.33^{c}	15.33^{b}	--	--
	20-30	55.67^{d}	49.33^{c}	29^{c}	--	--
	30-40	21.66^{b}	27.33^{b}	16.33^{b}	15^{c}	7^{b}
	40-50	27.33^{b}	23.33^{b}	11.66^{ab}	11.33^{b}	5.66^{a}
	50-60	11.67^{a}	13.33^{a}	7.33^{a}	7^{a}	8^{b}

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

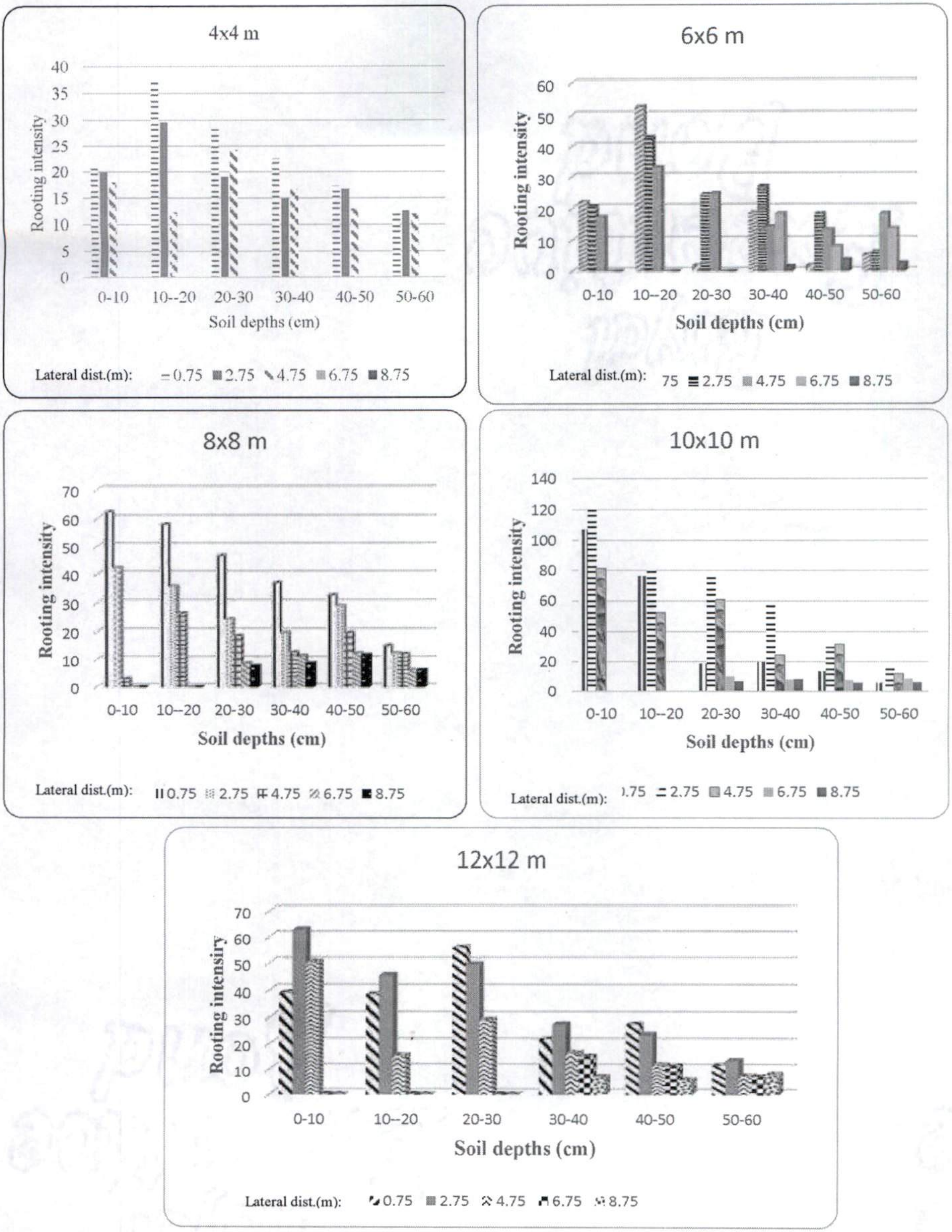


Fig. 24 Rooting intensity (m^{-2}) of >2.5 mm roots at different depth and lateral distances as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Table 21. Total rooting intensity (m^{-2}) of <2.5 + >2.5 mm roots at different depth and lateral distances as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Lateral distance (m) from the clump					
	Soil depth (cm)	**0.75**	**2.75**	**4.45**	**6.75**	**8.75**
4x4	0-10	172.33^{e}	120.66^{d}	96^{d}	--	--
	10--20	75.33^{d}	66^{c}	25.33^{b}	--	--
	20-30	52^{c}	33.66^{b}	45^{c}	--	--
	30-40	38.33^{b}	23.66^{a}	26^{b}	--	--
	40-50	26.33^{a}	21.66^{a}	18.33^{a}	--	--
	50-60	22.66^{a}	16.66^{a}	16^{a}	--	--
6x6	0-10	155.66^{d}	136.66^{f}	114.33^{e}	--	--
	10--20	91^{c}	86^{e}	65.33^{d}	--	--
	20-30	43^{b}	57.66^{d}	39^{c}	--	--
	30-40	37^{b}	48.33^{c}	29.66^{ab}	18.33^{c}	1.66^{a}
	40-50	8.33^{a}	23.66^{b}	27.33^{a}	8^{a}	3.66^{c}
	50-60	10.33^{a}	11^{a}	36.66^{bc}	13.66^{b}	2.66^{b}
8x8	0-10	181.33^{e}	118.33^{e}	36.33^{c}	--	--
	10--20	105.66^{d}	68.33^{d}	81.33^{d}	--	--
	20-30	70.33^{b}	45.33^{c}	32^{bc}	14.33^{a}	10.33^{a}
	30-40	82.33^{c}	35^{b}	23.66^{a}	21.66^{b}	15.66^{b}
	40-50	53.33^{b}	40^{bc}	29.66^{b}	20.33^{b}	19^{c}
	50-60	27^{a}	19.66^{a}	19.33^{a}	13^{a}	12.33^{a}
10x10	0-10	202.66^{e}	209^{f}	106.66^{d}	--	--
	10--20	148.33^{d}	135.33^{e}	102^{d}	--	--
	20-30	49.33^{c}	107.33^{d}	93.66^{c}	10.33^{a}	7^{a}
	30-40	38.33^{b}	72.66^{c}	37.33^{b}	10.66^{a}	9.67^{b}
	40-50	24^{a}	42.33^{b}	42^{b}	15.33^{b}	9.67^{b}
	50-60	18^{a}	28^{a}	16.33^{a}	16.66^{b}	8^{ab}
12x12	0-10	101.66^{c}	127.66^{d}	71.33^{e}	--	--
	10--20	159.33^{d}	154.67^{f}	38.33^{bc}	--	--
	20-30	102.33^{c}	139^{e}	53.33^{d}	--	--
	30-40	57.33^{b}	74.66^{c}	43^{c}	26.33^{b}	16^{a}
	40-50	55.33^{b}	56.66^{b}	30^{b}	23.66^{b}	16^{a}
	50-60	18.33^{a}	18.66^{a}	12.33^{a}	20.33^{a}	17.66^{a}

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

Table 22. Total rooting intensity (m^{-2}) of <2.5+>2.5 mm roots (per cent) at different depth and lateral distances as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

		Lateral distance (m) from the clump				
Spacings (m)	**Soil depth (cm)**	**0.75**	**2.75**	**4.45**	**6.75**	**8.75**
4x4	0-10	44.53	42.74	42.35	--	--
	10--20	19.47	23.38	11.18	--	--
	20-30	13.44	11.92	19.85	--	--
	30-40	9.91	8.38	11.47	--	--
	40-50	6.80	7.67	8.09	--	--
	50-60	5.86	5.90	7.06	--	--
6x6	0-10	45.08	37.62	36.61	--	--
	10--20	26.35	23.67	20.92	--	--
	20-30	12.45	15.87	12.49	--	--
	30-40	10.71	13.30	9.50	45.83	20.83
	40-50	2.41	6.51	8.75	20.00	45.83
	50-60	2.99	3.03	11.74	34.17	33.33
8x8	0-10	34.87	36.23	16.34	--	--
	10--20	20.32	20.92	36.58	--	--
	20-30	13.53	13.88	14.39	20.67	18.02
	30-40	15.83	10.71	10.64	31.25	27.33
	40-50	10.26	12.25	13.34	29.33	33.14
	50-60	5.19	6.02	8.70	18.75	21.51
10x10	0-10	42.16	35.15	26.80	--	--
	10--20	30.86	22.76	25.63	--	--
	20-30	10.26	18.05	23.53	19.50	20.39
	30-40	7.98	12.22	9.38	20.13	28.16
	40-50	4.99	7.12	10.55	28.93	28.16
	50-60	3.74	4.71	4.10	31.45	23.30
12x12	0-10	20.57	22.35	28.73	--	--
	10--20	32.23	27.07	15.44	--	--
	20-30	20.70	24.33	21.48	--	--
	30-40	11.60	13.07	17.32	37.44	32.22
	40-50	11.19	9.92	12.08	33.65	32.22
	50-60	3.71	3.27	4.97	28.91	35.58

Table 23. Total rooting intensity (m^{-2}) up to 60 cm depth as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Lateral distance from the clump				
	0.75	**2.75**	**4.45**	**6.75**	**8.75**
4x4	152(20.58)^{a}	125.66(15.68)^{a}	108.33(18.50)^{a}	--	--
6x6	132.66(18.07)^{a}	150.66(27.95)^{b}	121.33(33.57)^{ab}	32.66(8.14)^{a}	2.33(0.02)^{a}
8x8	324.66(15.77)^{d}	211.33(18.62)^{c}	130.66(20.23)^{b}	45(6.92)^{b}	40.66(3.21)^{d}
10x10	242.33(17.03)^{c}	385(34.35)^{d}	262.33(26.21)^{c}	34.66(4.23)^{a}	27.66(4.23)^{c}
12x12	193.66(12.05)^{b}	221.33(25.68)^{c}	130(27.93)^{b}	33.33(8.23)^{a}	20.66(3.26)^{b}
Per cent					
Spacings (m)	**0.75**	**2.75**	**4.45**	**6.75**	**8.75**
4x4	39.38	32.56	28.07	--	--
6x6	30.17	34.27	27.60	7.43	0.53
8x8	43.15	28.09	17.37	5.98	5.41
10x10	25.46	40.44	27.56	3.64	2.91
12x12	32.33	36.95	21.70	5.56	3.45

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

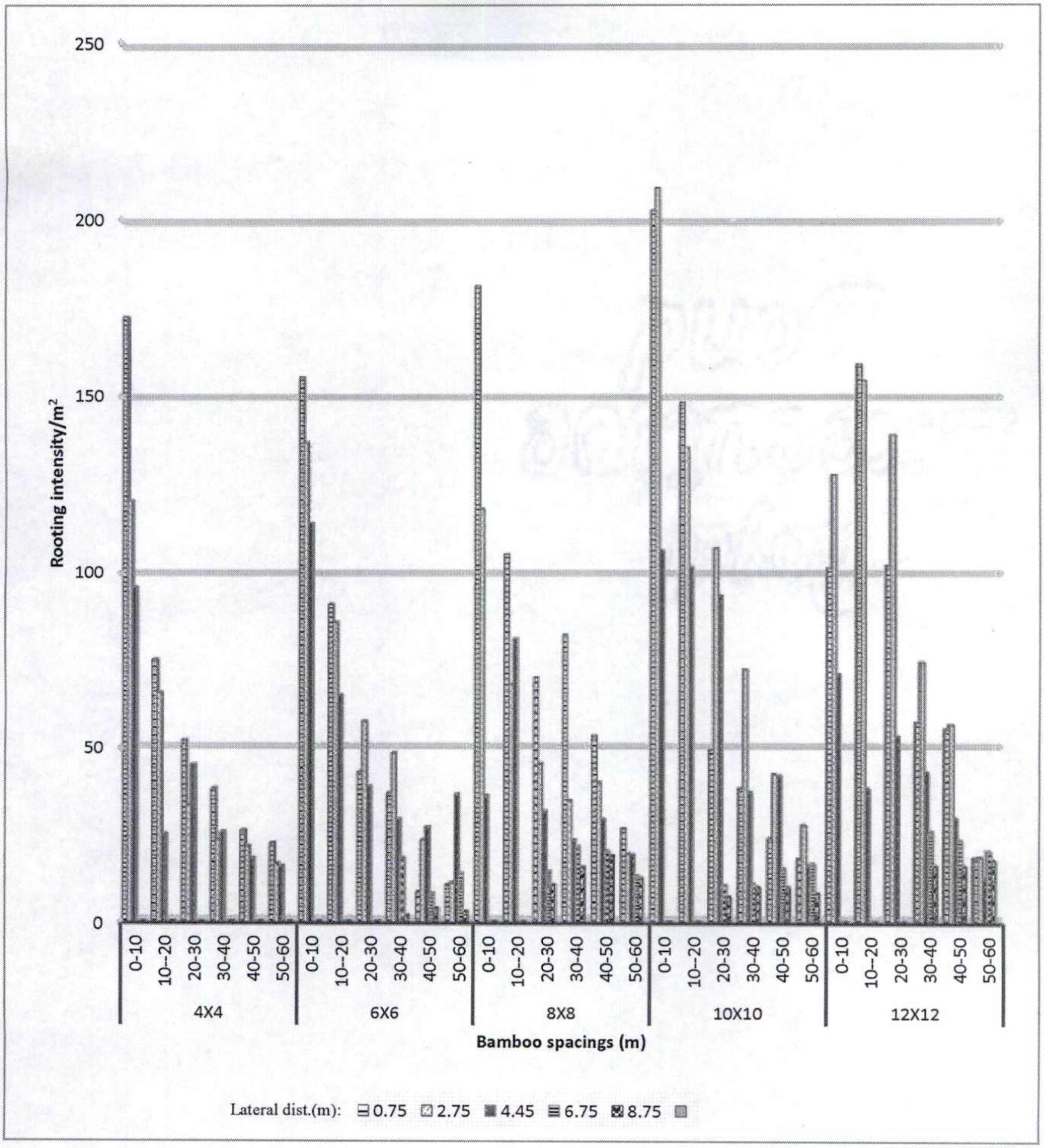


Fig. 25 Rooting intensity (m^{-2}) of <2.5 + >2.5 mm roots at different lateral distances as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

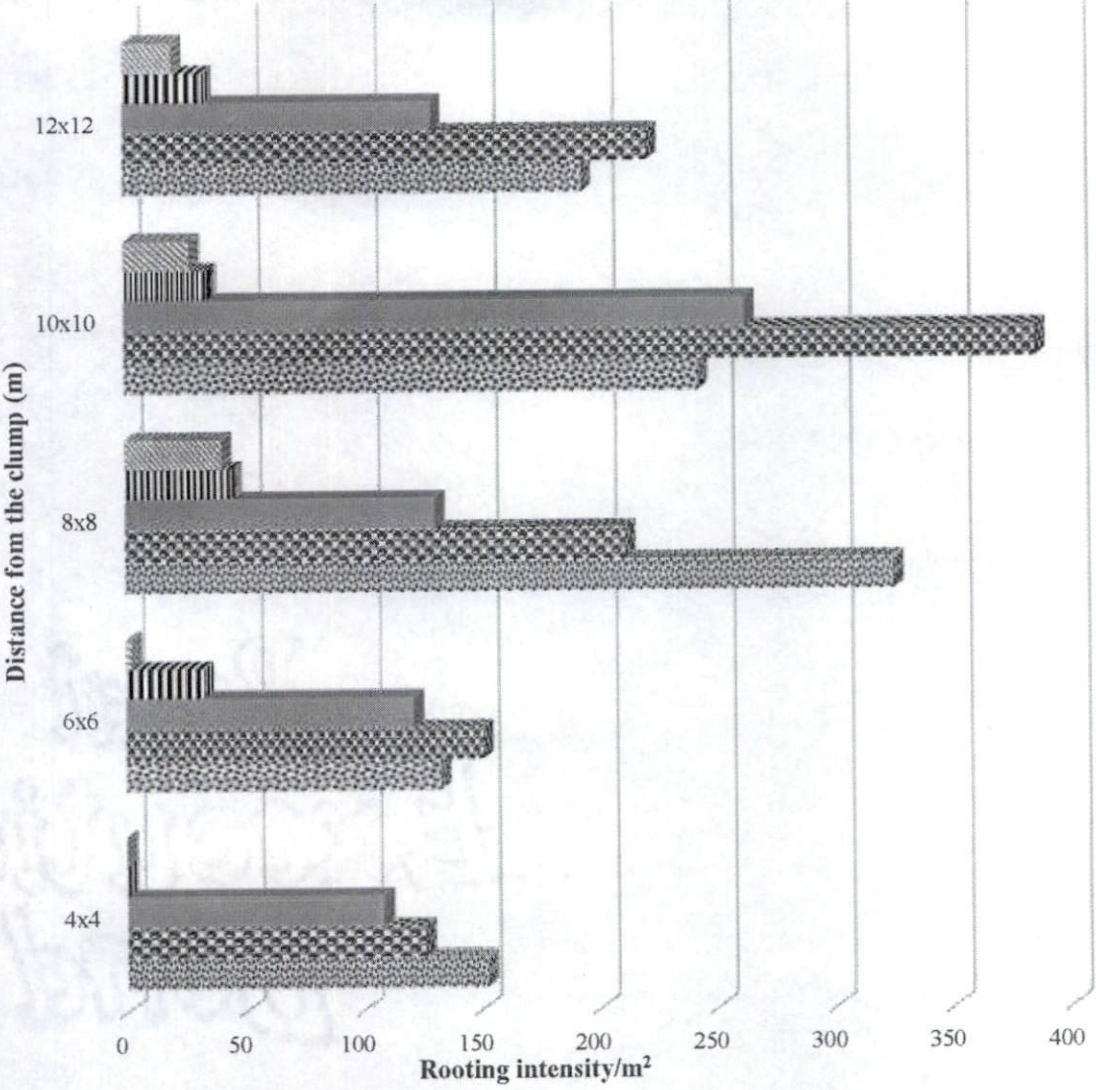
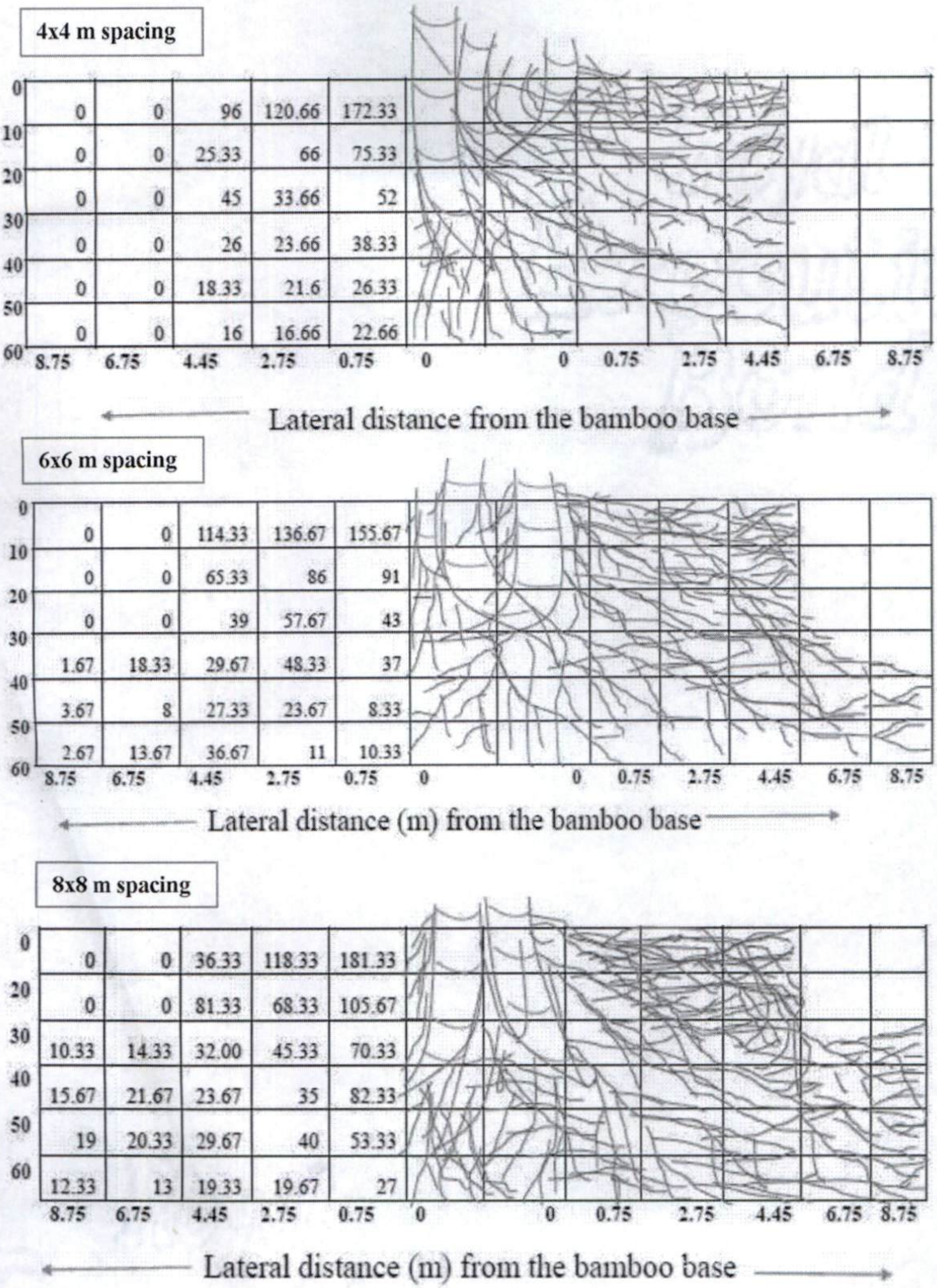


Fig. 26 Total rooting intensity (m^{-2}) upto 60 cm depth as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)



4x4 m spacing

0	0	96	120.66	172.33
0	0	25.33	66	75.33
0	0	45	33.66	52
0	0	26	23.66	38.33
0	0	18.33	21.6	26.33
0	0	16	16.66	22.66

6x6 m spacing

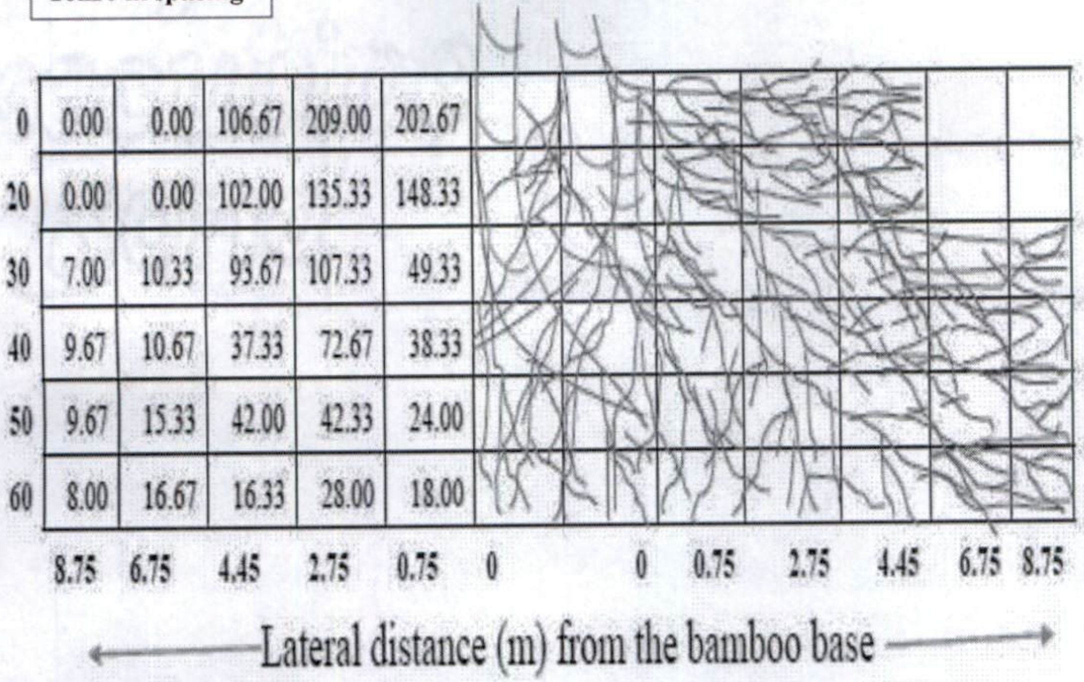
0	0	114.33	136.67	155.67
0	0	65.33	86	91
0	0	39	57.67	43
1.67	18.33	29.67	48.33	37
3.67	8	27.33	23.67	8.33
2.67	13.67	36.67	11	10.33

8x8 m spacing

0	0	36.33	118.33	181.33
0	0	81.33	68.33	105.67
10.33	14.33	32.00	45.33	70.33
15.67	21.67	23.67	35	82.33
19	20.33	29.67	40	53.33
12.33	13	19.33	19.67	27

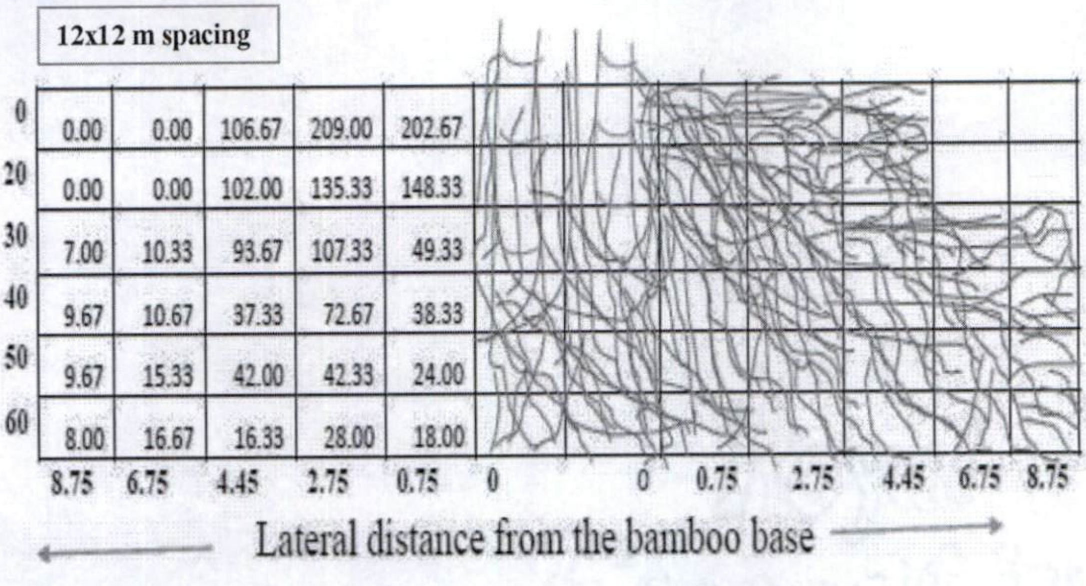
Fig. 27 Schematic presentation of the roots architecture pattern of clumps from 4x4, 6x6 and 8x8 spacings of bamboo.

10x10 m spacing



	8.75	6.75	4.45	2.75	0.75
0	0.00	0.00	106.67	209.00	202.67
20	0.00	0.00	102.00	135.33	148.33
30	7.00	10.33	93.67	107.33	49.33
40	9.67	10.67	37.33	72.67	38.33
50	9.67	15.33	42.00	42.33	24.00
60	8.00	16.67	16.33	28.00	18.00

12x12 m spacing



	8.75	6.75	4.45	2.75	0.75
0	0.00	0.00	106.67	209.00	202.67
20	0.00	0.00	102.00	135.33	148.33
30	7.00	10.33	93.67	107.33	49.33
40	9.67	10.67	37.33	72.67	38.33
50	9.67	15.33	42.00	42.33	24.00
60	8.00	16.67	16.33	28.00	18.00

Fig. 28 Schematic presentation of the roots architecture pattern of clumps from 10x10 and 12x12 m spacings of bamboo.

depth thereafter decreased steeply. While under intermediate (8x8 m) and wider (10x10 m) spacings the rooting intensity decreased with increasing depth.

The sum of <2.5 and >2.5 mm size diameter class roots were highest (202 roots m^{-2}) under 10x10 m followed by 8x8 m (181 roots m^{-2}) at surface layer (0-10 cm), which decreased with increasing depth (Table 21 and Fig. 25). The close spacings (4x4 and 6x6 m) recorded lesser lateral distribution of roots as compared to wide spacings (10x10 and 12x12 m). As the depth and lateral distance increased the rooting intensity decreased. For instance under 4x4 m spacing 0.75, 2.75 and 4.45 m lateral distance recorded 172.33, 120.66 and 96 roots m^{-2} and under same spacing with increasing depth from 0-10 to 50-60 cm the rooting intensity decreased from 172.33 to 22.66 roots m^{-2} respectively. At 4x4 m and 6x6 m spacings recorded roots upto 4.45 m away from the clump, whereas 10x10 and 12x12 m spacings roots were found beyond 4.45 m distance and recorded upto 8.75 m.

The maximum rooting intensity was within 0-30 cm soil depth and upto 4.45 m lateral distance under all the spacings. However, illustration from table 22 and fig. 26 reveal that higher intensity of vertical distribution of roots were found within 30 cm depth and lateral spread of roots was within 4.45 m distance. For example, 6x6 m spacing at 0.75 lateral distance recorded 45 and 26 per cent of roots at 0-10 and 10-20 cm soil depth while at same depth at 4.45 m away from clump 36 and 20 per cent roots were observed. Under all the spacings of bamboo almost 70 per cent of roots were found to be distributed laterally within 4.45 m distance from the clump (Table 22 and Fig. 26). Due to wide spacings (10x10 and 12x12 m) of bamboo the lateral distribution of roots were observed beyond 8.75 m. For instance, under 12x12 m spacing at 8.75 m away from the clump and beyond 30 cm soil depth recorded almost 30 per cent of roots. With increasing spacings of bamboo, the horizontal and vertical spread of roots significantly increased. The bamboo roots were found upto 8.75 m laterally from the base of clump in all the spacings of bamboo except 4x4 m. The total rooting intensity (0-60 cm depth) in widest spacing was 193.66 roots/m^2 at 0.75 m distance, which decreased to 20.66 root/m^2 at 8.75 m lateral distance from the clump (Table 23 and Fig. 26). The bamboo roots were not recorded at surface layer (0-20 cm) in all the spacings of bamboo; as the lateral distance increased beyond 4.45 m distance the lateral roots were counted at greater depth (beyond 20 cm) in all the spacings of bamboo except 4x4 m. Therefore, results clearly reveal that the varying spacings of bamboo have significantly affected the root distribution both vertically and laterally.

4.8 Root activity study in bamboo using radio isotope

The experiment was laid in a factorial RBD design with lateral distances and soil depth as factors. The PVC access tubes inserted into the holes at 3 lateral distances *viz.* 50 cm, 1.00 m and 2.00 m from the bamboo and at 2 depths *viz.* 50 cm and 1 m. An amount of 2.11 mCi of isotope solution was applied to eight tubes around each clump. The leaf assay of treated bamboo clumps was made at 15th and 30th day after application (DAA) of isotope. The results are given in table 24 and 25. The ^{32}P activity were expressed as counts per minute (cpm per gram leaf dry weight). The cpm/min values retransformed to $\log_{10}$ (x+1) are given in the parenthesis.

The extent of ^{32}P recovery from the bamboo leaves at each lateral distance and soil depth of ^{32}P placement indicates the presence of active roots in the position. The data on ^{32}P absorption by bamboo as a function of soil depth and lateral distance are shown in the table 24. In general, with increasing lateral distance and depth of placement, the absorption of ^{32}P by bamboo decreased significantly. For instance, under closest spacing (4x4m), when the tracer was applied at 50 cm depth and 50 cm lateral distance, the ^{32}P absorption by bamboo was significantly higher (809 cpm) which gradually decreased beyond 1 m (448 cpm) and 2 m lateral distance (196 cpm). At this depth (50 cm) as high as 55 per cent absorption of ^{32}P by bamboo was observed (Table 25 and Fig. 29). When placed at 1 m lateral distance the absorption decreased upto 30 per cent. Further decline was observed by placing 1 m depth and 2 m away from the bamboo clump (13 per cent). The absorption of ^{32}P by bamboo was comparatively higher at 50 cm depth of placement as compared to 1 m depth. For example, under widest spacing at 50 cm depth x 50 cm distance

737 counts recorded (log cpm 2.86), while with increase of depth to 1 m and 50 cm lateral distance 354 counts were recorded (log cpm 2.55). Under intermediate spacing of bamboo having 50 cm lateral distance and 1 m depth of placement, the ^{32}P absorption was 419 cpm (47 per cent) which decreased to 414 cpm (46 per cent) and 53 cpm (6 per cent) when the distance increased to 1 m and 2 m lateral distance from the bamboo clumps respectively. The data also depict that, trend of gradually increase in ^{32}P absorption with decreasing spacings between the bamboo was observed upto 50 cm depth and 50 cm lateral distance. On the other hand while placing at 50 cm depth and 1 m and 2 m lateral distances, the absorption gradually increased with increasing spacings between the bamboo. The absorption of ^{32}P in 50 cm depth x 50 cm lateral distance under closest spacing recorded 301 cpm, while at 1 m x 50 cm recorded significantly lesser counts (184 cpm). The widest spacing of 12x12 m was having significantly more number of active roots at 50 cm depth and 2 m lateral distance compared to 1 m depth and 2 m lateral distance.

At 30th day after application of tracer, general trend of decrease in ^{32}P absorption with increasing depths and lateral distances was observed. With increasing lateral distances upto 1 m and 2 m, the absorption decreased significantly. When the tracer was placed at 1 m depth, the tracer absorption was highest in shortest lateral distance (50 cm) under closest spacing (184 cpm) and this decreased with increase of lateral distances and also with increase in spacings between the bamboo. Under closest spacing, almost 56 per cent absorption of ^{32}P at 1 m depth and 50 cm lateral distance was observed as compared to 1 m (38 per cent) and 2 m (4 per cent) lateral distance under the same depth (Fig. 30 to 32). The higher absorption in closest spacing (4x4 m) of bamboo revealed the presence of higher number of functional roots confined to 50 cm depth and 50 cm lateral distance. The distance beyond 1 m depth and 1 and 2 m lateral distances, the absorption of ^{32}P was increased with increasing spacings of bamboo. The higher ^{32}P absorption in greater depth and distances was because of lesser root competition between the bamboo under wide spacings.

Table 24. Root activity patterns by application of ^{32}P at varying depths and lateral distances on 7 year old bamboo (*Dendrocalamus strictus*) grown at different spacings.

50 cm depth						
Spacings (m)	**15th DAA (counts/min)**			**30th DAA (counts/min)**		
	50x50[*]	**50x1[#]**	**50x2[$]**	**50x50**	**50x1**	**50x2**
4x4	809^{dC} (2.90)	448^{aB} (2.65)	196^{aA} (2.29)	301^{dC} (2.48)	167^{aB} (2.23)	73^{aA} (1.87)
6x6	791^{cC} (2.89)	526^{bB} (2.72)	221^{bA} (2.34)	295^{cC} (2.47)	196^{bB} (2.30)	84^{bA} (1.93)
8x8	781^{cC} (2.89)	656.33^{dB} (2.81)	223^{bA} (2.35)	291^{cC} (2.47)	227^{cB} (2.39)	83^{bA} (1.93)
10x10	756^{bC} (2.88)	624^{cB} (2.79)	268^{cA} (2.42)	282^{bC} (2.45)	232^{cB} (2.37)	100^{cA} (2.01)
12x12	737^{aC} (2.86)	609^{cB} (2.78)	311^{dA} (2.49)	275^{aC} (2.44)	244^{dB} (2.36)	117^{dA} (2.07)
1 m depth						
Spacings (m)	**15th DAA (counts/min)**			**30th DAA (counts/min)**		
	1x50[**]	**1x1[##]**	**1x2[$$]**	**1x50**	**1x1**	**1x2**
4x4	495^{eC} (2.69)	361^{bB} (2.55)	39^{aA} (1.60)	184^{eC} (2.27)	124^{aB} (2.10)	15^{aA} (1.21)
6x6	442^{dC} (2.64)	335^{aB} (2.52)	55^{bcA} (1.74)	164^{dC} (2.22)	134^{bB} (2.13)	21^{bA} (1.35)
8x8	419^{cB} (2.62)	414^{cB} (2.62)	53^{bA} (1.73)	155^{cB} (2.20)	153^{cB} (2.19)	21^{bA} (1.34)
10x10	380^{bB} (2.58)	434^{dC} (2.64)	65^{cdA} (1.82)	141^{bB} (2.15)	161^{dC} (2.21)	24^{bcA} (1.41)
12x12	354^{aB} (2.55)	445^{dC} (2.65)	72^{dA} (1.86)	131^{aB} (2.12)	165^{dC} (2.22)	28^{cA} (1.47)

[*] 50x50 = 50 cm depth and 50 cm lateral distances
[#] 50xl = 50 cm depth and 1 m lateral distances
[$] 50x2 = 50 cm depth and 2 m lateral distances

[**] 1x50 = 1 m depth and 50 cm lateral distances
[##] 1x1 = 1m depth and 1 m lateral distances
[$$] 1x2 = 1m depth and 2 m lateral distances

Values in the parenthesis are $\log_{10}(x+1)$ retransformed values of cpm
Means followed by same capital letter superscript in a row do not differ significantly (LSD, $P<0.05$).
Means followed by same small letter superscript in a in a column do not differ significantly (LSD, $P<0.05$)

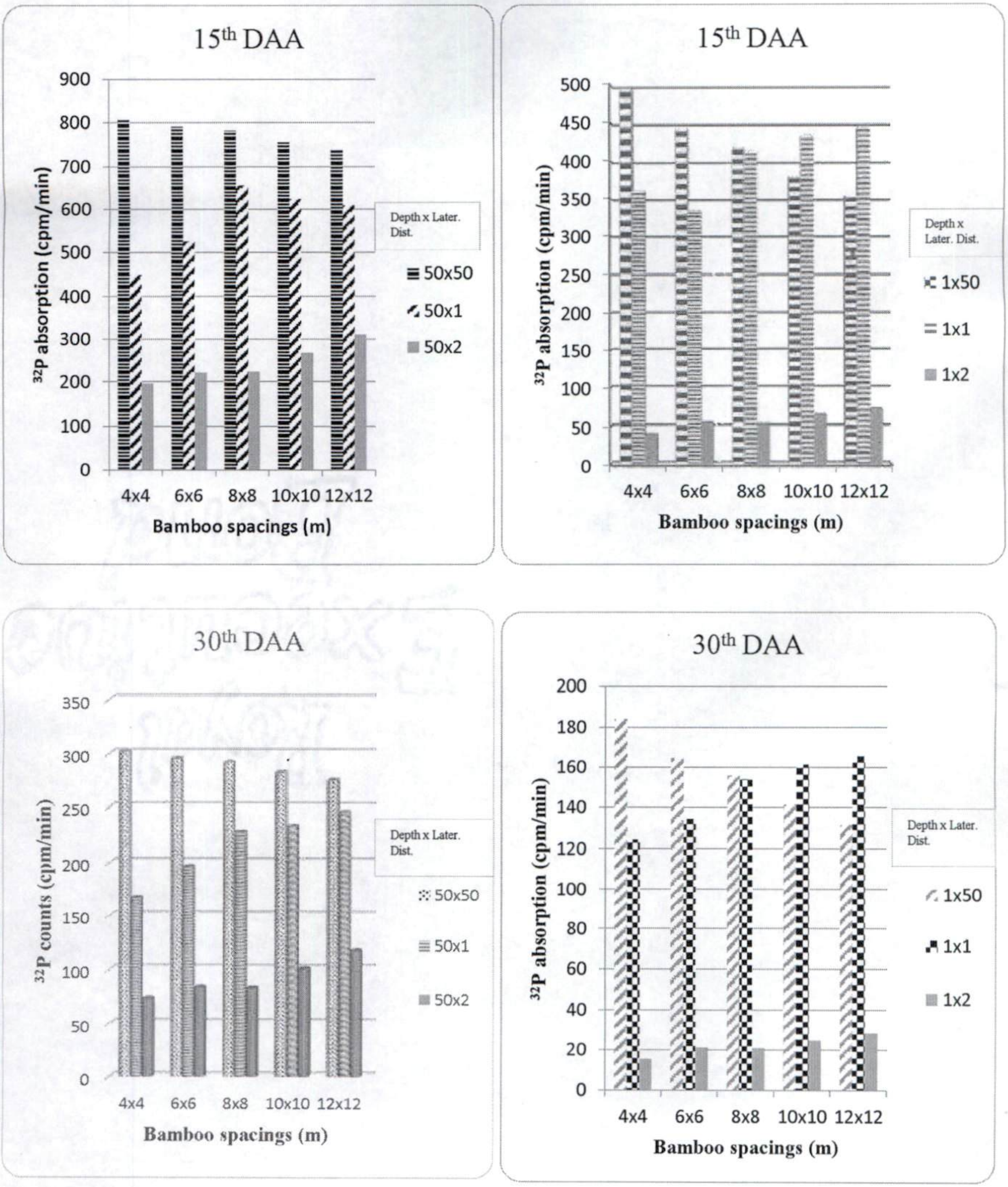


Fig. 29 Root activity patterns at varying depths and lateral distances on 15th and 30th day after application of ^{32}P in 7 year old bamboo (*Dendrocalamus strictus*) grown at varying spacings.

Table 25. Root activity patterns (percent of absorption) by application of ^{32}P at varying depths and lateral distances on 7 year old bamboo (*Dendrocalamus strictus*) grown at different spacings.

50 cm depth						
Spacings (m)	**15th DAA (counts/min)**			**30th DAA (counts/min)**		
	50x50[*]	**50x1[#]**	**50x2[$]**	**50x50**	**50x1**	**50x2**
4x4	55.64	30.86	13.50	55.58	30.83	13.59
6x6	51.41	34.19	14.41	51.29	34.10	14.61
8x8	47.04	39.50	13.46	48.42	37.75	13.83
10x10	45.88	37.86	16.26	45.83	37.81	16.36
12x12	44.45	36.75	18.80	43.17	38.44	18.39
1 m depth						
Spacings (m)	**15th DAA (counts/min)**			**30th DAA (counts/min)**		
	1x50[**]	**1x1[##]**	**1x2[$$]**	**1x50**	**1x1**	**1x2**
4x4	55.29	40.32	4.39	56.83	38.45	4.72
6x6	53.14	40.22	6.64	51.44	41.93	6.62
8x8	47.28	46.71	6.02	47.11	46.53	6.36
10x10	43.22	49.32	7.46	43.18	49.26	7.56
12x12	40.60	51.08	8.33	40.42	50.83	8.78

[*] 50x50 = 50 cm depth and 50 cm lateral distances
[#] 50x1 = 50 cm depth and 1 m lateral distances
[$] 50x2 = 50 cm depth and 2 m lateral distances

[**] 1x50 = 1m depth and 50 cm lateral distances
[##] 1x1 = 1m depth and 1 m lateral distances
[$$] 1x2 = 1m depth and 2 m lateral distances

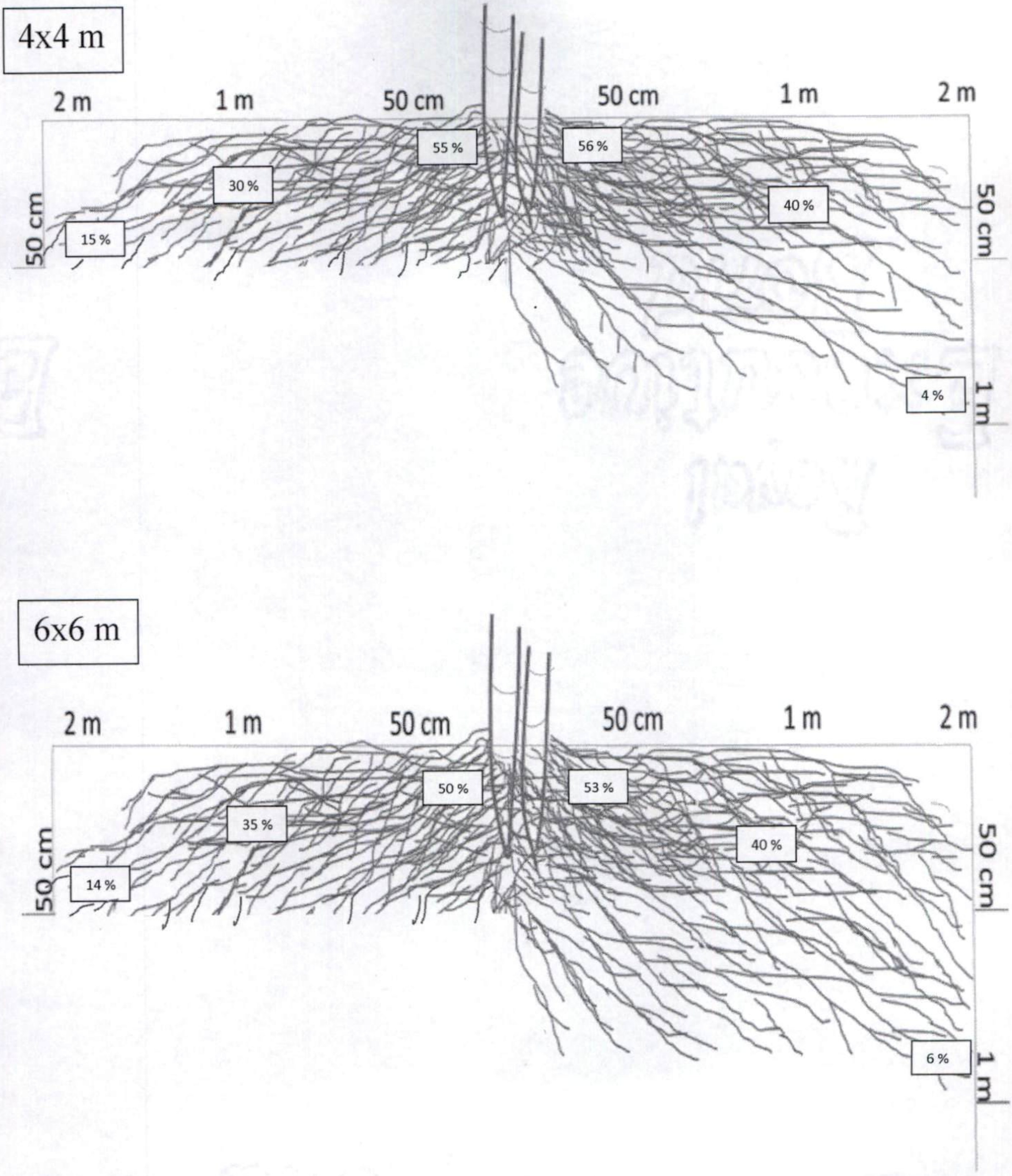


Fig. 30 Schematic presentation of physiologically active roots distributed at various distances and depths in 4x4 m and 6x6 m spacings of bamboo (*Dendrocalamus strictus*)

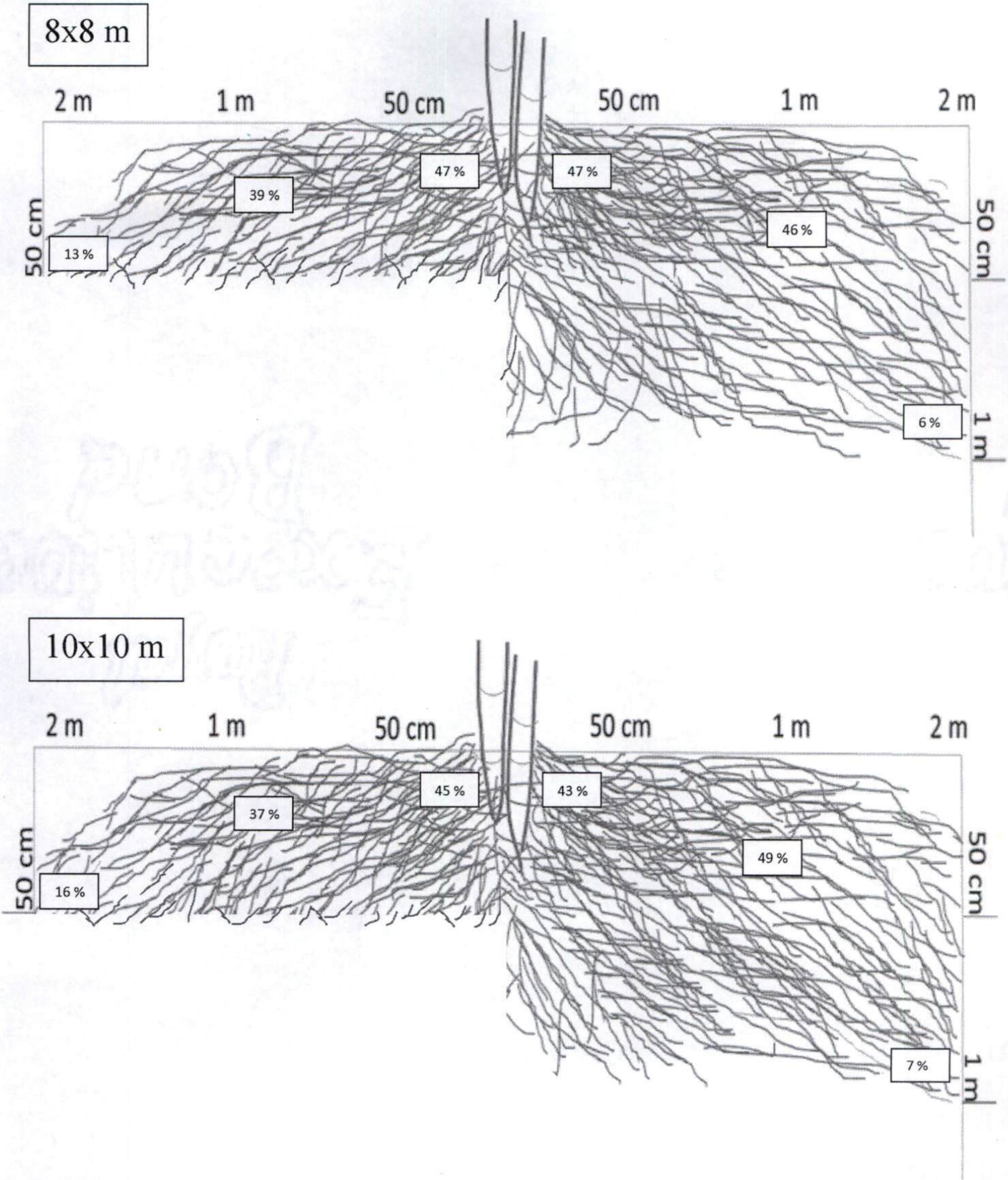


Fig. 31 Schematic presentation of physiologically active roots distributed at various distances and depths in 8x8 m and 10x10 m spacings of bamboo (*Dendrocalamus strictus*)

12x12 m

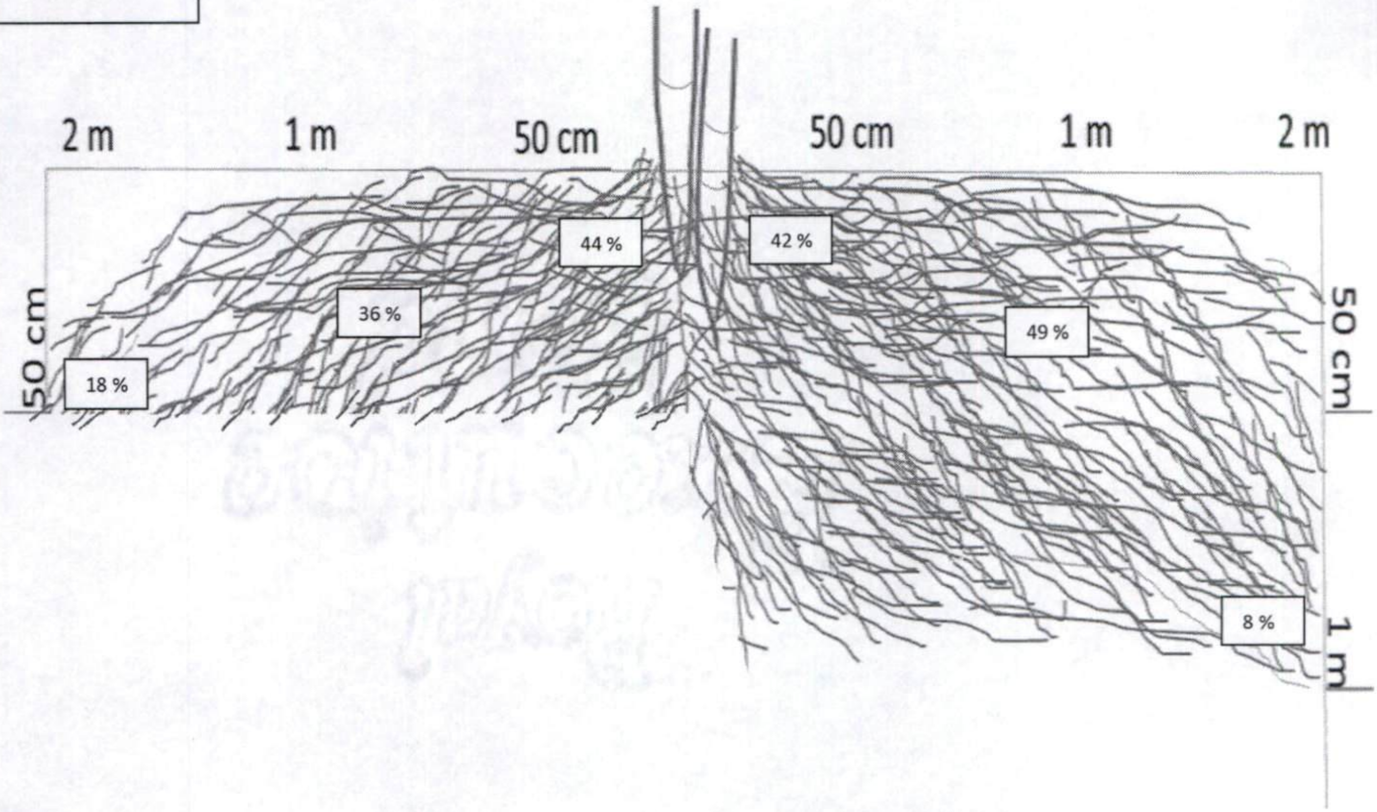


Fig. 32 Schematic presentation of physiologically active roots distributed at various distances and depths in 12x12 m spacing of bamboo (*Dendrocalamus strictus*)

4.9.1 Physico-chemical properties of soil as affected by varying spacings of bamboo

Soil samples obtained from the different spacings of (4x4 m, 6x6 m, 8x8 m, 10x10 m, 12x12 m) bamboo as well as a bambooless control plot were analysed for various attributes viz., bulk density, p^H, total N, available P and avail. K. A pit of 1 m width x 1 m depth was dug up in the center of each plot and soil was collected at four depths (0-20 cm, 20-50 cm, 50-80 cm and 100 cm). The soil samples were then subjected to physico-chemical analysis by standard procedures. The results are furnished in the tables 26 to 33.

Data presented in the table 26 reveal that, the varying spacings of bamboo significantly affected the bulk density of soil. The trend of increase in bulk density with increasing depth of soil was observed under all the spacings of bamboo. The bambooless control plot recorded higher bulk density than bamboo at varying spacings. The soil depths under varying spacings of bamboo have moderately affected the p^H of the soil. Under 4x4 m spacing of bamboo, the p^H of soil was increased with increasing soil depth except 80-100 cm.

Total Nitrogen

Perusal of data on total N presented in the table 27 and fig. 33 depict that, at surface soil (0-20 cm), the amount of total nitrogen decreased with increasing spacings of bamboo except 12x12 m. For example, closest spacing (4x4 m) was found to have maximum amount (2109.8 kg/ha) of total N which decreased with increasing spacings of bamboo and recorded lowest 1430.8 kg/ha under 10x10 m spacings of bamboo. As the depth of soil increased the total N significantly decreased in all the spacings of bamboo and open plot. Almost 56 per cent of total N was confined to surface soil (0-20 cm) under all the spacings of bamboo including bambooless control plot (Table 28 and Fig. 34). The remaining depths contributed comparatively lesser value. The total N under intermediate and widest spacings of bamboo was at par with that of bambooless control. The amount of N upto 1 m depth recorded highest (3738.42 kg/ha) under closest followed by bambooless

Table 26. **Soil bulk density and p^{H} at various depth as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)**

Spacings (m)	Depth (cm)	BD Mg/m^{3}	p^{H}
4x4	0-20	1.11(0.01)^{a}	5.7(0.1)^{a}
	20-50	1.19(0.01)^{b}	5.73(0.15)^{a}
	50-80	1.26(0.01)^{c}	6.03(0.20)^{b}
	80-100	1.36(0.02)^{d}	5.86(0.05)^{ab}
6x6	0-20	1.15(0.01)^{a}	5.8(0.10)^{a}
	20-50	1.23(0.02)^{b}	5.96(0.06)^{a}
	50-80	1.29(0.01)^{c}	6(0.10)^{a}
	80-100	1.35(0.01)^{d}	5.96(0.15)^{a}
8x8	0-20	1.24(0.01)^{a}	5.93(0.20)^{a}
	20-50	1.33(0.02)^{b}	5.96(0.11)^{a}
	50-80	1.35(0.005)^{b}	6.06(0.05)^{a}
	80-100	1.45(0.01)^{c}	6(0.1)^{a}
10x10	0-20	1.31(0.01)^{a}	6(0.1)^{a}
	20-50	1.47(0.01)^{b}	6.03(0.05)^{a}
	50-80	1.52(0.015)^{c}	6.03(0.11)^{a}
	80-100	1.57(0.01)^{d}	6(0.1)^{a}
12x12	0-20	1.46(0.01)^{a}	6.16(0.05)^{b}
	20-50	1.47(0.02)^{a}	6.03(0.15)^{ab}
	50-80	1.5(0.01)^{b}	6.03(0.05)^{ab}
	80-100	1.54(0.01)^{c}	5.93(0.05)^{a}
Control	0-20	1.52(0.01)^{a}	5.96(0.15)^{a}
	20-50	1.62(0.02)^{b}	6.16(0.05)^{a}
	50-80	1.62(0.01)^{b}	6.06(0.11)^{a}
	80-100	1.63(0.011)^{b}	6.1(0.1)^{a}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

Table 27. Soil total nitrogen (kg/ha) at varying depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depths (cm)	Total N					
	4x4	**6x6**	**8x8**	**10x10**	**12x12**	**Control**
0-20	2109.8^{a}	1986.6^{b}	1767.5^{c}	1430.8^{d}	1808.8^{c}	1829.1^{c}
20-50	996.1^{e}	675.99^{g}	966^{e}	873.6^{f}	710.5^{g}	912.1^{ef}
50-80	385.21^{hi}	379.19^{hi}	350.98^{hij}	398.09^{hi}	429.8^{h}	390.88^{hi}
80-100	247.31^{k}	278.53^{jk}	244.09^{k}	252.21^{k}	306.39^{ijk}	265.37^{jk}
Total	3738.42^{D}	3320.31^{BC}	3328.57^{BC}	2954.7^{A}	3255.49^{B}	3397.45^{C}

Values followed by same superscript in a column and row do not differ significantly (LSD, $P<0.05$)
Means followed by same capital letter superscript in a column do not differ significantly (LSD, $P<0.05$).

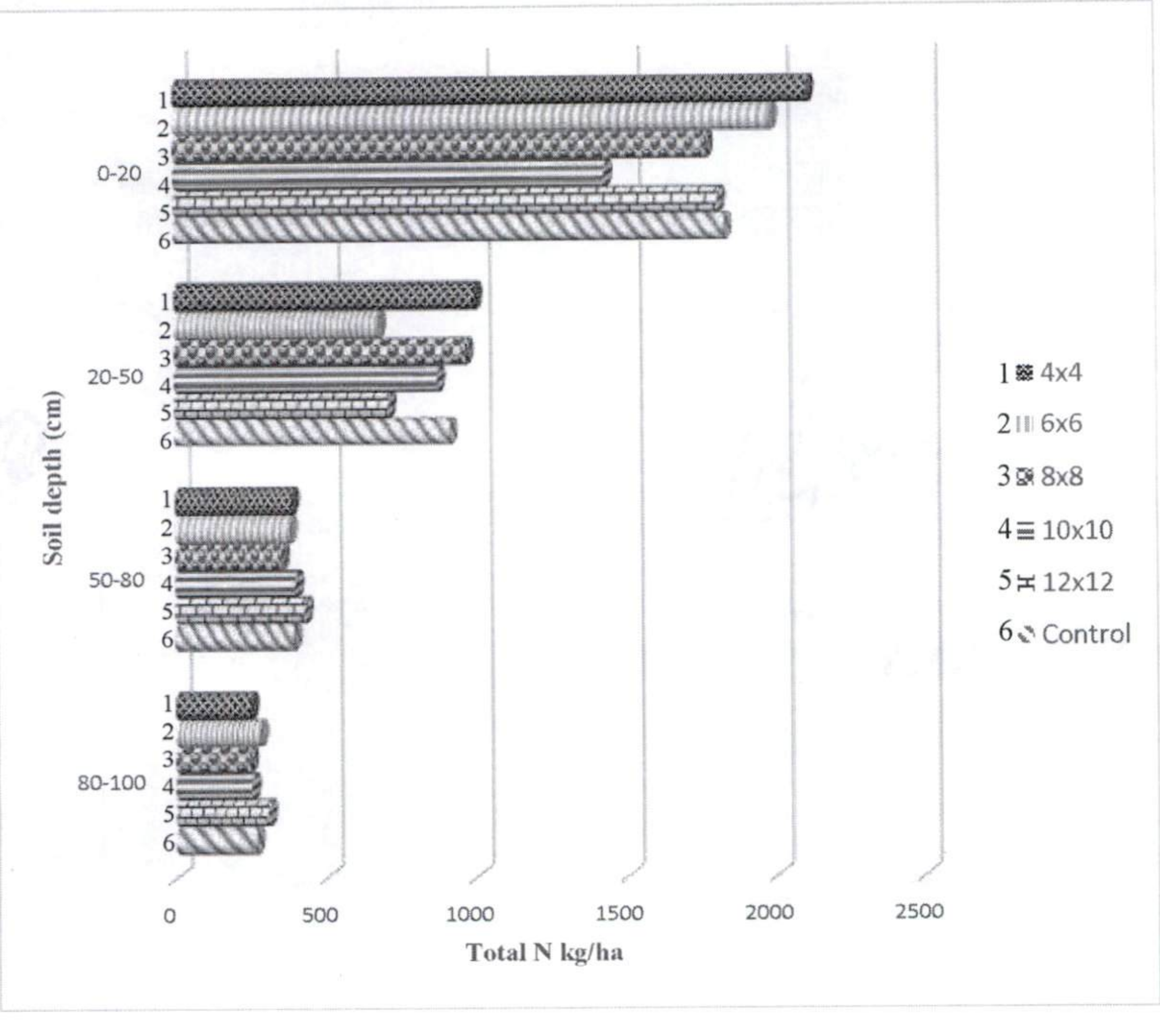


Fig. 33 Soil total nitrogen (kg/ha) at varying depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Table 28. Per cent of total nitrogen in soil at various depth as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depth (cm)	Spacings (m)					
	4x4	6x6	8x8	10x10	12x12	Control
0-20	56.44	59.83	53.10	48.42	55.56	53.84
20-50	26.64	20.36	29.02	29.57	21.82	26.85
50-80	10.30	11.42	10.54	13.47	13.20	11.51
80-100	6.62	8.39	7.33	8.54	9.41	7.81

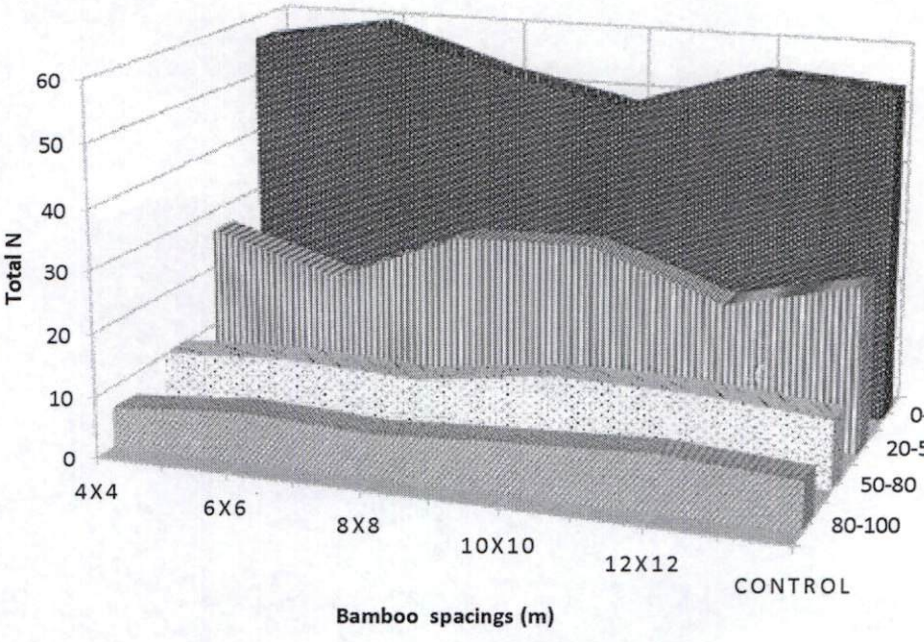


Fig. 34 Per cent of total nitrogen in soil at various depth as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

control (3397.45 kg/ha), 8x8 m (3328.57 kg/ha) and lowest (2954.7 kg/ha) at 10x10 m spacing of bamboo. The widest spacing, 12x12 m recorded 0.87 times lesser amount compared to closest spacing of bamboo (4x4 m).

Available Phosphorus

The available phosphorus significantly varied with depths and spacings of bamboo (Table 29 and Fig. 35). The avail. P at surface soil (0-20 cm) ranged from 20.91 kg/ha at closest spacing to 12.86 kg/ha under bambooless control plot. 0-20 cm soil depth at closest spacing (4x4 m) recorded 20.91 kg/ha of avail. P and this was 0.62 per cent higher compared to bambooless. Soil depth has significant effect on avail P. Drastic decrease of soil avail. P with increasing depth was observed. The avail. P upto 1 m soil depth recorded highest (42 kg/ha) in closest spacing and decreased with increasing spacings of bamboo and recorded 20.31 kg/ha at control plot.

Available Potassium

Soil depths and spacings of bamboo significantly influenced the soil available potassium. table 31 and fig. 37 depict the trend of decrease of avail. K with increasing depth and spacings of bamboo. The closest spacing of bamboo (4x4 m) had (0-20 cm) highest 269.8 kg/ha and widest spacing (12x12 m) recorded lowest (210.15 kg/ha). As compared to bambooless control about 21.36 per cent higher avail. K was found under closest spacing of bamboo (Fig. 38). The total avail. K upto 1 m depth of soil was highest (608.97 kg/ha) in closest spacing (4x4 m) and this was 35.21 per cent higher compared to widest spacings of 12x12 m.

4.9.2 Particle size distribution

The data on aggregate distribution of silt and clay (<53 μm), micro (53–250 μm) and macro (250–2000 μm) in each depth under varying spacings of bamboo and bambooless control are presented in the table 33. The results reveal that silt and clay fraction (per cent) was highest in closest spacing (58.23 per cent) and lowest in 10x10 m spacing of bamboo at 0-20 cm soil depth. The silt and clay aggregate

Table 29. Soil available phosphorus (kg/ha) at varying depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depths (cm)	Available P					
	4x4	**6x6**	**8x8**	**10x10**	**12x12**	**Control**
0-20	20.91^{a}	18.17^{b}	15.76^{c}	15.43^{c}	14.02^{d}	12.86^{e}
20-50	10.18^{f}	8.18^{g}	6.94^{h}	5.69^{i}	4.45^{jk}	3.20^{mn}
50-80	7.44^{h}	5.86^{i}	4.61^{j}	3.70^{klm}	4.03^{jkl}	3.78^{klm}
80-100	3.47^{lmn}	4.28^{jk}	4.37^{jk}	2.96^{n}	1.46^{0}	0.47^{p}
Total	42^{C}	36.49^{AB}	31.68^{AB}	27.78^{AB}	23.96^{AB}	20.31^{A}

Values followed by same superscript in a column and row do not differ significantly (LSD, $P<0.05$)
Means followed by same capital letter superscript in a column do not differ significantly (LSD, $P<0.05$).

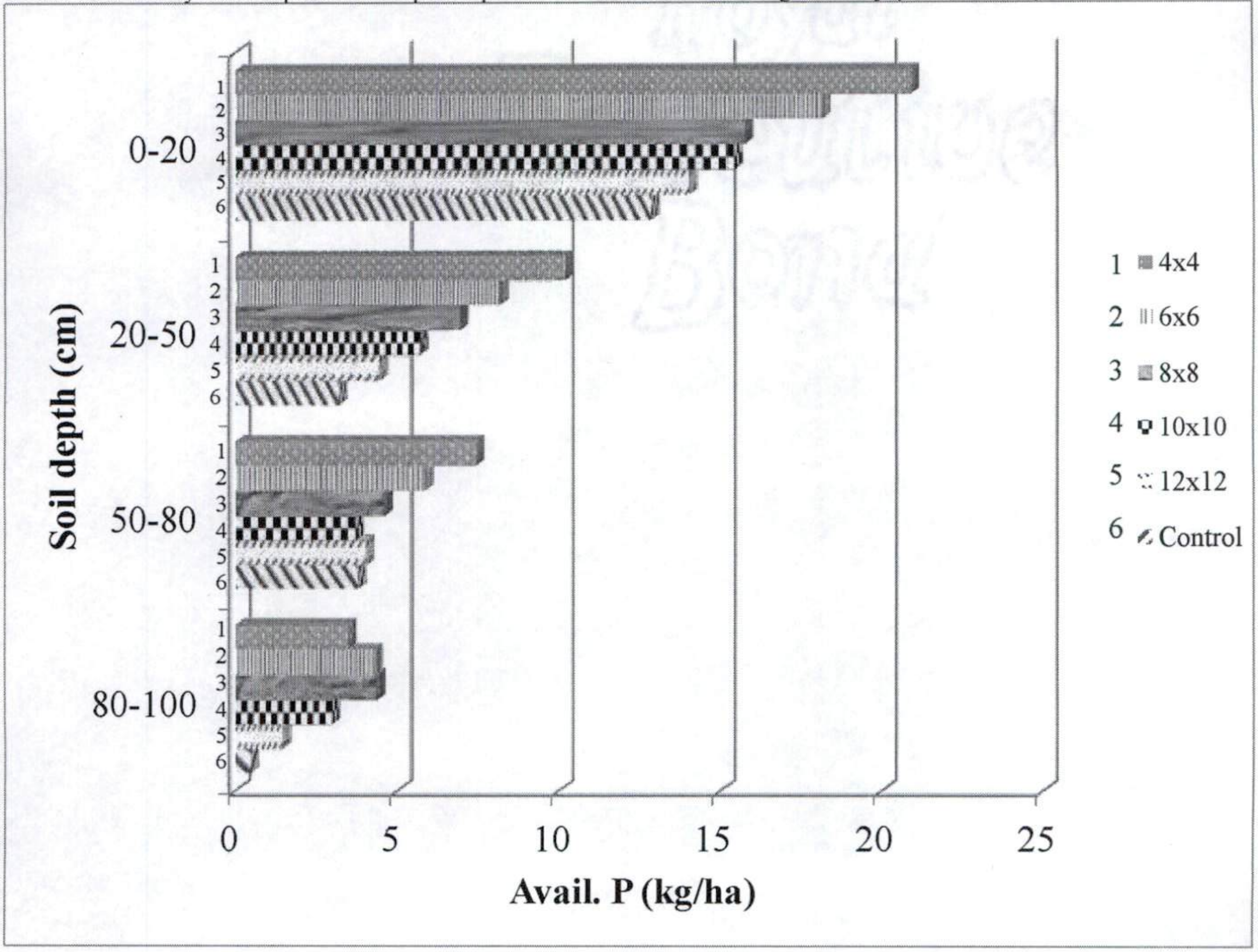


Fig. 35 Soil available phosphorus (kg/ha) at varying depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Table 30. Per cent of available phosphorus in soil at various depth as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depth (cm)	Spacings (m)					
	4x4	**6x6**	**8x8**	**10x10**	**12x12**	**Control**
0-20	49.78	49.79	49.74	55.54	58.51	63.31
20-50	24.23	22.41	21.90	20.48	18.57	15.75
50-80	17.71	16.05	14.57	13.31	16.81	18.62
80-100	8.26	11.72	13.79	10.65	6.09	2.31

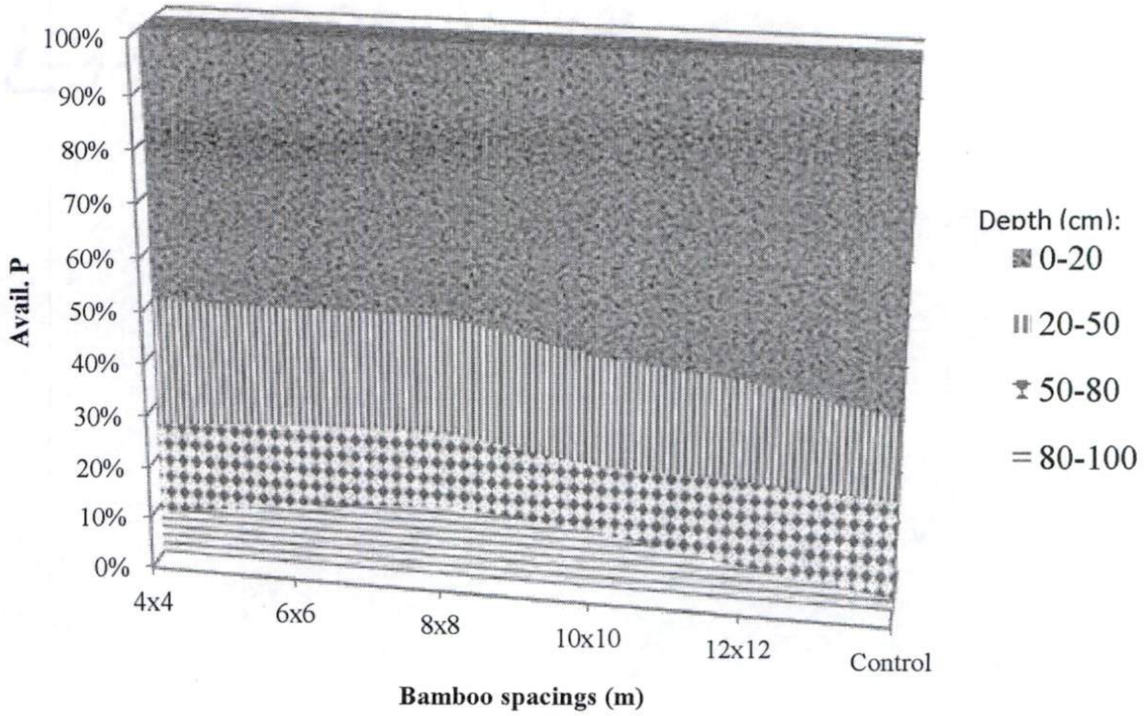


Fig. 36 Per cent of available phosphorus in soil at various depth as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Table 31. Soil available potassium (kg/ha) at varying depths as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depths (cm)	Available K					
	4x4	**6x6**	**8x8**	**10x10**	**12x12**	**Control**
0-20	269.8^{a}	247.03^{b}	227.7^{c}	212.29^{d}	210.15^{d}	222.3^{c}
20-50	174.8^{e}	134.12^{f}	124.66^{g}	114.79^{h}	110.99^{hi}	106.4^{i}
50-80	98.15^{j}	85.13^{k}	84.14^{k}	83.65^{k}	81.45^{k}	77.97^{k}
80-100	66.22^{l}	50.42^{m}	46.35^{m}	52.38^{m}	47.79^{m}	49.8^{m}
Total	608.97^{D}	516.7^{C}	482.85^{B}	463.11^{A}	450.38^{A}	456.47^{A}

Values followed by same superscript in a column and row do not differ significantly (LSD, $P<0.05$)

Means followed by same capital letter superscript in a column do not differ significantly (LSD, $P<0.05$).

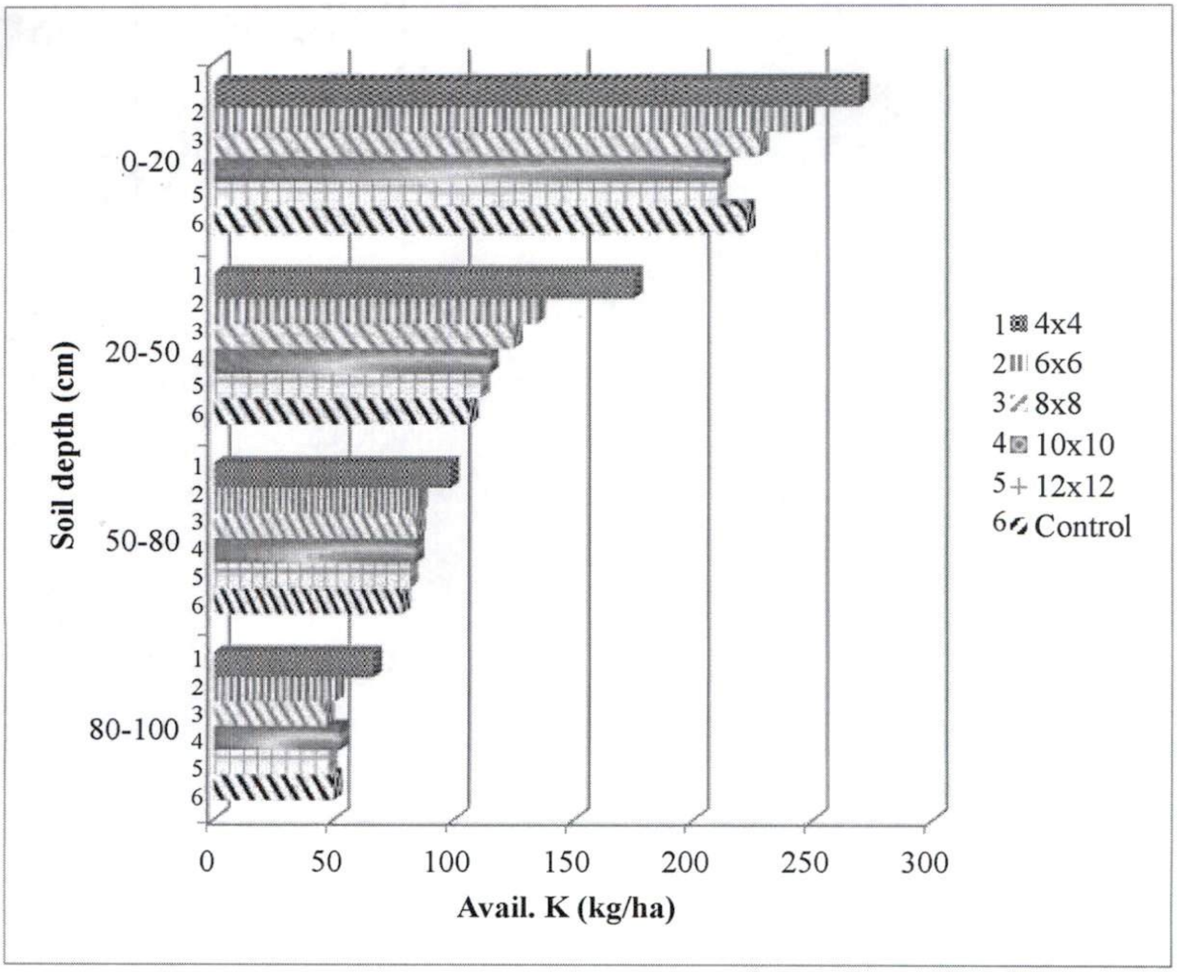


Fig. 37 Soil available potassium (kg/ha) at varying depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Table 32. Per cent of available potassium in soil at various depth as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depth (cm)	Spacings (m)					
	4x4	6x6	8x8	10x10	12x12	Control
0-20	48.61	46.66	45.84	47.15	47.80	44.30
20-50	23.30	24.64	24.78	25.81	25.95	28.70
50-80	17.08	18.08	18.06	17.47	16.41	16.11
80-100	10.87	9.75	9.59	11.39	10.61	10.90

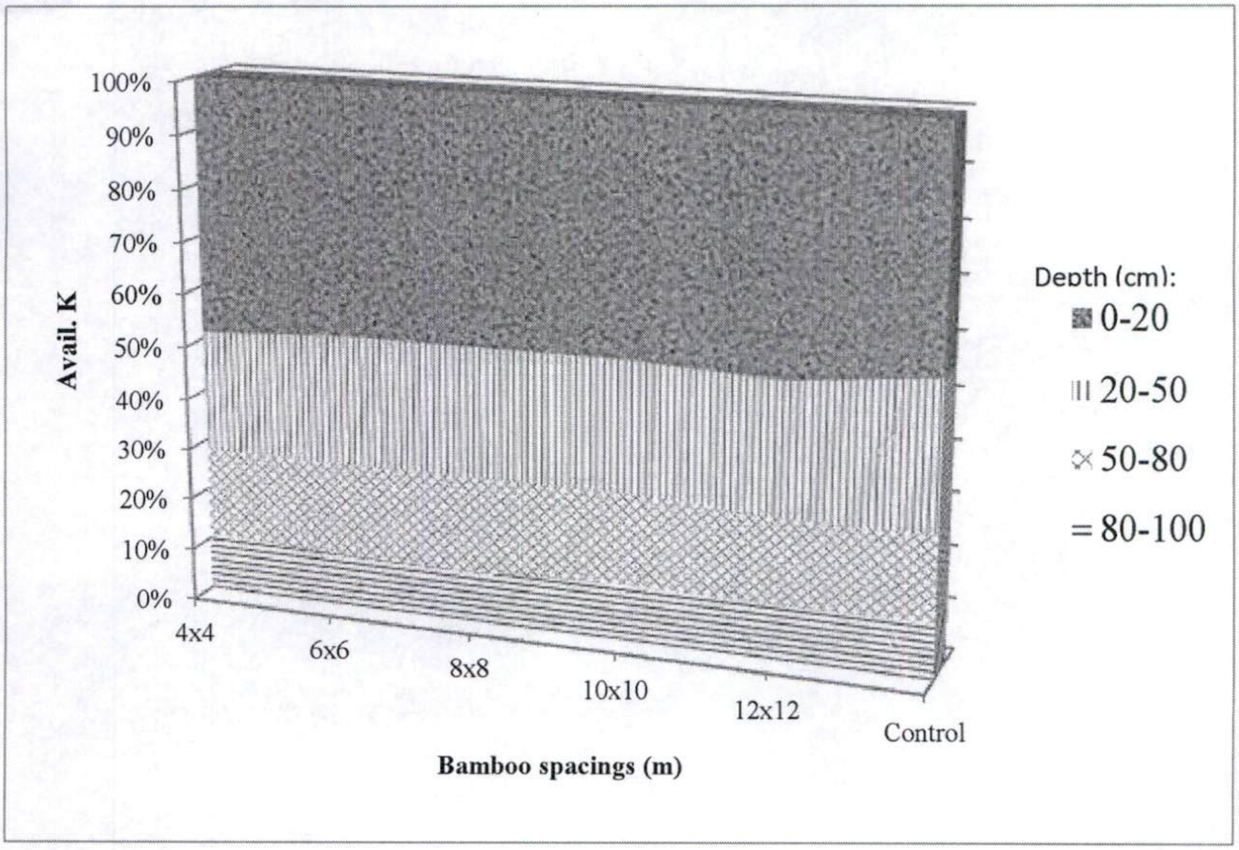


Fig. 38 Per cent of available potassium in soil at various depth as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

was more in 4x4, 6x6 and 8x8 m spacings of bamboo; this was less in wide spacings (10x10 and 12x12 m) of bamboo compared to micro and macro size fraction of soil. In general, as the spacings of bamboo increased the silt and clay content in surface soil (0-20 cm) decreased. However, no trend of increase/decrease of aggregate class was observed with increasing depth at varying spacings of bamboo.

4.9.3 Soil organic carbon (SOC) in whole soil

The data on variation in SOC at various depths as influenced by different spacings in a seven year old bamboo plantation are given in the table 34 and fig. 39. The amount of SOC in whole soil at 0-20 cm was highest (11.50 Mg/ha) in 4x4 m spacing of bamboo. This decreased significantly with increasing spacings of bamboo and recorded lowest (6.61 Mg/ha) in widest spacing (12x12 m) of bamboo; this decrease was upto the tune of 42.52 per cent compared to closest spacing (4x4 m). The bambooless control plot recorded 7.21 Mg/ha of SOC. At 20-50 cm depth also the SOC was highest (12.15 Mg/ha) in closest spacing (4x4 m) which declined significantly with increase in spacings of bamboo to 4.58 Mg/ha in widest spacing of bamboo; this decline was equal to 62.30 percent compared to closest spacing. However, the SOC in the control plot (4.38 Mg/ha) was at par with that in widest spacing of bamboo. At 50-80 cm depth the SOC was found highest (7.68 mg/ha) and declined with increasing spacings of bamboo; this decline was equal to 75.39 per cent compared to closest spacing (4x4 m). Similar trend was also followed at 80-100 cm depth. The total SOC upto 1 m depth in closest spacing (4x4 m) accounted 36.51 Mg/ha and 14.97 Mg/ha in widest spacing (12x12 m); this declined by 143.88 per cent compared to closest spacing.

4.9.4 Distribution of organic carbon in various aggregate classes

Invariably SOC in silt and clay aggregate (<53 μm) was highest (15.92 Mg/ha) due to closest spacing of 4x4 m and lowest (5.20 Mg/ha) in bambooless control plot at 20-50 cm soil depth (Table 35 and Fig. 40). Irrespective of depth, the gradual and significant reduction in SOC was observed with increase in spacing of bamboo; lowest (7.91 Mg/ha) SOC was observed at widest spacing of bamboo (12x12 m)

Table 33. Soil aggregates (silt and clay, micro and macro) distribution at various depths as influenced by different spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	Soil depth (cm)	Aggregates distribution (per cent 100 g^{-1} soil)		
		Silt and Clay	Micro	Macro
4x4	0-20	58.23	25.12	17.15
	20-50	72.45	12.38	14.97
	50-80	35.23	30.43	33.69
	80-100	34.59	31.51	34.00
6x6	0-20	58.03	27.15	25.18
	20-50	70.60	14.63	14.97
	50-80	27.16	18.56	54.38
	80-100	39.82	11.51	48.99
8x8	0-20	51.18	28.36	20.74
	20-50	49.01	33.49	17.40
	50-80	19.35	36.37	44.26
	80-100	19.37	45.44	35.10
10x10	0-20	20.33	59.93	20.22
	20-50	51.99	33.40	14.54
	50-80	25.65	29.82	45.21
	80-100	28.40	21.34	50.70
12x12	0-20	33.23	42.21	24.71
	20-50	20.20	29.75	49.79
	50-80	53.45	26.85	19.84
	80-100	25.80	32.81	41.40
Control	0-20	23.83	29.94	46.12
	20-50	11.52	79.16	9.36
	50-80	18.99	33.21	48.06
	80-100	22.80	42.61	34.06

Table 34. Soil organic carbon (Mg/ha) of whole soil at various depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depth (cm)	Spacings (m)					
	4x4	6x6	8x8	10x10	12x12	Control
0-20	11.50^{b}	10.08^{d}	8.85^{e}	6.72^{i}	6.6^{1i}	7.21^{h}
20-50	12.15^{a}	10.32^{c}	8.43^{f}	5.0^{1k}	4.58^{l}	4.38^{l}
50-80	7.68^{g}	6.66^{i}	5.46^{j}	2.7^{1o}	2.27^{p}	1.89^{q}
80-100	5.18^{k}	4.12^{m}	3.89^{n}	2.63^{o}	1.5^{1r}	1.69^{qr}
Total	36.51^{E}	31.18^{D}	26.63^{C}	17.07^{B}	14.97^{A}	15.17^{A}

Means followed by same superscript in a column and row do not differ significantly (LSD, $P<0.05$)
Means followed by same capital letter superscript in a row do not differ significantly (LSD, $P<0.05$).

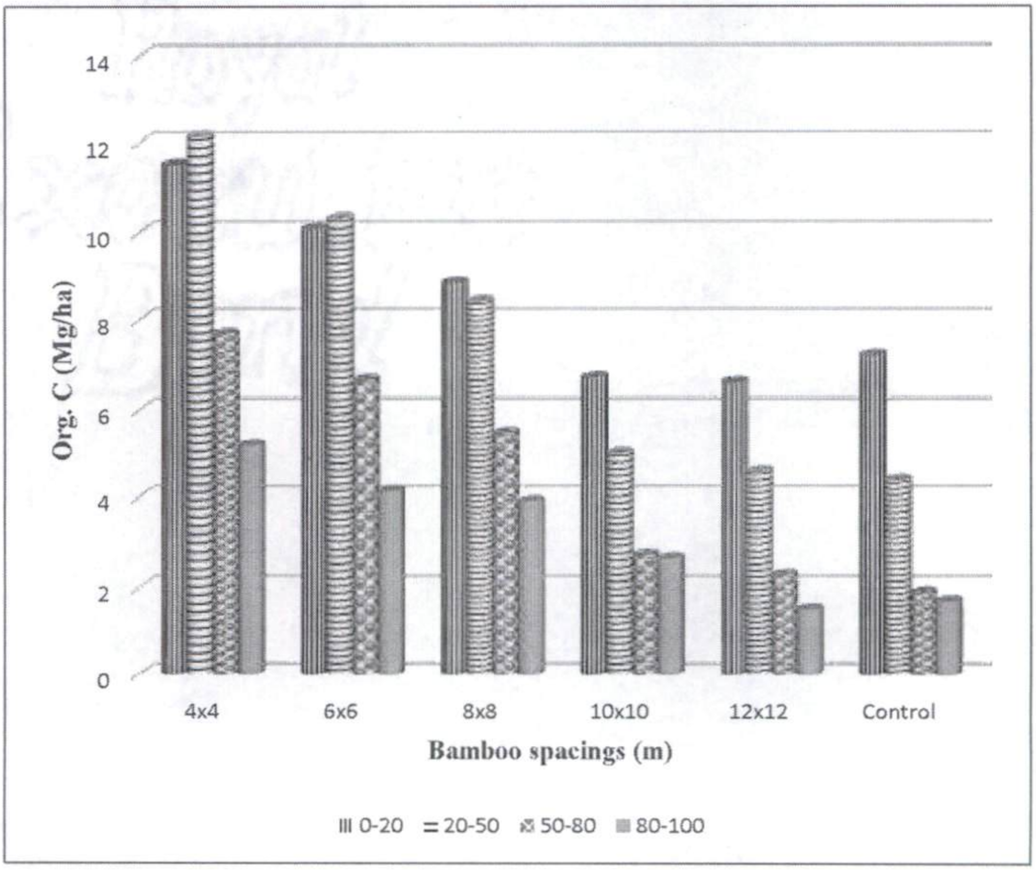


Fig. 39 Soil organic carbon (Mg/ha) whole soil at various depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

followed by bambooless control plot (8.22 Mg/ha). As compared to closest spacing of bamboo, the reduction in SOC at widest spacing was 43.17 per cent at 0-20 cm depth, 66.33 per cent at 20-50 cm, 65.34 per cent at 50-80 cm and 69.32 per cent at 80-100 cm soil depth respectively. However, the SOC in silt and clay aggregate upto 1 m soil depth recorded maximum of 47.57 Mg/ha in closest spacing and minimum of 17.48 Mg/ha in bambooless control; the decline was upto the tune of 63.24 per cent.

The SOC in micro aggregate (53-250 µm) was significantly affected by spacings of bamboo. As the spacing of bamboo increased the SOC was significantly decreased upto 10x10 m spacing and the lowest amount of (6.51 Mg/ha) SOC was recorded in 10x10 m spacing of bamboo (Table 36 and Fig. 41). The bambooless control plot recorded significantly higher SOC than widest spacing of bamboo. The reduction in SOC in micro sized aggregate fraction at widest spacing (12x12 m) was about 32.27 per cent compared to closest spacing (4x4 m) at 0-20 cm soil depth. However, the reduction of SOC at 80-100 cm depth was 102.13 and 579.64 per cent compared to surface soil (0-20 cm) in closest and widest spacings of bamboo respectively. The total SOC upto 1 m depth in closest spacing was 39.79 Mg/ha and 16.19 Mg/ha in widest spacing.

The SOC in macro aggregate class (>250-2000 µm) also declined gradually and significantly with increasing spacings of bamboo (Table 37 and Fig. 42). As compared to closest spacing, 2.18 times decline of SOC was observed in widest spacing; this reduction was upto the tune of 54.27 per cent. However, with increasing soil depth the SOC in macro size aggregate fraction significantly decreased. In closest spacing of bamboo 9.23 Mg/ha of SOC was recorded at 0-20 cm depth; this decreased to 2.27 Mg/ha at 80-100 cm depth. Whereas widest spacing of bamboo recorded 4.22 Mg/ha in surface soil (0-20 cm) and decreased to 1.05 Mg/ha at lowest depth (80-100 cm). However, the SOC upto 1 m depth was highest (22.17 Mg/ha) in closest spacing (4x4 m) and lowest (9.62 Mg/ha) in widest spacing (12x12 m) of bamboo.

Table 35. Soil organic carbon (Mg/ha) of silt and clay aggregate fraction (<53μm) at various depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depth (cm)	Spacings (m)					
	4x4	6x6	8x8	10x10	12x12	Control
0-20	13.92^{b}	12.54^{c}	10.85^{d}	8.40^{gh}	7.91^{hi}	8.22^{ghi}
20-50	15.92^{a}	14.14^{b}	12.39^{c}	6.38^{j}	5.36^{l}	5.20^{lm}
50-80	10.07^{e}	9.343^{f}	8.56^{g}	4.30^{n}	3.49^{o}	2.37^{p}
80-100	7.66^{i}	5.60^{kl}	6.04^{jk}	4.74^{mn}	2.35^{p}	1.69^{q}
Total	47.57^{E}	41.62^{D}	37.84^{C}	23.82^{B}	19.11^{A}	17.48^{A}

Means followed by same superscript in a column and row do not differ significantly (LSD, P<0.05)
Means followed by same capital letter superscript in a row do not differ significantly (LSD, P<0.05).

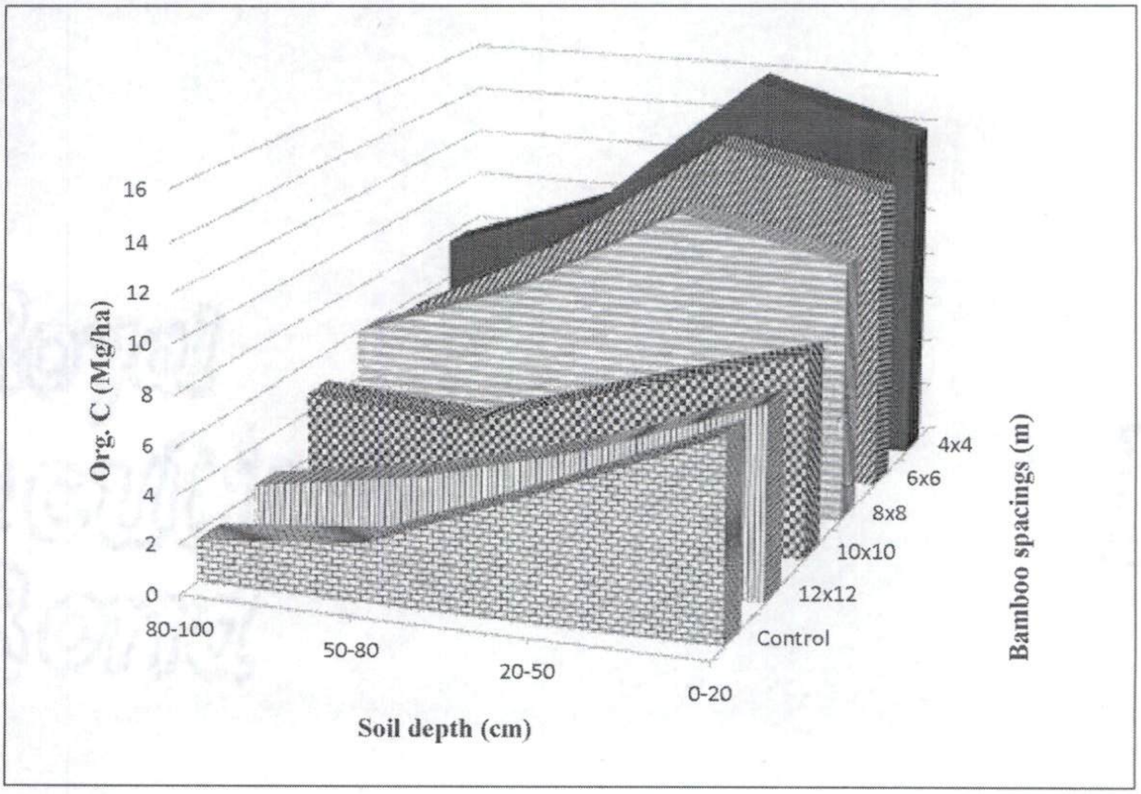


Fig. 40 Soil organic carbon (Mg/ha) of silt and clay aggregate fraction (<53μm) at various depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Table 36. Soil organic carbon (Mg/ha) of micro aggregate fraction (53–250 μm) at various depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depth (cm)	Spacings (m)					
	4x4	6x6	8x8	10x10	12x12	Control
0-20	11.34^{b}	10.35^{c}	8.48^{e}	6.51^{g}	7.68^{f}	8.67^{e}
20-50	14.21^{a}	11.50^{b}	9.65^{d}	5.34^{h}	5.14^{h}	4.55^{i}
50-80	8.63^{e}	8.38^{e}	6.34^{g}	2.44^{j}	2.24^{j}	2.09^{j}
80-100	5.61^{h}	4.68^{i}	4.49^{i}	2.13^{j}	1.13^{k}	2.14^{j}
Total	39.79^{D}	34.91^{C}	28.96^{B}	16.42^{A}	16.19^{A}	17.45^{A}

Means followed by same superscript in a column and row do not differ significantly (LSD, $P<0.05$)
Means followed by same capital letter superscript in a row do not differ significantly (LSD, $P<0.05$).

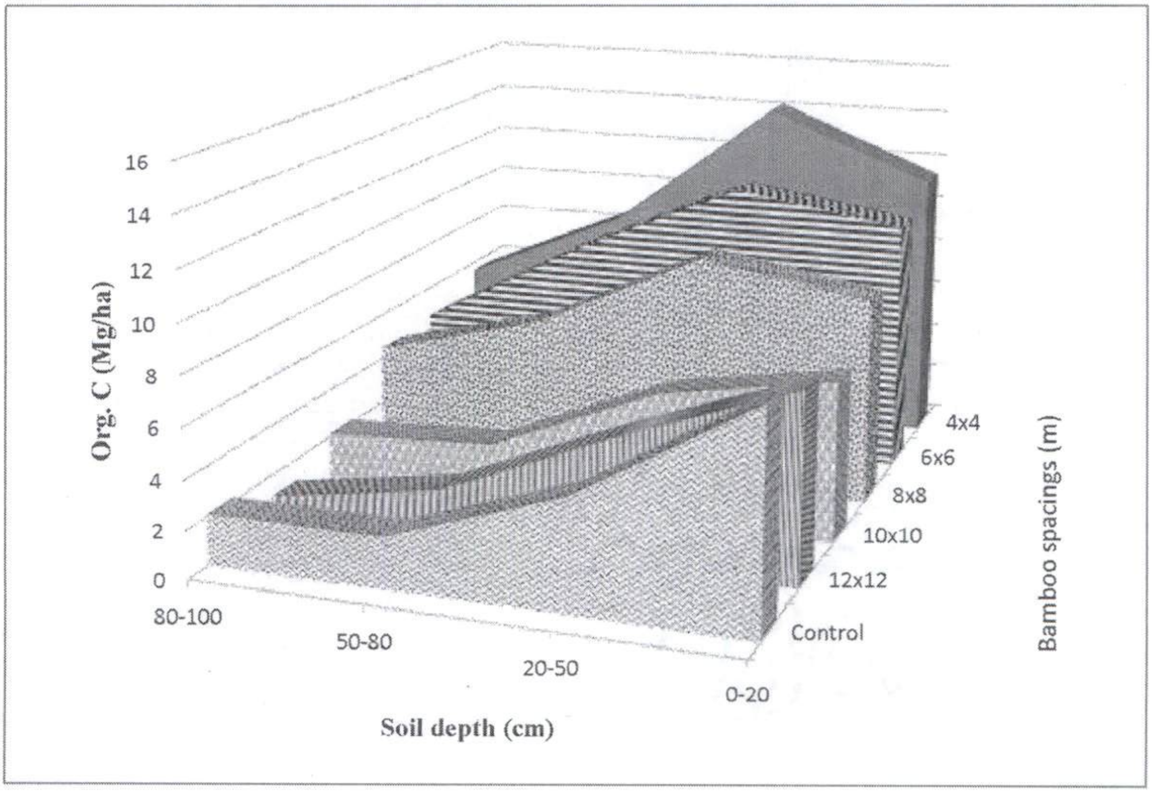


Fig. 41 Soil organic carbon (Mg/ha) of micro aggregate fraction (53–250 μm) at various depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Table 37. Soil organic carbon (Mg/ha) of macro aggregate fraction (>250–2000 µm) at various depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Depth (cm)	Spacings (m)					
	4x4	6x6	8x8	10x10	12x12	Control
0-20	9.23^{a}	7.36^{b}	7.21^{b}	5.24^{d}	4.22^{f}	4.75^{e}
20-50	6.32^{c}	5.31^{d}	3.26^{g}	3.32^{g}	3.26^{g}	3.39^{g}
50-80	4.35^{f}	2.27^{h}	2.02^{i}	1.4^{1j}	1.09^{kl}	1.22^{jk}
80-100	2.27^{h}	2.06^{i}	1.14^{kl}	1.0^{11}	1.05^{kl}	1.23^{jk}
Total	22.17^{D}	17^{C}	13.63^{B}	10.98^{A}	9.62^{A}	10.59^{A}

*Means followed by same superscript in a column and row do not differ significantly (LSD, P<0.05)
Means followed by same capital letter superscript in a row do not differ significantly (LSD, P<0.05).

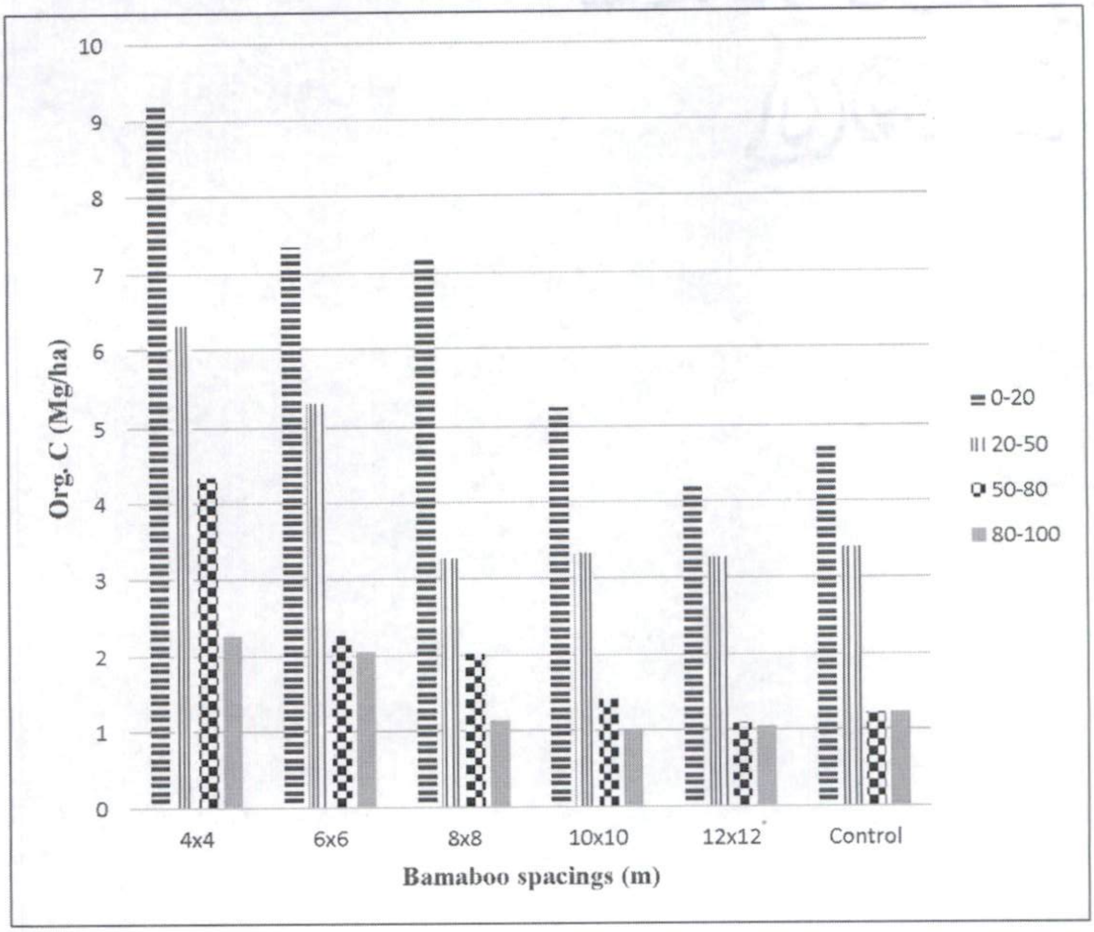


Fig. 42 Soil organic carbon (Mg/ha) of macro aggregate fraction (>250–2000 µm) at various depths as influenced by spacings of 7 year old bamboo (*Dendrocalamus strictus*)

4.10 Biomass production

4.10.1 Growth parameters of bamboo

The bamboo growth attributes were recorded and presented in the table 38 and fig. 43. It was found that clump height decreased significantly with increasing spacings of bamboo. The closest spacing of 4x4 m recorded maximum (8.86 m) clump height; this height decreased gradually when the spacings between the bamboo increased. As compared to closest spacings (4x4 m) about 23.13 per cent decrease in height was recorded in widest spacings of bamboo (12x12 m). In case of intermediate spacings of 8x8 m the bamboo height was 7.60 m; this was 14.22 per cent lesser than closest spacing (4x4 m) of bamboo. The clump diameter increased significantly with increasing spacings; when the spacings of bamboo increased to 12x12 m the clump diameter increased by 51.88 per cent compared to closest spacing (4x4 m). The crown spread was maximum (8.15 m) at widest spacings (12x12) and minimum (4.71 m) at closest spacing (4x4 m) of bamboo. The increase in crown width was upto the tune of 73.03 per cent due to increase of spacings from 4x4 m to 12x12 m. The mean annual increment of bamboo significantly varied due to spacings. As the spacings of bamboo increased the MAI of a clump gradually and significantly increased. The minimum (1.04 m^3/clump/year) MAI was recorded by closest spacing (4x4 m) and maximum (1.98 m^3/clump/year) in widest spacing (12x12 m).

After harvesting of bamboo culms, the live and dead culms in a clump were counted. The number of live culms were maximum (130/clump) in the widest spacing (12x12 m) and its count decreased significantly with decreasing spacings. The reduction in the live culms was 63.33 per cent in closest spacings compared to widest spacing of bamboo. The dead culms were maximum (7/clump) at widest spacings (12x12 m) and minimum (2.66/clump) in the 6x6 m spacings of bamboo. However the total number (live+dried) of culms per clump was highest (137 culm/clump) in the widest spacing (12x12 m) of bamboo and lowest (51.66

Table 38. Growth parameters of 7 year old bamboo (*Dendrocalamus strictus*) as influenced by its spacings

Spacings (m)	Clump height (m)	Clump DBH (m)	Crown width (m)	MAI (m^3/clump/yr)	Number of Live culms/clump	Number of dried culms/clump	Total culms
4x4	8.86(0.05)^{e}	1.06(0.08)^{a}	4.71(0.17)^{a}	1.04(0.014)^{a}	47.66(11.59)^{a}	4(1.21)^{ab}	51.66(9.07)^{a}
6x6	8.29(0.2)^{d}	1.30(0.09)^{b}	6.63(0.23)^{b}	1.08(0.016)^{b}	75(21.65)^{b}	2.66(0.57)^{a}	77.66(21.12)^{ab}
8x8	7.6(0.01)^{c}	1.47(0.06)^{c}	7.4(0.13)^{c}	1.47(0.019)^{c}	103.66(9.86)^{c}	3(1.0)^{a}	106.66(8.96)^{bc}
10x10	6.9(0.05)^{b}	1.58(0.01)^{cd}	7.81(0.16)^{d}	1.72(0.01)^{d}	111.33(3.21)^{cd}	5(2.0)^{ab}	131(17.19)^{bc}
12x12	6.81(0.07)^{a}	1.61(0.03)^{d}	8.15(0.14)^{e}	1.98(0.007)^{e}	130(9.29)^{d}	7(1.0)^{b}	137(14.79)^{c}

Values in the parenthesis are Standard Deviation of the Mean

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

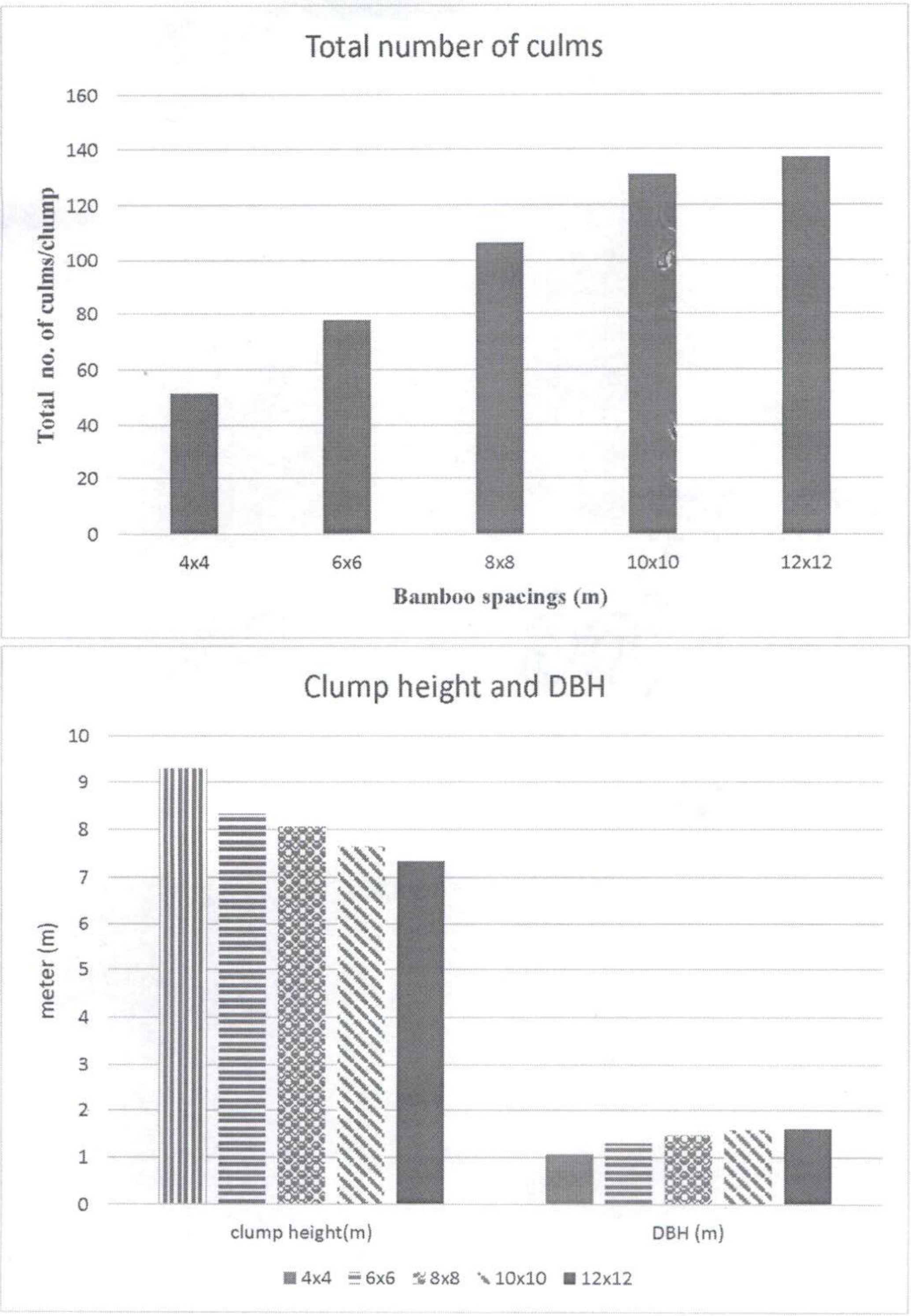


Fig. 43 Growth parameters of 7 year old bamboo (*Dendrocalamus strictus*) as influenced by its spacings

culms/clump) in closest spacing (4x4 m). The total number of culms per clump in the widest spacings were 137 and in the closest spacings were 51.66/clump.

4.10.2 Aboveground biomass production

Biomass allocation to components viz., culm wood, twig, leaf and dried culm and its per cent contribution to the total biomass are presented in the table 39 and fig. 44. Invariably stemwood constituted highest per cent to the total biomass in all the spacings of bamboo and its contribution varies from the maximum of 70 per cent in closest spacing (4x4 m) to minimum of 60 per cent at intermediate spacings (8x8 m). The culm wood at closest spacing (4x4 m) of bamboo was 78.41 kg/clump. This was 54.68 per cent less compared to widest spacings (12x12 m) of bamboo. The twig biomass accounted second largest share to the total biomass. Maximum (28 per cent) was recorded at 6x6 m and 8x8 m spacings of bamboo and closest spacing (4x4 m) recorded minimum (19 per cent). The twig biomass at closest spacing of 4x4 m was 21.65 kg/clump which increased to 195.79 per cent at 12x12 m spacing. The significant increase in twig biomass with increasing spacings of bamboo was observed. The same trend of increase was also observed for leaf biomass. The leaf biomass at closest spacing (4x4 m) was 4.63 kg/clump; this increased by 325 per cent in 12x12 m spacing of bamboo (Fig. 45). The leaf biomass contribution to the total biomass at closest spacing (4x4 m) was minimum (4 per cent) and widest spacing of bamboo (12x12 m) recorded maximum (7 per cent). The dried culm biomass was 15 kg/clump at widest spacing (12x12 m) and closest spacing (4x4 m) of bamboo recorded 7.66 kg/clump. The dried culm contribution to the total biomass at 4x4 m spacing was 7 per cent and 5 per cent at 12x12 m spacing (Fig. 45).

The total aboveground biomass significantly increased with increasing spacings of bamboo. The total aboveground biomass at closest spacings (4x4 m) of bamboo was 112.36 kg/clump which increased to 271.79 kg/clump by increasing spacings of bamboo to 12x12 m; this increase accounted about 142 per cent compared to closest spacing (4x4 m).

Table 39. Aboveground components biomass production (kg/clump) in 7 year old bamboo (*Dendrocalamus strictus*) grown at different spacings

Spacings (m)	culms	twigs	leaves	dried culms	Total
4x4	78.41(3.74)^{a}	21.65(4.83)^{a}	4.63(0.78)^{a}	7.66(1.52)^{a}	112.36 (10.23)^{a}
6x6	91.04(7.66)^{a}	42.56(3.36)^{b}	6.99(1.43)^{a}	8.66(0.57)^{ab}	149.26(13.84)^{b}
8x8	119.13(3.92)^{b}	55.90(1.0)^{c}	12.96(1.51)^{b}	12(2.00)^{c}	200.00(14.96)^{c}
10x10	162.56(7.24)^{c}	62.58(3.33)^{cd}	13.98(1.31)^{b}	11(1.00)^{bc}	250.13(10.54)^{d}
12x12	173.04(12.02$^{)c}$	64.04(5.68)^{d}	19.70(3.55)^{c}	15(3.00)^{d}	271.79(15.79)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

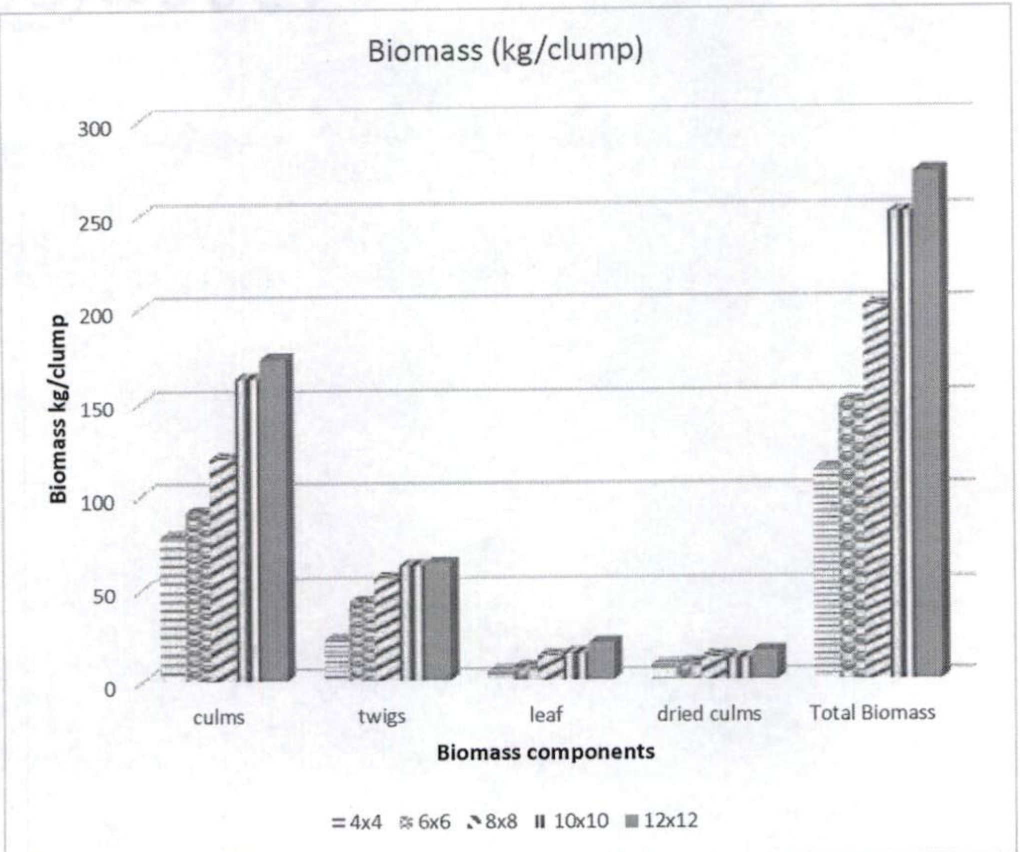


Fig. 44 Aboveground components biomass (kg/clump) production in 7 year old bamboo (*Dendrocalamus strictus*) grown at different spacings

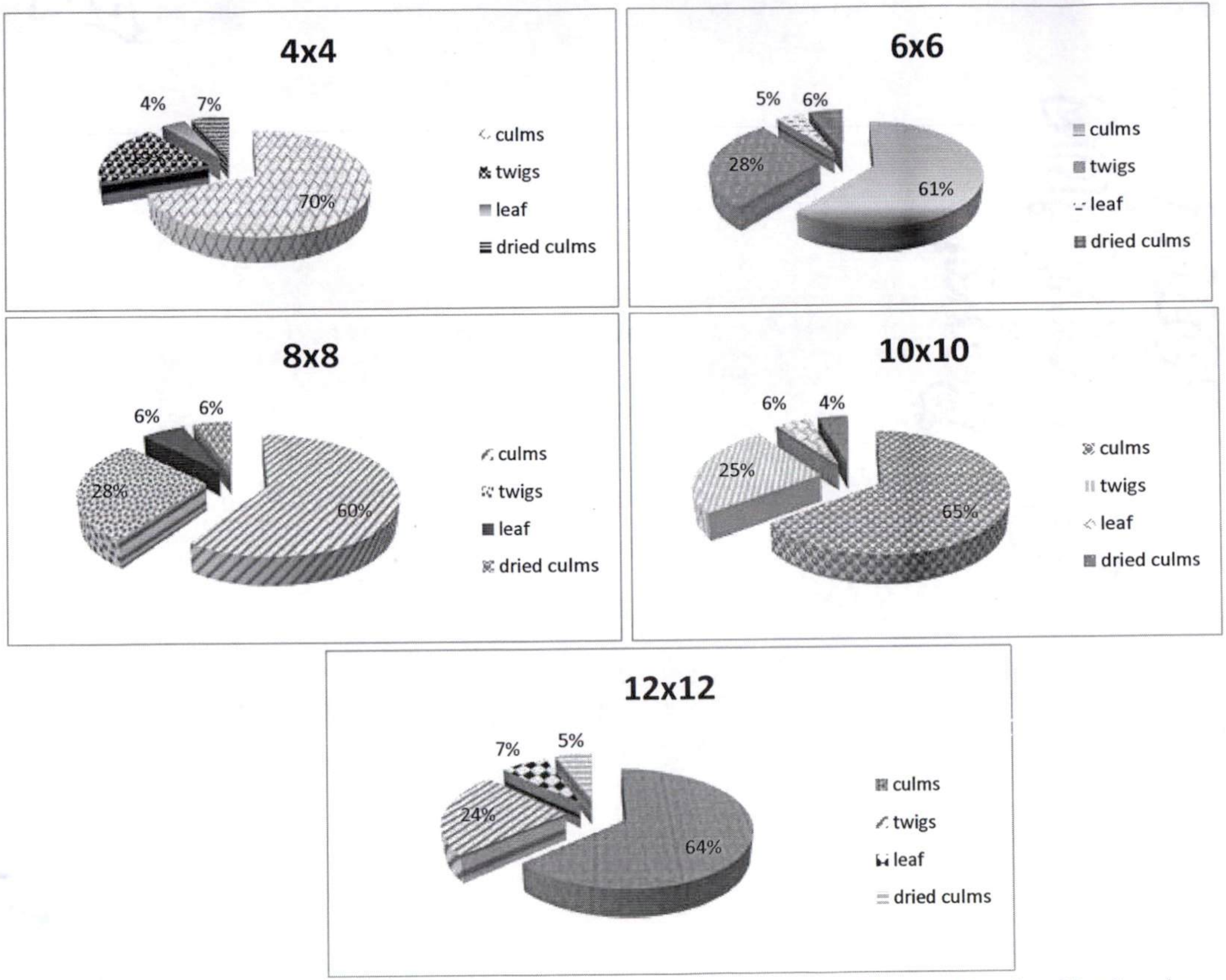


Fig. 45 Proportional distribution of components biomass as influenced by varying spacings of 7 year old bamboo (*Dendrocalamus strictus*)

Aboveground biomass production on at different stand densities (Mg/ha)

The biomass production is a function of stand density in any plantation. So the results of aboveground biomass production per clump were extrapolated into Mega grams per hectare. Considerable variation in the aboveground stand biomass accumulation has been observed (Table 40 and Fig. 46). As the density of bamboo increased the aboveground biomass also increased significantly. The culm wood biomass found maximum (49 Mg/ha) in densest bamboo of 625 clumps per hectare. This decreased significantly to 11.94 Mg/ha when the density decreased to 69 clumps per hectare. The increase of stemwood biomass accounted to the tune of 310 per cent at densest bamboo (625 clumps/ha) compared to least dense (69 clumps/ha). The twig biomass recorded 13.53 Mg/ha at densest and which was 207per cent more than least dense (69 clumps/ha). The leaf biomass was 2.89 Mg/ha at density of 625 clump/ha and 1.35 Mg/ha in 69 clumps/ha. The leaf biomass reduction in 69 clumps/ha was 114 per cent compared to densest stand (625 clumps/ha). The dried culm biomass was significantly high (4.79 Mg/ha) at densest bamboo (625 clumps/ha) and was 1.03 Mg/ha at a density of 69 clumps/ha.

The results clearly show that total aboveground biomass of bamboo was significantly affected by its density. The total aboveground biomass at 625 clumps/ha (70.22 Mg/ha) increased by 274.50 per cent as compared 69 clumps/ha (18.75 Mg/ha). This reveals the inverse relation between the spacings of bamboo and total aboveground biomass production. Therefore results clearly show that, the aboveground biomass accumulation at different components in the bamboo was maximum when grown in the wider spacings of 10x10 and 12x12 m. But the overall biomass accumulation at stand level was high at denser stands of bamboo (625 and 277 clump/ha) because of more number of clumps per hectare.

4.11 Nutrients (N, P and K) in aboveground components of bamboo

Nitrogen (N) concentration (%)

N concentration in the biomass varied significantly due to varying spacings of bamboo. The N concentration at all the spacings of bamboo decreased in the order

Table 40. Aboveground components biomass production (Mg/ha) in 7 year old bamboo (*Dendrocalamus strictus*) grown at different spacings

Clumps Per ha	culms	twigs	leaves	dried culms	Total
625	49(2.33)^{d}	13.53(3.02)^{c}	2.89(0.49)^{c}	4.79(0.95)^{c}	70.22 (5.12)^{a}
277	25.21(2.12)^{c}	11.79(0.93)^{c}	1.93(0.39)^{ab}	2.40(0.15)^{b}	41.34(4.39)^{b}
156	18.58(0.61)^{b}	8.72(0.15)^{b}	2.02(0.23)^{b}	1.87(0.31)^{ab}	31.20(4.47)^{c}
100	16.25(0.72)^{b}	6.25(0.33)^{ab}	1.39(0.13)^{a}	1.1(0.1)^{a}	25.01(2.39)^{d}
69	11.94(0.82)^{a}	4.41(0.39)^{a}	1.35(0.24)^{a}	1.03(0.069)^{a}	18.75(3.23)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

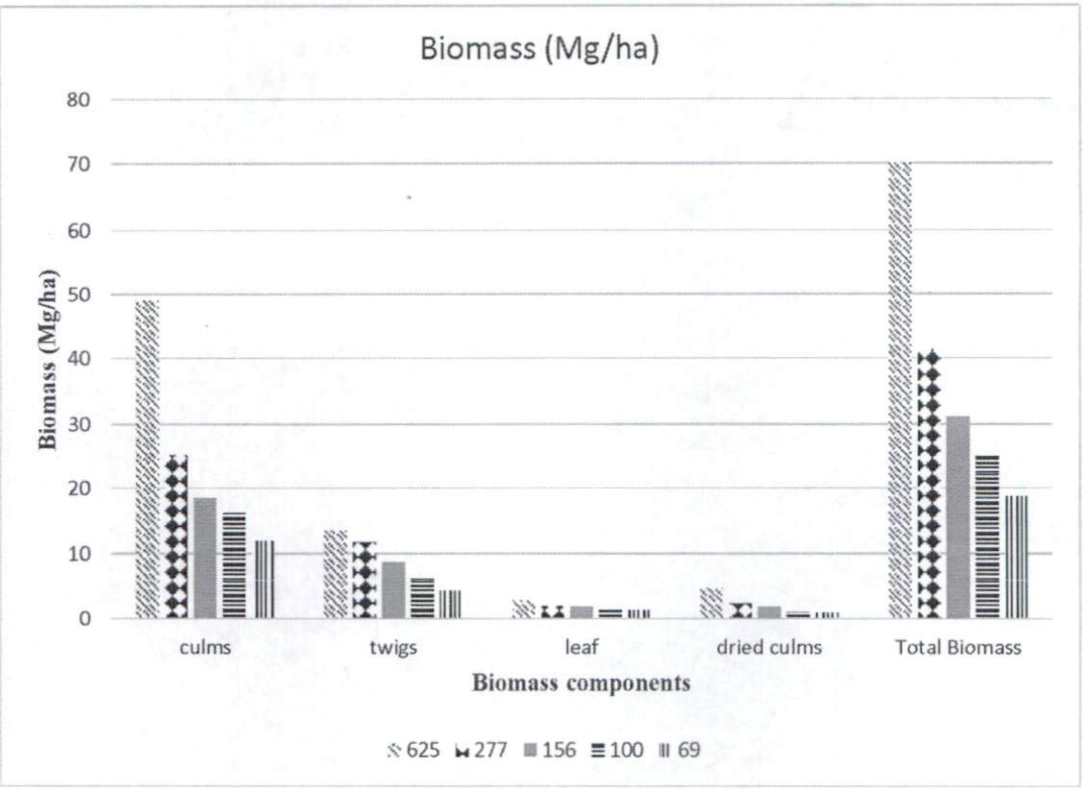


Fig. 46 Aboveground components biomass (Mg/ha) production in 7 year old bamboo (*Dendrocalamus strictus*) grown at different spacings

of leaf>twig>culm wood>dried culm (Table 41). Lowest N concentration (0.45%) was recorded at closest spacing of bamboo (4x4 m) which increased significantly with increasing spacings. At widest spacing of 12x12 m, the stemwood N was 0.58 per cent. Significant increase of twig biomass N with increasing spacings of bamboo was observed. Similar trend was also recorded for leaf samples.

The N accumulation in a culm wood at varies from 0.35 kg/clump at closest spacing to 1 kg/clump at widest spacing. The twig and leaf parts recorded 0.1 kg/clump and 0.026 kg/clump; this was significantly increased to 0.38 kg/clump and 0.12 kg/clump when spacings of bamboo increased to 12x12 m. Total N accumulation in the aboveground biomass at closest spacing was 0.50 kg/clump and increased to 1.55 kg/clump; this increase was 210 % in 12x12 m compared to 4x4 m spacing of bamboo (Table 42 and Fig. 47).

Table 41. Aboveground biomass N concentration (%) in 7 year old bamboo (*Dendrocalamus strictus*) as influenced by its spacings

Spacings (m)	culms	twig	leaf	dried culm
4x4	0.45(0.01)^{a}	0.49(0.01)^{a}	0.97(0.02)^{a}	0.40(0.005)^{ab}
6x6	0.49(0.01)^{b}	0.50(0.011)^{a}	1.01(0.035)^{b}	0.45(0.01)^{b}
8x8	0.52(0.01)^{c}	0.54(0.01)^{b}	1.04(0.02)^{bc}	0.37(0.08)^{a}
10x10	0.55(0.005)^{d}	0.56(0.01$^{)c}$	1.04(0.005)^{bc}	0.36(0.01)^{a}
12x12	0.58(0.01)^{e}	0.6(0.01)^{d}	1.07(0.01)^{c}	0.36(0.01)^{a}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, P<0.05).

N accumulation kg/ha

N accumulation was highest in culm wood (221.98 kg/ha) in densest stand (625 clumps/ha) and lowest (69.29 kg/ha) in least dense stand (69 clumps/ha). The N accumulation in twig and leaf were 66.13 and 16.24 kg/ha in densest stand and decreased to 35.48 and 9.04 kg/ha in least dense stand (69 clumps/ha). However,

Table 42. Aboveground biomass N accumulation (kg/clump) at various densities (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings	clump	twigs	leaf	dried culms	Total
4x4	0.35(0.01)^{a}	0.10(0.02)^{a}	0.026(0.004)^{a}	0.03(0.006)^{a}	0.50(0.007)^{a}
6x6	0.44(0.03)^{b}	0.21(0.01)^{b}	0.04(0.008)^{a}	0.039(0.003)^{ab}	0.72(0.012)^{b}
8x8	0.61(0.03)^{c}	0.30(0.009)^{c}	0.079(0.009)^{b}	0.044(0.003)^{b}	1.03(0.01)^{c}
10x10	0.89(0.04)^{d}	0.35(0.02)^{d}	0.09(0.007)^{b}	0.039(0.005)^{ab}	1.36(0.01)^{d}
12x12	1.00(0.08)^{e}	0.38(0.02)^{d}	0.12(0.02)^{c}	0.054(0.004)^{c}	1.55(0.05)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, P<0.05)

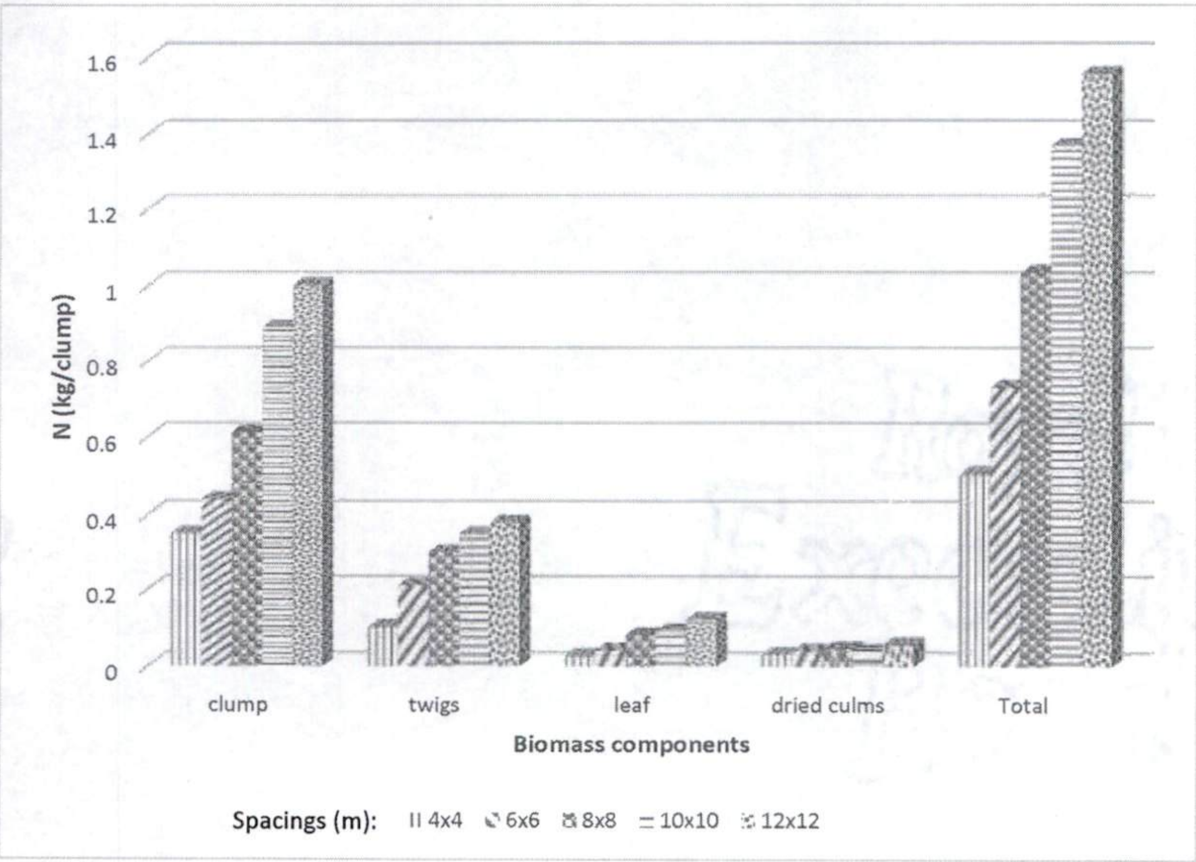


Fig. 47 Aboveground biomass N accumulation (kg/clump) at various densities (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

Table 43. Aboveground biomass N accumulation (kg/ha) at various densities (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

Density/ha (Spacings)	clump	twig	leaf	dried culms	Total
625(4x4)	221.98(6.51)^{d}	66.13(13.48)^{c}	16.24(3.00)^{b}	19.33(3.88)^{c}	323.69(25.07)^{d}
277(6x6)	123.45(9.26)^{c}	59.32(4.53)^{c}	11.24(2.39)^{a}	10.88(0.88)^{b}	204.90(13.13)^{c}
156(8x8)	96.67(4.96)^{b}	47.10(1.48)^{b}	12.33(1.42)^{a}	6.89(0.49)^{a}	163.00(6.82)^{b}
100(10x10)	89.96(4.56)^{b}	35.48(2.55)^{ab}	9.04(0.79)^{a}	3.97(0.54)^{a}	138.46(6.47)^{b}
69 (12x12)	69.29(5.72)^{a}	26.48(1.92)^{a}	8.93(1.63)^{a}	3.72(0.31)^{a}	108.44(5.00)^{a}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, P<0.05)

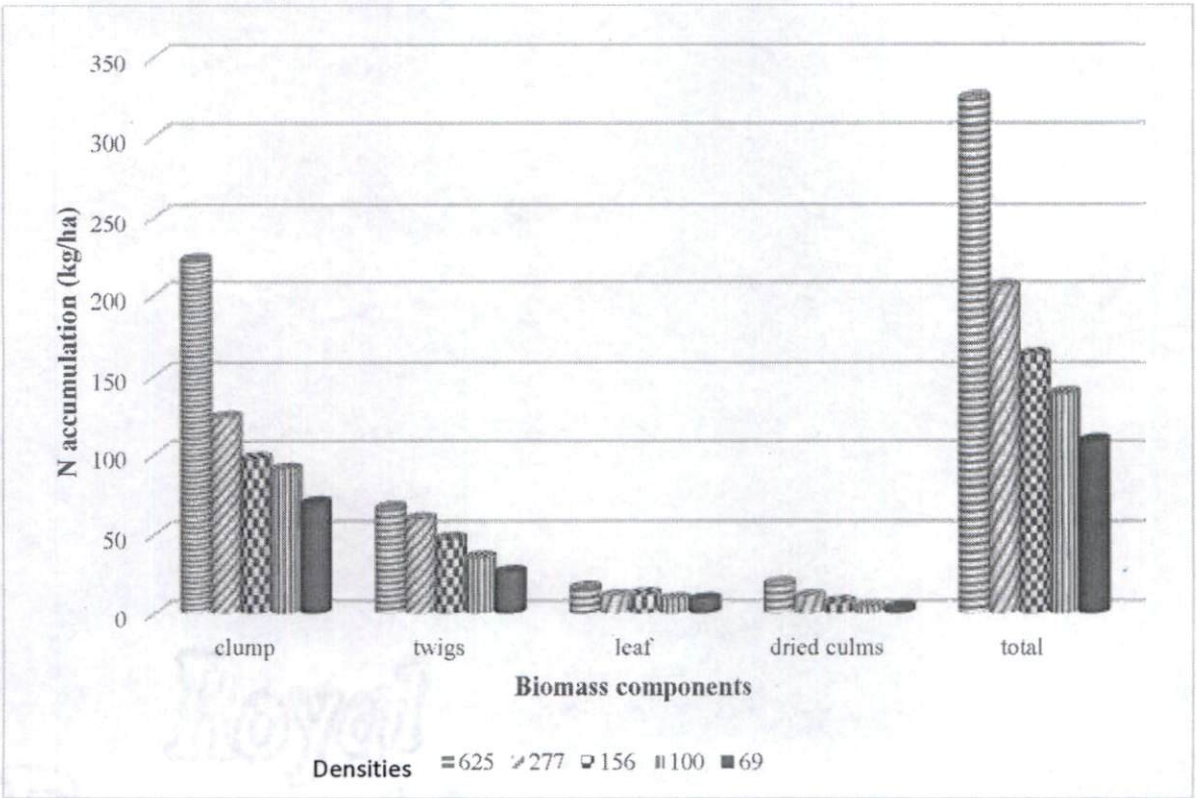


Fig. 48 Aboveground biomass N accumulation (kg/ha) at various densities (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

the intermediate density (156 clumps/ha) had lesser than densest stand (625 clumps/ha) and higher than least stand (69 clumps/ha). The dried culm contribution for N accumulation ranged between 19.33 kg/ha in densest stand and 3.72 kg/ha in least dense stand (69 clumps/ha). However, the total N accumulation in the aboveground biomass was highest (323.69 kg/ha) in densest stand and lowest (108.44 kg/ha) in least dense stand of 69 clumps/ha. The increase of N accumulation due to variation in stand density was upto the tune of 198.49 per cent (Table 43 and Fig. 48).

Phosphorus (P) concentration (%)

The tissue P concentration (per cent) significantly varied with spacings of bamboo. The P concentration in the aboveground parts decreased in the order of leaf>twig>culm wood>dried culm at all the spacings of bamboo (Table 44). P concentration in culm wood due to closest spacing (4x4 m) was lowest (0.19 per cent), which increased to 0.28 per cent at 12x12 m spacing. The P concentration in the twigs is second highest among the aboveground, which was highest (0.36 per cent) in widest spacings (12x12 m) and lowest (0.26 per cent) due to closest spacings (4x4 m) of bamboo. The trend of increase of P concentration in the twigs with increasing spacings of bamboo was observed. The leaf P concentration was highest among the aboveground parts of bamboo. In case of dried culm, the P concentration in 6x6 m spacing was 0.18 per cent which was at par with 10x10 m spacing of bamboo.

Spacings of bamboo significantly affected the P accumulation. The P accumulation in the aboveground biomass components gradually increased with increasing spacings of bamboo. Highest P in a clump was accumulated in the culm portion. Because of wide spacings the P accumulation in the clump significantly increased compared to close spacings (Table 45 and Fig. 49). For, instance, at closest spacings the P accumulation in the culm wood was 0.15 kg/clump; this increased to 0.48 kg/clump. In the twig component P accumulation was maximum at widest spacing and gradually and significantly decreased due to decrease of spacings of bamboo. Similar trend also recorded for leaf and dried culm components. However, total aboveground P accumulation varies between 0.23 kg/clump in closest spacing and 0.74 kg/clump in widest spacing of bamboo. The total aboveground P accumulation in the closest spacing was 68.91 per cent less compared to aboveground P in the widest spacing (12x12 m) of bamboo.

Table 44. Aboveground biomass P concentration (%) in 7 year old bamboo (*Dendrocalamus strictus*) as influenced by its spacings

Spacings (m)	culms	twig	leaf	dried culm
4x4	0.19(0.01)^{a}	0.26(0.01)^{a}	0.55(0.01)^{a}	0.16(0.01)^{ab}
6x6	0.22(0.006)^{b}	0.27(0.01)^{a}	0.57(0.01)^{b}	0.18(0.006)^{bc}
8x8	0.24(0.006)^{c}	0.30(0.011)^{b}	0.59(0.006)^{c}	0.15(0.01)^{a}
10x10	0.26(0.006)^{d}	0.32(0.006)^{c}	0.61(0.006)^{cd}	0.18(0.006)^{bc}
12x12	0.28(0.01)^{e}	0.36(0.006)^{d}	0.62(0.01)^{d}	0.18(0.006)^{c}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).

P accumulation (kg/ha)

P accumulation in culm wood was maximum (97.13 kg/ha) at densest stand (625 clumps/ha). By decreasing stand density to 69 clumps/ha the P accumulation also decreased by 15.94 kg/ha; this decrease was 188.90 per cent in least dense stand (69 clumps/ha). The twig and leaf biomass contribution for P accumulation ranged between 15.94 and 8.51 kg/ha in the stand density of 69 clumps/ha to 36.05 and 16.01 kg/ha in the densest stand (625 clumps/ha). The increase of P accumulation in twigs due to increasing stand density was 12.61 per cent in densest stand (625 clumps/ha) compared to least dense stand (69 clumps/ha). Significant amount of P also accumulated in the dried culm components ranging from 7.92 kg/ha in densest stand (625 clumps/ha) to 1.90 kg/ha in least dense stand (69 clumps/ha). The total

Table 45. Aboveground biomass P accumulation (kg/clump) at various densities (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	clump	twigs	leaf	dried culms	Total
4x4	0.15(0.015)^{a}	0.05(0.01)^{a}	0.025(0.004)^{a}	0.012(0.002)^{a}	0.23(0.001)^{a}
6x6	0.20(0.011)^{a}	0.11(0.009)^{b}	0.04(0.007)^{a}	0.015(0.001)^{ab}	0.36(0.012)^{b}
8x8	0.28(0.015)^{b}	0.16(0.008)^{c}	0.077(0.008)^{b}	0.018(0.003)^{bc}	0.53(0.01)^{c}
10x10	0.42(0.02)^{c}	0.20(0.014)^{d}	0.085(0.008)^{b}	0.019(0.001)^{c}	0.72(0.03)^{d}
12x12	0.48(0.04)^{d}	0.23(0.017)^{e}	0.012(0.024)^{c}	0.027(0.003)^{d}	0.74(0.02)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, P<0.05)

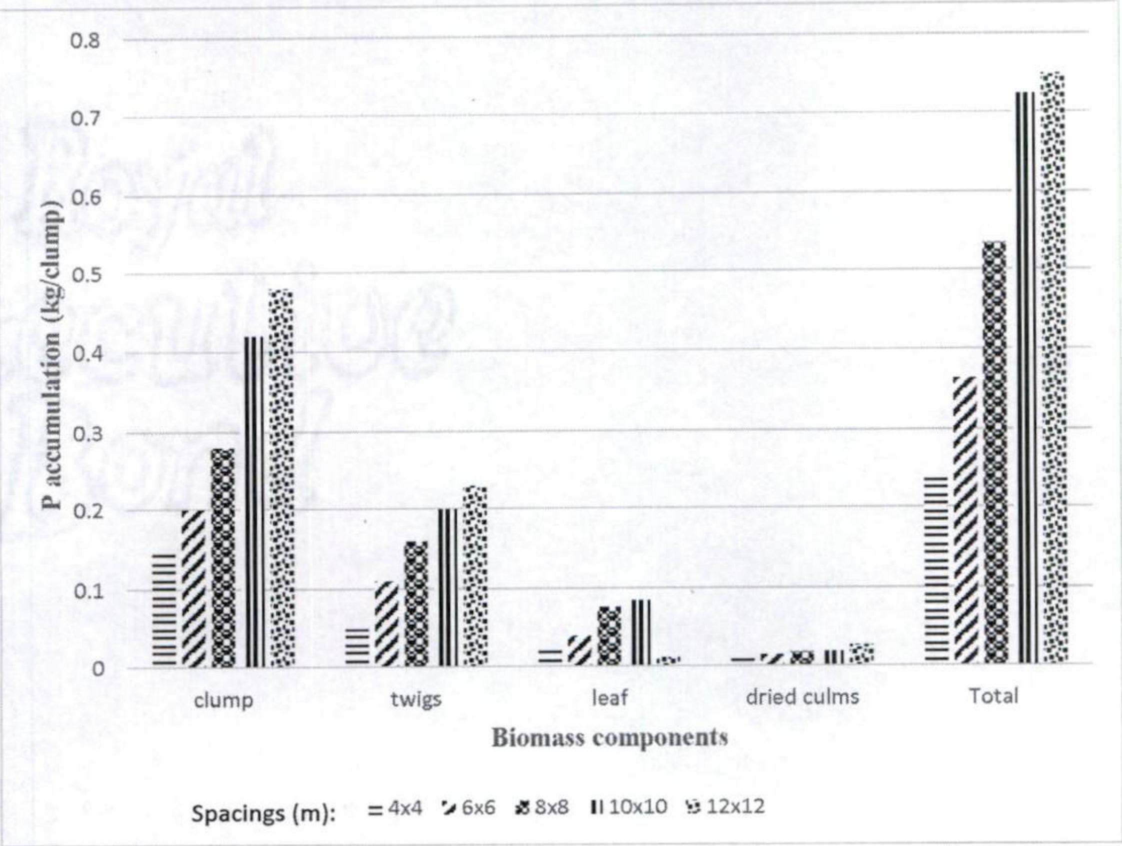


Fig. 49 Aboveground biomass P accumulation (kg/clump) at various densities (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

Table 46. Aboveground biomass P accumulation (kg/ha) at various densities (spacings)of 7 year old bamboo (*Dendrocalamus strictus*)

Density/ha (Spacings)	clump	twig	leaf	dried culms	Total
625(4x4)	97.13(9.53)^{d}	36.05(7.25)^{d}	16.01(2.97)^{b}	7.92(1.13)^{c}	157.13(20.05)^{d}
277(6x6)	55.95(3.27)^{c}	31.91(2.56)^{cd}	11.08(2.18)^{a}	4.33(0.38)^{b}	103.29(5.84)^{c}
156(8x8)	45.18(2.37)^{b}	26.35(1.38)^{bc}	12.07(1.36)^{a}	2.91(0.41)^{a}	86.53(4.20)^{bc}
100(10x10)	42.91(2.55)^{b}	20.65(1.42)^{ab}	8.56(0.88)^{a}	1.98(0.13)^{a}	74.11(3.15)^{ab}
69(12x12)	33.62(3.32)$^{)a}$	15.94(1.21)^{a}	8.51(1.67)^{a}	1.90(0.188)^{a}	59.99(3.21)^{a}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, P<0.05)

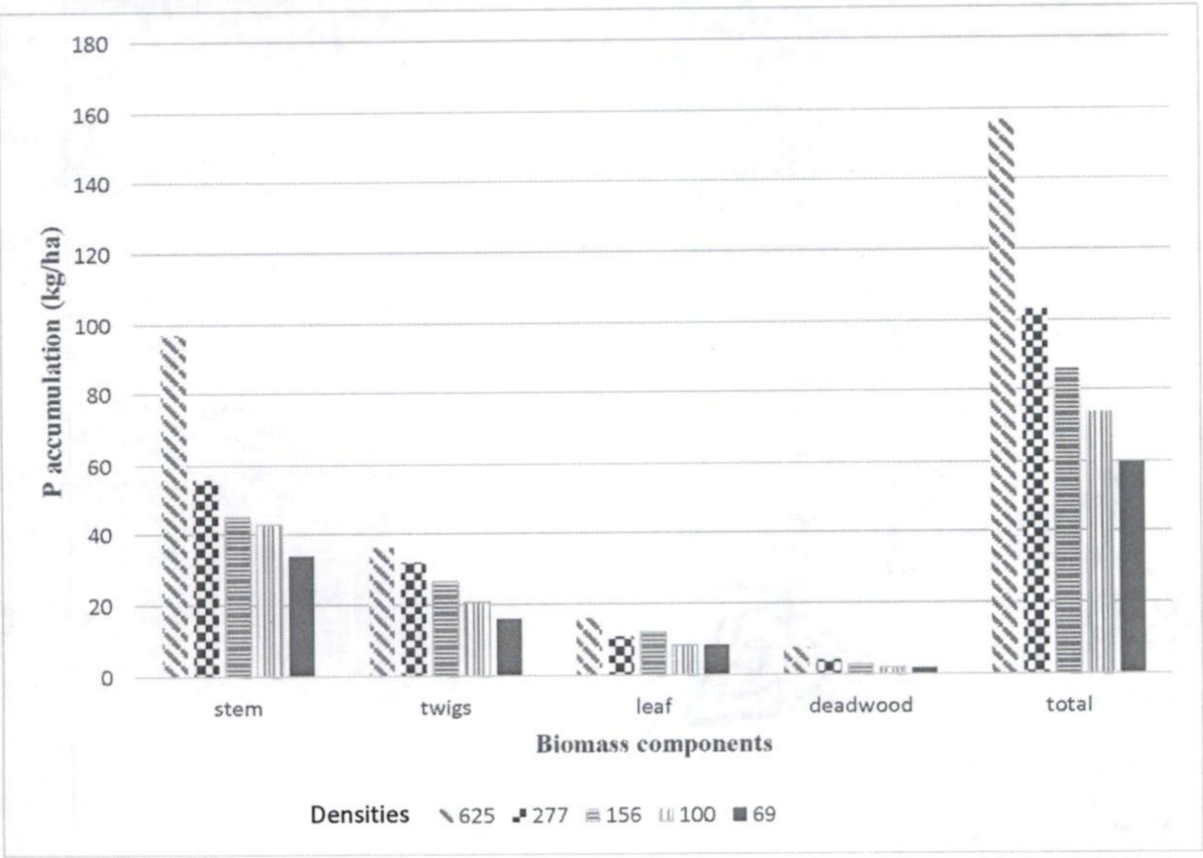


Fig. 50 Aboveground biomass P accumulation (kg/ha) at various densities (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

P accumulation in the aboveground biomass of bamboo varied from 157.13 kg/ha in densest stand (625 clumps/ha) to 59.99 kg/ha in least dense stand (69 clumps/ha). Therefore aboveground P accumulation increased in densest stand by 162 per cent compared to 69 clumps/ha (Table 46 and Fig. 50).

Potassium (K) concentration (%)

The K concentration varied significantly due to the spacings of bamboo (Table 47). The K per cent in culm wood and twig at closest spacing of bamboo (4x4 m) was 0.49 and 0.52 per cent and this gradually increased to 0.84 per cent in 12x12 m spacing. The K concentration in the culm wood due to intermediate spacings (8x8 m) was at par with 10x10 m spacings. The K concentration in the twig component was second highest among the aboveground biomass components. The leaf K concentration was highest among the aboveground bamboo parts in all the spacings of bamboo. The K concentration in leaf and dried culm varied from 0.68 and 0.47 per cent in closest spacing (4x4 m) to 0.93 and 0.68 per cent in widest spacing (12x12 m). The trend of increase of leaf K concentration with increasing spacings of bamboo was observed. For dried culm, the K concentration modestly increased with increasing spacings of bamboo. The bamboo grown at 4x4 m spacing was found to have 0.47 per cent dried culm K whereas at 12x12 m spacing this was recorded upto 0.68 per cent.

Table 47. Aboveground biomass K concentration (%) in 7 year old bamboo (*Dendrocalamus strictus*) as influenced by its spacings

Spacings (m)	culms	twig	leaf	dried culm
4x4	0.49(0.005)^{a}	0.52(0.03)^{a}	0.68(0.02)^{a}	0.47(0.31)^{a}
6x6	0.56(0.05)^{b}	0.59(0.03)^{a}	0.77(0.01)^{b}	0.52(0.02)^{a}
8x8	0.74(0.03)^{c}	0.76(0.06)^{b}	0.82(0.01)^{c}	0.58(0.02)^{b}
10x10	0.78(0.02)^{c}	0.81(0.03)^{bc}	0.88(0.02)^{d}	0.64(0.02)^{c}
12x12	0.84(0.01)^{d}	0.84(0.04)^{c}	0.93(0.04)^{e}	0.68(0.03)^{c}

Values in the parenthesis are Standard Deviation of the Mean

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).

The culm wood K accumulation in the clump was highest 1.45 kg/clump at widest spacing; this significantly decreased to 0.38 kg/clump due to decrease of spacings to 4x4 m (Table 48 and Fig. 51). The twig, leaf and dried culm component P accumulation ranged from 0.11, 0.03 and 0.03 kg/clump in 4x4 m spacing to 0.54, 0.18 and 0.10 kg/clump in widest spacing of bamboo. However, the total aboveground K accumulation in the bamboo biomass was varies from 0.55 kg/clump to 2.27 kg/clump at widest spacing; about 312.72 per cent increase in biomass K was recorded due to increase of spacings to 12x12 m.

K accumulation kg/ha

The K accumulation in the aboveground component parts varied significantly with varying spacings of bamboo (Table 49 and Fig. 52). The K accumulation in culm wood significantly decreased with stand density. The K accumulation was maximum (240.64 kg/ha) at culm wood in the densest stand (625 clumps/ha) and minimum (100.48 kg/ha) in least dense stand (69 clump/ha). Highest culm wood K accumulation recorded by densest stand and this was decreased to 100.48 kg/ha in stand density of 69 clumps/ha. The increase of K accumulation in culm wood due to stand density was 139.49 per cent in densest stand (625 clumps/ha) compared to 69 clumps/ha. However, the twig and leaf had 71.14 and 19.96 kg/ha of K in densest stand (625 clumps/ha) to 37.27 and 12.73 kg/ha in least dense stand (69 clumps/ha) respectively. The dried culm accounted 23.02 kg/ha of K accumulation in densest stand to lowest of 7.10 kg/ha in the density of 156 clumps/ha. The total amount of K accumulated in aboveground bamboo biomass ranged between 354.77 kg/ha in densest stand (625 clumps/ha) and 157.60 kg/ha at the density of 69 clumps/ha. The ultimate increase of K accumulation in dense stand was 125.10 per cent. The results reveal significant amount of nutrients (N P K) stored in the aboveground biomass components. This storage was maximum when the bamboo grown at dense stand of 625 and 277 clumps/ha rather than 69 and 100 clumps/ha.

Table 48. Aboveground biomass K accumulation (kg/clump) at various densities (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

Spacings (m)	clump	twigs	leaf	dried culms	Total
4x4	0.38(0.019)^{a}	0.11(0.02)^{a}	0.03(0.007)^{a}	0.03(0.009)^{a}	0.55(0.01)^{a}
6x6	0.51(0.02)^{b}	0.25(0.01)^{b}	0.05(0.012)^{a}	0.04(0.001)^{a}	0.85(0.008)^{b}
8x8	0.88(0.02)^{c}	0.42(0.03)^{c}	0.10(0.011)^{b}	0.06(0.001)^{b}	1.46(0.04)^{c}
10x10	1.27(0.08)^{d}	0.51(0.03)^{d}	0.12(0.012)^{b}	0.07(0.007)^{b}	1.97(0.06)^{d}
12x12	1.45(0.12)^{e}	0.54(0.03)^{d}	0.18(0.04)^{c}	0.10(0.004)^{c}	2.27(0.09)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, P<0.05)

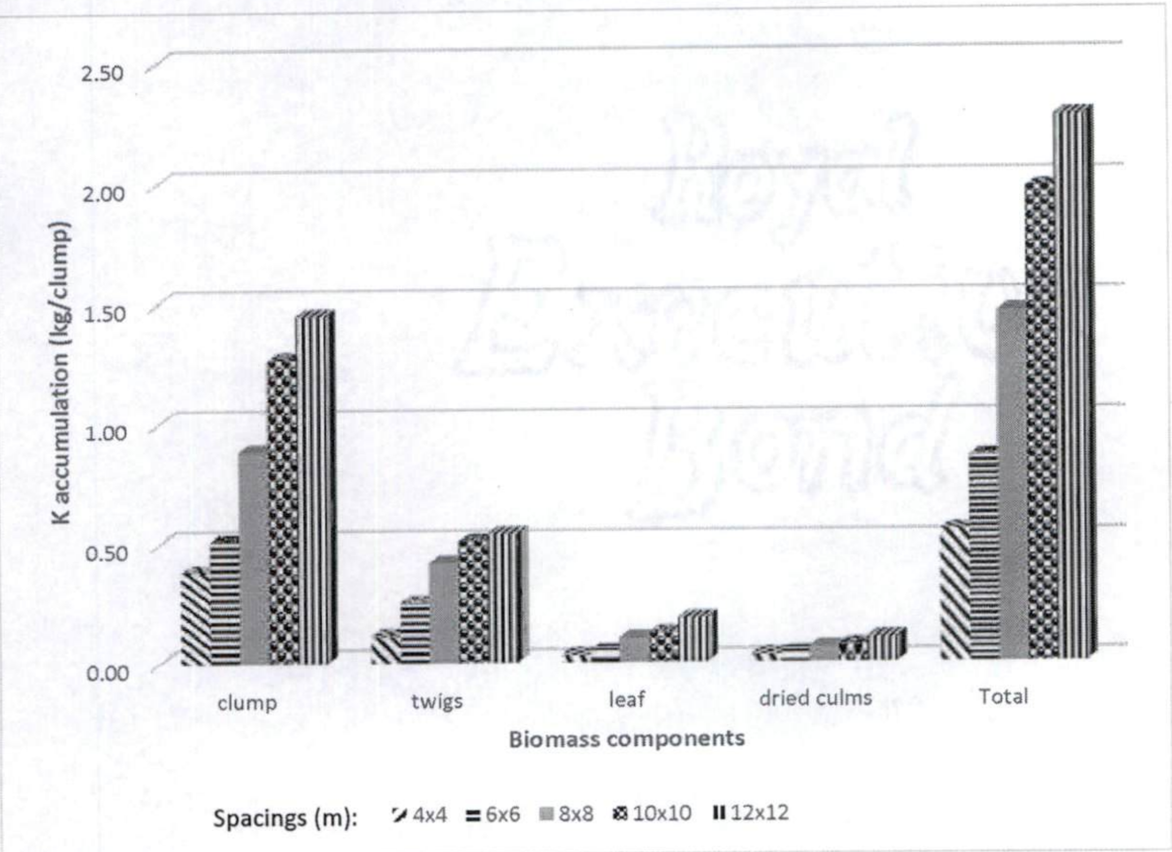


Fig. 51 Aboveground biomass K accumulation (kg/clump) at various densities (spacings) of 7 year old bamboo (*Dendrocalamus strictus*)

Table 49. Aboveground biomass K accumulation (kg/ha) in 7 year old bamboo (*Dendrocalamus strictus*) as influenced by its spacings

Density/ha (Spacings)	clump	twig	leaf	dried culms	Total
625(4x4)	240.64(12.31)^{c}	71.14(14.27)^{c}	19.96(4.05)^{b}	23.02(5.79)^{c}	354.77(13.6)^{e}
277(6x6)	142.22(6.98)^{b}	70.00(3.73)^{c}	14.99(3.32)^{ab}	12.63(0.32)^{b}	239.86(6.88)^{d}
156(8x8)	138.74(4.52)^{b}	67.00(6.06)^{c}	16.71(1.75)^{ab}	10.89(1.75)^{ab}	233.36(10.16)^{c}
100(10x10)	127.50(8.74)^{b}	51.23(3.88)^{b}	12.42(1.20)^{a}	7.10(0.73)^{a}	198.27(10.56)^{b}
69(12x12)	100.48(8.33)^{a}	37.27(2.11)^{a}	12.73(2.79)^{a}	7.11(0.34)^{a}	157.60(7.26)^{a}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$)

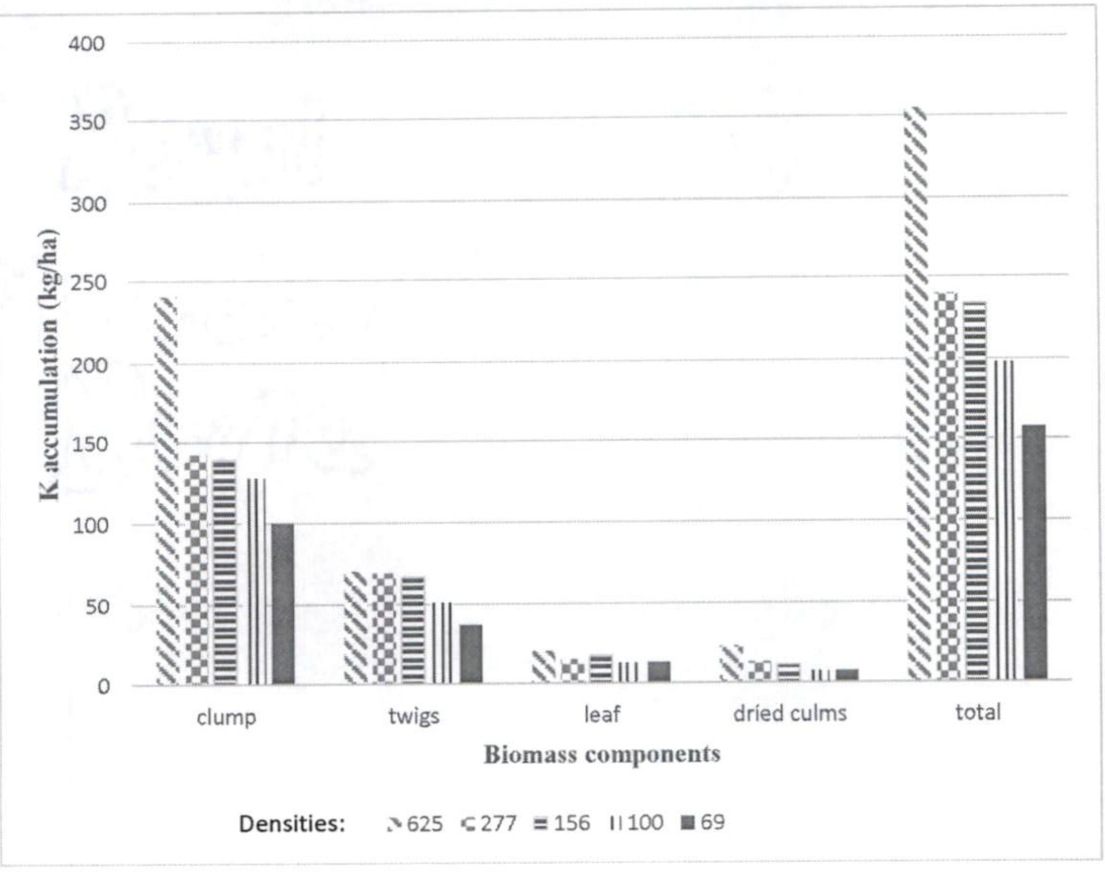


Fig. 52 Aboveground biomass K accumulation (kg/ha) in 7 year old bamboo (*Dendrocalamus strictus*) as influenced by its spacings

4.12 Carbon accumulation in bamboo

Carbon partition in the aboveground biomass

The carbon partition in the aboveground components of culm wood, twig, leaf and dried culm under varying spacings of 7 year old bamboo are presented in the table 50. The results reveal that, the C concentration (%) in the aboveground component parts was in the order: leaf>twig>culm wood>dried culm. The culm wood was maximum (79.12 kg/clump) in the widest spacings (12x12 m) and minimum (35.21 kg/clump) at closest spacings (4x4 m) of bamboo (Table 51 and Fig. 53).

Table 50. C concentration (%) in the aboveground components of 7 year old bamboo (*Dendrocalamus strictus*) grown at varying spacings

Spacings (m)	culms	twig	leaf	dried culm
4x4	44.9(0.57)^{a}	48.21(0.97)^{a}	55.24(0.99)^{a}	43.62 (0.53)^{b}
6x6	46.16(0.91)^{b}	50.84(1.20)^{b}	54.46(1.14)^{a}	43.57(1.50)^{b}
8x8	46.66(0.27)^{b}	50.66(1.30)^{b}	54.38(1.13)^{a}	40.83(1.19)^{a}
10x10	46.08(0.49)^{b}	49.64(0.47)^{ab}	55.50(1.17)^{a}	42.36(1.01)^{ab}
12x12	45.72(0.10)^{ab}	50.11(1.62)^{ab}	54.60(0.66)^{a}	41.97(1.13)^{ab}

Values in the parenthesis are Standard Deviation of the Mean

Values followed by same superscript in a column do not differ significantly (LSD, $P<0.05$).

The C accumulation in the wide spacings (10x10 and 12x12 m) was increased by 112.75 and 124.70 per cent compared to closest spacings of 4x4 m. The C accumulation in the 10x10 m spacing (74.91 kg/clump) was at par with 12x12 m spacings of bamboo. As the spacings of bamboo increased, the C accumulation in the culm wood was significantly increased. Similar trend of C accumulation was also found for twig parts. The C accumulation in the twig components was second highest after culm wood, this was 10.46 kg/clump at closest spacings (4x4 m) and increased to 32.15 kg/clump in the widest spacings of 12x12 m. The C accumulation in 12x12 m spacings was 3.07 times more compared to 4x4 m

Table 51. C accumulation (kg/clump) in aboveground components of 7 year old bamboo (*Dendrocalamus strictus*) grown at varying spacings

	C kg/clump				
Spacings (m)	**clump**	**twig**	**leaf**	**dried culms**	**Total C**
4x4	35.21(1.87)^{a}	10.46(2.55)^{a}	2.56(0.48)^{a}	3.33(0.63)^{a}	51.58(5.38)^{a}
6x6	42.01(3.44)^{b}	21.61(1.24)^{b}	3.81(0.82)^{a}	3.78(0.35)^{ab}	71.21(5.24)^{b}
8x8	55.58(1.57)^{c}	28.33(1.22)^{c}	7.04(0.80)^{b}	4.91(0.95)^{c}	95.87(3.20)^{c}
10x10	74.91(3.55)^{d}	31.07(1.93)^{c}	7.75(0.67)^{b}	4.65(0.35)^{bc}	118.40(4.33)^{d}
12x12	79.12(5.33)^{d}	32.15(3.82)^{c}	10.75(1.89)^{c}	6.28(0.28)^{d}	128.32(3.20)^{e}

Values in the parenthesis are Standard Deviation of the Mean
Values followed by same superscript in a column do not differ significantly (LSD, P<0.05)

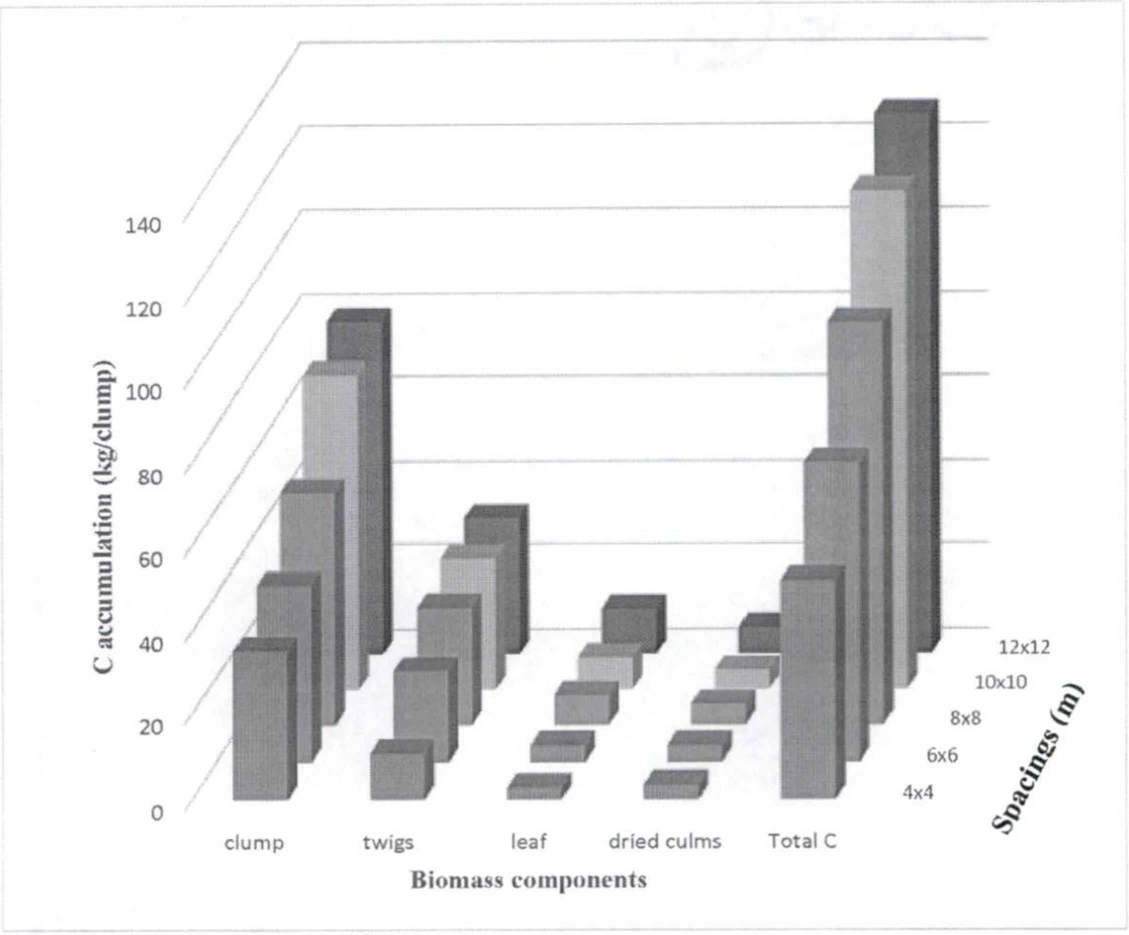


Fig. 53 C accumulation (kg/clump) in aboveground components of 7 year old bamboo (*Dendrocalamus strictus*) grown at varying spacings

spacings. In case of leaf and dried culm, the C accumulation at intermediate spacings (8x8 m) was 2.75 and 1.47 times higher compared to closest spacings (4x4 m). Whereas the C accumulation in leaf and dead wood in the widest spacings of 12x12 m was 10.75 kg/clump and 6.28 kg/clump, this was 319.92 and 88.58 per cent more compared to closest spacing of 4x4 m. The C accumulation in the leaf biomass in the intermediate spacings (8x8 m) was at par with C accumulation in 10x10 m spacing. The total C accumulation in the aboveground biomass was significantly high in the wide spacings of 10x10 and 12x12 m compared to close spacings of 4x4 and 6x6 m. At 4x4 m spacings the total aboveground C accumulation was 51.58 kg/clump which was increased when the spacings increased to 12x12 m and recorded upto the tune of 128.32 kg/clump. The increase of C accumulation in the widest spacings of 12x12 m was 2.51 times high compared to closest spacings (4x4 m).

C accumulation at different stand densities (Mg/ha)

When the C accumulation in the aboveground biomass components at varying spacings of bamboo plots were extrapolated into stand level, significant difference in carbon accumulation in the aboveground biomass components was observed under all the spacings of 7 year old bamboo (Table 52 and Fig. 54). Due to densest stand (625 clumps/ha) significantly higher amount (22 Mg/ha) of culm wood C accumulation was recorded. As the density decreased to least (69 clumps/ha), the stemwood C accumulation decreased to 5.45 Mg/ha; this decrease was 304 per cent compared to stand density having 625 clumps/ha. For twigs and leaf, the C accumulation followed the trend of decrease with decreasing stem density. For instance, the densest stand (625 clumps/ha) recorded 6.54 and 1.60 Mg/ha of C in the twig and leaf components which decreased to 2.21 and 0.74 Mg/ha when the density of clumps decreased to 69 clumps/ha. However C accumulation in the leaf components with density of 277 clumps/ha was 1.05 Mg/ha. This was at par with densities of 156, 100 and 69 clumps/ha. In case of dried culm, the C accumulation at density of 100 clumps/ha was at par with dried culm C accumulation in 69 clumps/ha. The dried culm C accumulation in densest stand (625 clumps/ha) was

Table 52. Aboveground component biomass C accumulation (Mg/ha) at various densities of 7 year old bamboo (*Dendrocalamus strictus*)

Density/ha (Spacings)	clump	twig	leaf	dried culms	Total C
625(4x4)	22.00(1.17)^{d}	6.54(1.59)^{c}	1.60(0.30)^{b}	2.08(0.39)^{c}	32.24(3.36)^{d}
277(6x6)	11.63(0.95)^{c}	5.98(0.34)^{c}	1.05(0.23)^{a}	1.04(0.09)^{b}	19.72(1.45)^{c}
156 (8x8)	8.67(0.24)^{b}	4.41(0.19)^{b}	1.09(0.12)^{a}	0.76(0.14)^{ab}	14.95(0.49)^{b}
100(10x10)	7.49(0.35)^{b}	3.10(0.19)^{ab}	0.77(0.07)^{a}	0.46(0.03)^{a}	11.84(0.43)^{a}
69(12x12)	5.45(0.36)^{a}	2.21(0.26)^{a}	0.74(0.13)^{a}	0.43(0.01)^{a}	8.85(0.22)^{a}

Values in the parenthesis are Standard Deviation of the Mean

Values followed by same superscript in a column do not differ significantly (LSD, P<0.05)

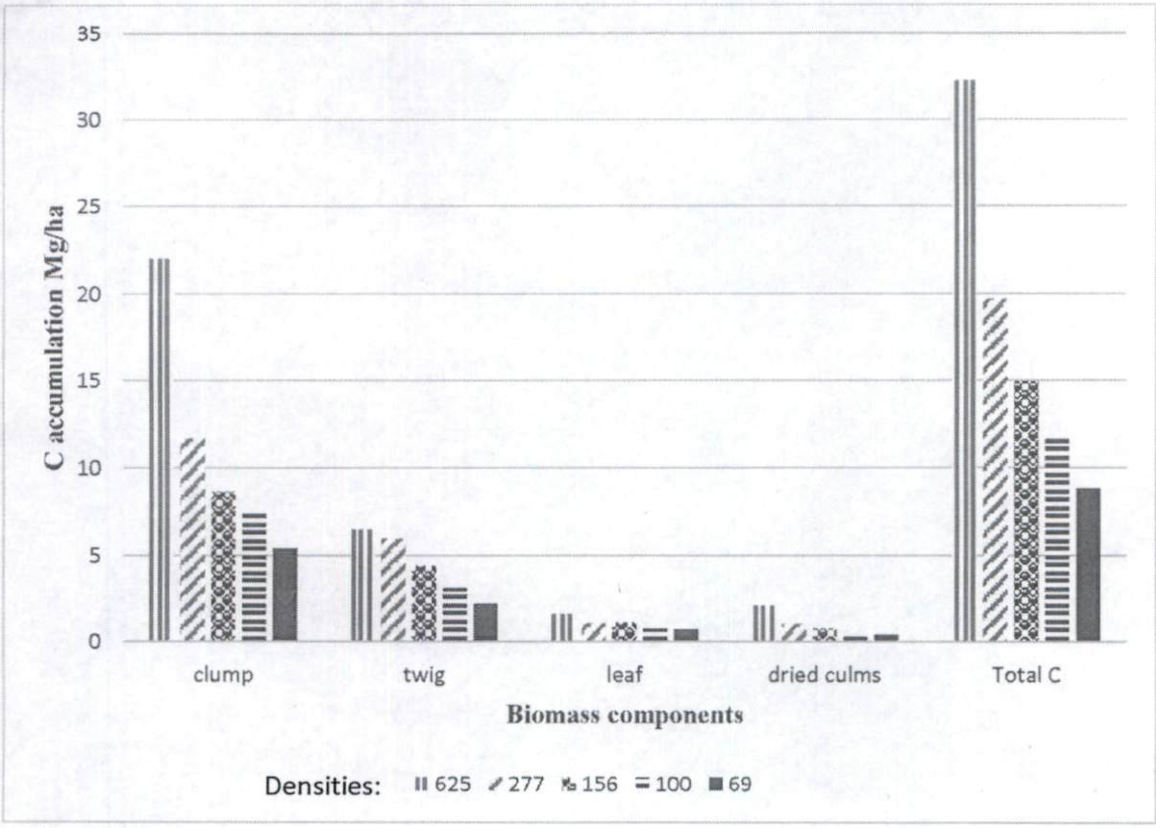


Fig. 54 Aboveground component biomass C accumulation (Mg/ha) at various densities of 7 year old bamboo (*Dendrocalamus strictus*)

2.08 Mg/ha. This was significantly low (0.43 Mg/ha) under least dense stand of 69 clumps/ha. The C accumulation in the aboveground biomass was invariably high (32.24 Mg/ha) at densest bamboo stand (625 clumps/ha) declined to 8.85 Mg/ha at 69 clumps/ha. This decrease was upto 264 per cent compared to densest stand of 625 clumps/ha.

Carbon accumulation potential

The carbon accumulation potential of bamboo per year under varying spacings of 7 year old bamboo plantation reveal that, the culm wood components accumulated maximum amount of carbon upto the tune of 3.14 Mg/ha/year at the densest bamboo stand of 625 clumps/ha (Fig. 55). The bamboo maintained at 156 clumps/ha had accumulated culm wood carbon up to 1.24 Mg/ha/year; this accumulation was 0.62 times lesser compared to bamboos density having 69 clumps/ha. The culm wood C accumulation per year contributed highest among the aboveground biomass components followed by twigs under all the spacings of bamboo. The twigs stored C up to 0.93 Mg/ha/year under the density of 625 clumps/ha, which significantly decreased with decreasing density of bamboo and recorded least accumulation of 0.32 Mg/ha/year in the density of 69 clumps/ha. The bamboo leaves also stored significant amount of carbon every year in their biomass. About 0.23 Mg/ha/year of leaf carbon can storage at densest stand of 625 clumps/ha compared to 0.11 Mg/ha/year under the density of 69 clumps/ha.

Therefore the results clearly show that, with varying spacings or stand density of bamboo, the carbon accumulation in the aboveground biomass also significantly varied. Within the clumps, the significant difference in C accumulation in the aboveground components parts (culm wood, twig, leaf and dried culm) was observed due to the influence of spacings of bamboo.

4.13 Allometric equations

Allometric relationships were attempted in the present study linking aboveground biomass carbon accumulation with variables like clump height, clump DBH and

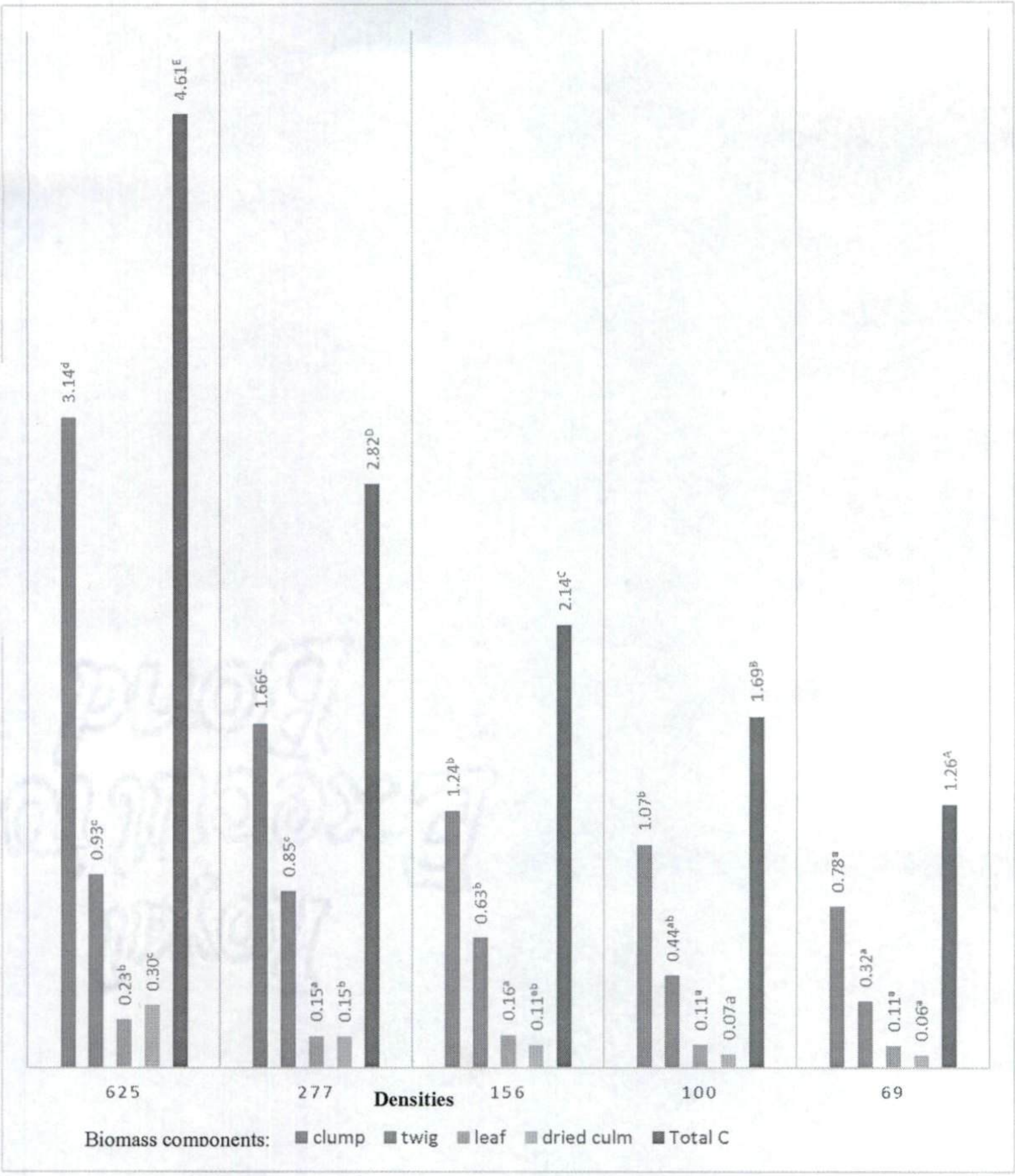


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Fig. 55 C accumulation potential (Mg/ha per year) in aboveground biomass components of 7 year old bamboo (*Dendrocalamus strictus*) grown at various density

Table 53. Allometric relationships linking aboveground biomass (kg/clump) with culms, DBH and height in 7 year old bamboo (*Dendrocalamus strictus*).

Dependent variables	Equations	R^2	Standard error
Clump wood biomass	$SB = 0.45\ C - 24.74\ D - 38.22\ H + 425.90$	0.81	18.95
	$SB = -193.88\ D + 357.51\ D^2 + 518.83$	0.85	16.04
Twig biomass	$TB = 0.16\ C + 23.47\ D - 8.01\ H + 65.11$	0.94	6.07
	$TB = 19.58\ D + 19.59\ D^2 - 17.72$	0.86	6.59
Leaf biomass	$Lb = 0.11\ C - 7.65\ D - 4.72\ H + 49.73$	0.83	2.63
	$LB = -74.74\ D + 36.60\ D^2 + 42.80$	0.77	2.95
Dried wood biomass	$Db = 0.048\ C - 2.67\ D - 1.99\ H + 26.16$	0.65	1.92
	$DB = -58.73\ D + 25.87\ D^2 + 41.18$	0.67	1.77
Total aboveground biomass	$TAB = 0.78\ C - 11.60\ D - 52.95\ H + 566.86$	0.89	22.82
	$TAB = -907.78\ D + 439.59\ D^2 + 585.09$	0.89	21.83

Independent variables are (1) C = number of culms/clump, (2) D = clump DBH (m), (3) H = clump height (m).

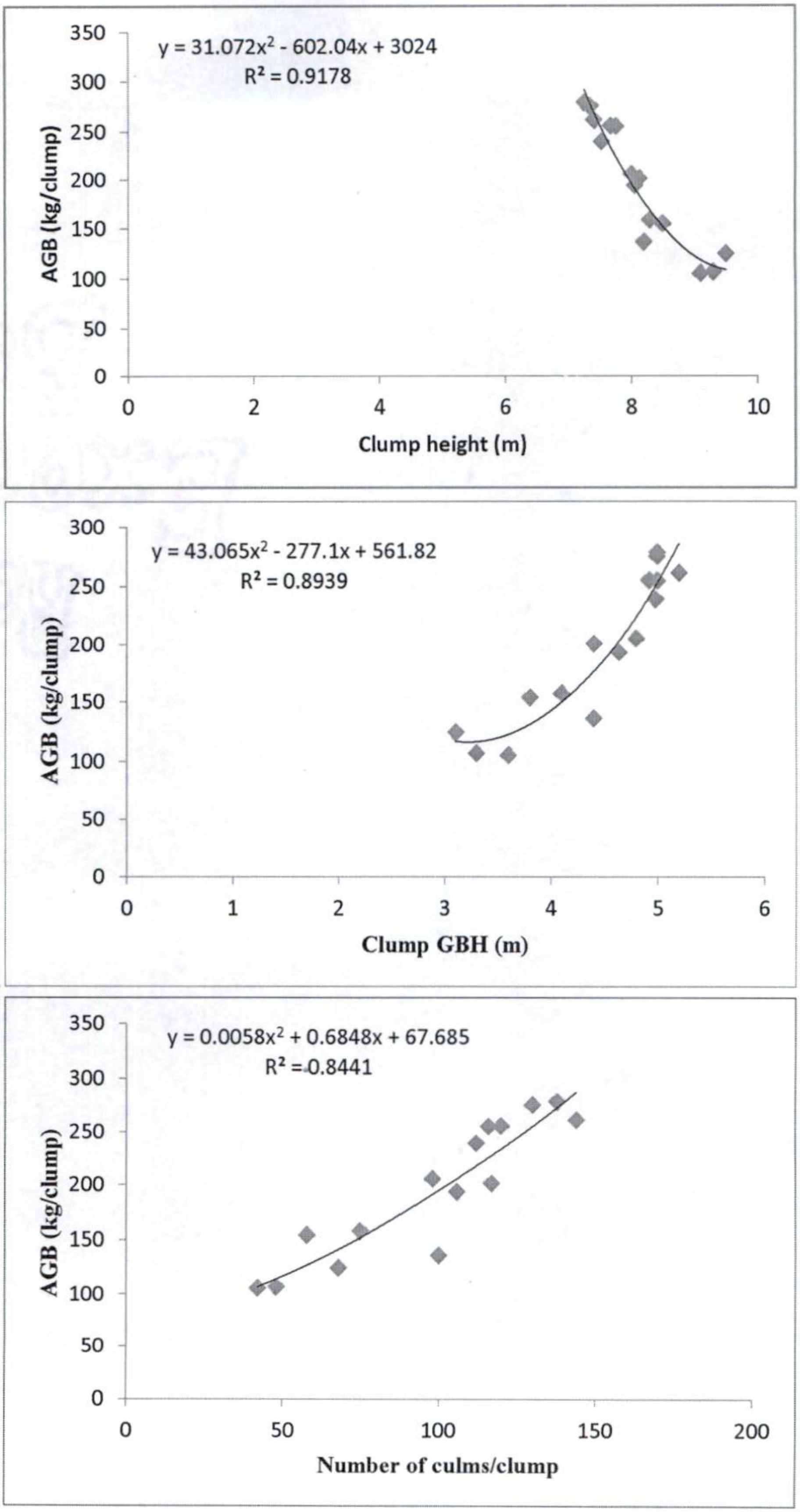

Fig. 56 Prediction models for aboveground component biomass in 7 year old bamboo (*Dendrocalamus strictus*)

Table 54. Allometric relationships linking aboveground biomass carbon with culms, GBH and height in 7 year old bamboo (*Dendrocalamus strictus*).

Dependent variables	Equations	R^2	Standard error
Clump wood	SC = 0.216 culms – 8.09 D – 16.68 H + 183.39	0.83	8.36
Twig	TC = 0.08 culms + 14.11 D – 3.26 H + 22.71	0.88	3.21
Leaf	LC = 0.062 culms – 4.11 D – 2.55 H + 26.80	0.84	1.41
Dried wood	DC = 0.016 culms – 1.56 D – 1.05 height + 13.78	0.62	0.79
Total aboveground biomass	TAC = 0.38 culms + 0.34 D – 23.55 height + 246.69	0.90	10.15

Independent variables are (1) C = number of culms/clump, (2) D = clump DBH (m), (3) H = clump height (m).

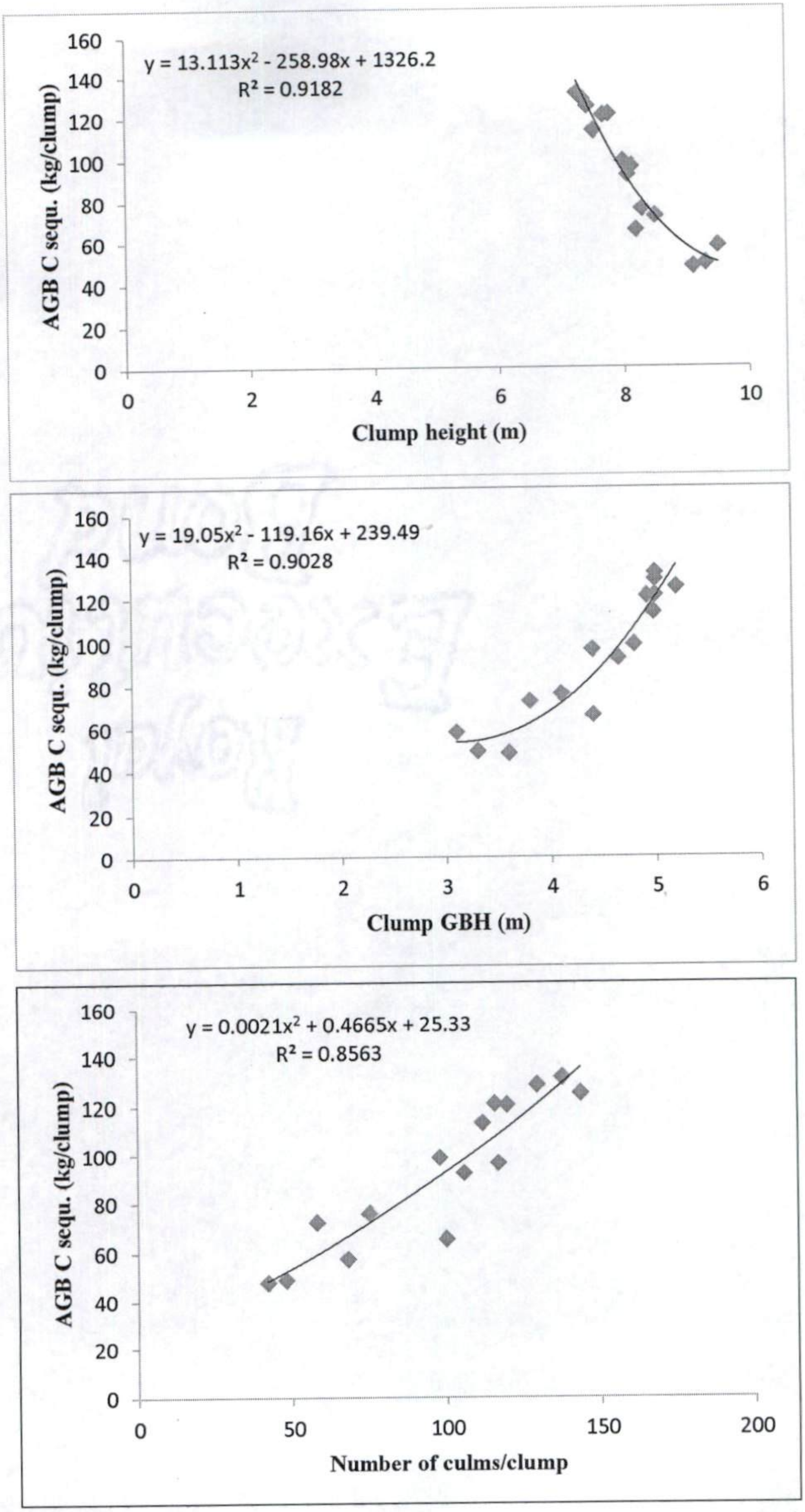

Fig. 57 Prediction models for aboveground component biomass carbon sequestration in 7 year old bamboo (*Dendrocalamus strictus*)

number of culms/clump which gave reasonably good predictions (Kumar et al. 2005). The simple linear, quadratic and logarithmic equations were fitted for biomass prediction. While for biomass C accumulation, linear and logarithmic equations were fitted (Table 53 and Fig. 56).

Among the equations attempted for estimating biomass, linear equations with three variable viz. number culms, clump height and clump DBH gave high R^2 values. The culm wood biomass (kg/clump) was found to be best fit with R^2 value of 0.81 ($SB = 0.45$ culms $- 24.74\ D - 38.22\ H + 425.90$). The quadratic equation for culm wood biomass with DBH as one variable show R^2, 0.85 which is comparatively higher than linear equation. In case of twig biomass, linear equation with highest R^2 value of 0.94 followed by leaf biomass ($R^2 = 0.83$). While the dried culm found low R^2, 0.65 value. However, for total aboveground biomass, the predicted equation was $TAB = 0.78\ C - 11.60\ D - 52.95\ H + 566.86$, $R^2 = 0.89$.

For predicting aboveground biomass carbon accumulation (kg/clump) the linear and logarithmic equations were tried (Table 54 and Fig. 57). Among the component biomass carbon, the maximum R^2 value was recorded for twig component ($TC = 0.08$ culms $+ 14.11\ D - 3.26\ H + 22.71$, $R^2 = 0.88$) followed by leaf (R^2, 0.84) and culm wood carbon (R^2, 0.83). The dried culm show weak relationship (R^2, 0.62). The twig biomass carbon fitted best with R^2 value of 0.85. However, for total aboveground C accumulation, the fitted equation was $TAC = 0.38$ culms $+ 0.34\ D - 23.55\ H + 246.69$, $R^2 = 0.90$.

Therefore, allometric equations with three variable viz. clump height, clump girth and number of culms presumably gave better prediction for both aboveground biomass and carbon accumulation.

Discussion

5. DISCUSSION

Bamboo is commonly known as "poor man's timber" and play a vital role in improving the socio-economic status of rural people. Husbandry of this vital crop in and around homesteads/farm lands vis-à-vis agroforestry systems may be one of the best ways, especially under the land constraint situations of Kerala. Thus selection of ideal spacing of bamboo in agroforestry is of paramount importance. Hence, attempts were made to boost production through appropriate local practices. The discussions hereunder deal with growth parameters of bamboo, overstorey light interception (PAR), belowground competition and standardization of spacings of bamboo for understorey herbaceous growth and productivity.

5.1 Intercropping with bamboo

5.1.1 Growth attributes of bamboo and physico-chemical properties of soil before understorey planting

Stand density reflects the degree of crowding of stems within the area (Gingrich 1967). The growth attributes of trees in a stand are greatly affected by stand density. The height growth is much influenced by stocking. Several researchers have shown that height growth increases with increasing stand density. Menzies *et al.* (1989) noted an increase in height growth with decreasing spacings of radiata pine from 200 to 800 stems/ha. Mason (1992) also found a reduction in height growth with decreasing stocking below 2000 stems/ha in Nelder experiments. The present study also showed a wide variation in the bamboo height and clump diameter increment with spacings. Due to decreasing bamboo spacings from 4x4 to 12x12 m, the clump height of bamboo decreased from 9.11 m to 7.31 and the clump DBH increased from 1.03 m to 1.58. Similar growth observations were made by Kibwage *et al.* (2008) in the bamboo-tobacco growing regions of Kenya. The ability of the tree to grow taller in denser stands and larger girth in less denser stands was evident; this is in confirmation with Hummel (2000). The number of live culms and crown spread of bamboo also increased with increasing spacings of bamboo. The lesser number of culms and crown spread in close spacings may be attributed to less available growing space and more crown competition. Fisher and Binkley (1999) reported that competition for light in mixed plantations result in decreasing crown diameter.

Generally, the relative importance of soil minerals influencing plant growth depends upon specific soil condition. In the present study the p^H of the soil decreased with the increasing stand density of bamboo (decreasing spacings). This may be due to lesser addition of organic matter due to decreasing density of bamboo. Thevathasan *et al.* (2004) reported that soil organic matter adjacent to tree rows was high as a result of more litterfall inputs and fine root turnover compared to wide rows. Baah-Acheamfour *et al.* (2014) revealed that lower soil p^H in the hedgerow than in the shelterbelt system is due to acidification of the soil by producing more organic acids during litter decomposition. The total N, avail. P and avail. K have declined with increasing spacings of bamboo and lowest was recorded by open plot. The higher nutrient content on close spacings may be attributed to addition of soil nutrients by bamboo through more litterfall and nutrient turnover as reported by Santantorio (1990). Das *et al.* (2010) reveal that *Acacia lenticularis* stand density in Bihar significantly affected the organic carbon, and available N, P and K with maximum values under density 2500 tree/ha and minimum under density 625 trees/ha. So the present study clearly reveal that soil fertility substantially increased at densest stand of 625 clumps/ha (4x4 m) compared to least dense stand of 69 clumps/ha (12x12 m) and open plot. However, understorey crop productivity is not only affected by soil factors but also the other factors like overstorey stocking, bamboo rooting intensity and distribution, extent of belowground competition etc. and these factors are discussed subsequently.

5.1.2 Photosynthetically Active Radiation (PAR)

Photosynthetically Active Radiation (PAR), one of the requirement for productive growth of plants, is used to evaluate the growth potential of understorey component in agroforestry systems. The important factor to be considered here is the light-use efficiency. The biomass yield limit is set by the available light, its efficiency of interception and the efficiency with which intercepted light is converted into biomass (Long *et al.*, 2006). This was confirmed by comparing PAR with spacings of bamboo. The daily mean values of PAR showed a clear positive relation with spacings. This is possibly because increasing spacings of bamboo decreased the light interception by canopy. Wider spacings of bamboo intercepted less solar radiation by canopy and allowed more solar radiation to reach the ground which might have stimulated the understorey growth and resulted in more understorey dry matter production. Kasanga and Monsi (1954) also revealed that, the understorey growth rate is proportional to the amount of radiation intercepted by the canopy. Baraldi *et al.* (1995) reported that, shading can change the quality of light reaching the understorey. PAR of 62 to 82 % resulted in better turmeric and ginger dry matter production and rhizome yield. However chittaratha in open plot recorded maximum dry matter production. Nevertheless, in widest spacing (12x12 m) of bamboo, chittaratha intercropping resulted in better dry matter production and rhizome yield compared to close spacings (4x4 and 6x6 m). Kunhamu *et al.* (2008) reported that ginger yield increased linearly with increasing PAR in *Acacia mangium* based intercropping. The reduced yield of intercrops in close spacings of bamboo may be primarily due to competition for light, in which larger plants have a disproportionate advantage by shading smaller ones (Casper and Jackson, 1997). On the other hand, Paul *et al.* (2002) reported that in the shelterbelt system, pronounced shading from the overstorey canopy may have inhibited the germination and growth of understory vegetation. Therefore measurement of light in the agroforestry is important for standardization of spacings. In the present study PAR with 60-80 % light interception by the bamboo canopy may be considered ideal for understorey medicinal crops and this was achieved under 10x10 and 12x12 m spacings of bamboo.

5.1.3 Stand Leaf Area Index (LAI)

Minimising competition between trees and crops and maximising the use of available resources is central to improving yields and overall productivity in any agroforestry systems (Cannell *et al.*, 1996). Trees minimise the amount of solar radiation reaching to understorey crops through shading. The extent of shade varies according to crown dimensions, tree phenology and leaf density. This is also applicable to bamboo. In the present study as bamboo spacing increased, the stand leaf area index of bamboo decreased. It was lowest (0.45) in widest spacing (12x12 m) and highest (6.78) in closest spacing (4x4 m). In agroforestry practices, the factors like LAI and crown development are of outmost importance for standardization of spacing. In monoculture systems, the competition between plants is mainly for light, but in polyculture system the plant competitive interaction was experienced for both belowground and aboveground resources (Faget *et al.*, 2012). The higher LAI may distress the understorey crop growth in close spacings of bamboo. This was substantiated by lesser dry matter production and rhizome yield in close spacings compared to wide spacings of bamboo. Nissen *et al.* (1999) reported that both shading and belowground competition decreased the yield of *Brassica oleracea* in a eucalyptus based alley cropping system in the Philippines. Understorey turmeric, ginger and chittaratha cultivated along with increasing spacings of bamboo exhibited increased plant height, number of tillers and leaves, dry matter production and rhizome yield. Gao *et al.* (2013) found that, increasing spacing of the overstorey crops influence the induced growth of understorey crops. Low understorey PAR levels resulting from high level of LAI significantly reduced yield of winter wheat near tree row in China (Chirko *et al.*, 1999).

5.1.4 Understorey herbaceous growth and productivity at varying spacings of bamboo

The spacings of bamboo significantly affected the understorey herbaceous growth and productivity. Invariably, the understorey turmeric and ginger responded better under large gaps (12x12 and 10x10 m) between the bamboo and chittaratha in control plot (open), implying a favorable effect of high radiation intensity and reduced belowground competition by overstorey. This is further exemplified by significantly higher number of tillers per hill and leaves in the wide (10x10 and 12x12 m) spacings and control plots (open). The dry matter production generally followed increasing trend with time-course. As the spacings of bamboo increased, the shoot, leaf and rhizome dry matter production significantly increased in all the understorey crops. This increase was highest in turmeric at 12x12 m spacings and in ginger was maximum in 10x10 m while chittaratha found its maximum component dry matter production in open plot followed by under widest spacing of bamboo. The lower dry matter in close spacings may be due to lesser PAR. Biscoe and Gallagher (1975) reported that plant dry matter production is generally directly related to the intercepted radiation. Further, the spacings of bamboo in turn exerted major impact on rhizome development and yield. The turmeric produced largest yield at widest (12x12 m) spacing of bamboo, while ginger yield was better at wider spacing (10x10 m) followed by 12x12 m and control plot. In case of chittaratha, the growth was better in open plot. The turmeric and ginger rhizome length, rhizome breadth and yield were drastically decreased under closer spacing while it was increased at wider spacings of poplars (Jaiswal *et al.*, 1993). The chittaratha yield in the present study was much higher than in the study conducted by Jessykutty and Jayachandran (2009). They also observed that the amount of dry matter production under medium and mature oil palms was lower compared to open plot. The maximum rhizome yield of 7.34 t/ha was recorded in open field followed by young (4.33 t/ha) and mature (4.09 t/ha) oil palm plantation.

Oleoresin is one of the imperative parameter over which the worthiness of medicinal crops is valued. The oleoresin content in turmeric ranged from 8.27 in the closest spacing of bamboo to 11.68 % in the control plot and in ginger lowest was in 4x4 m and highest in 8x8 m spacing of bamboo, while in case of chittaratha, highest in control followed by 12x12 m spacings which further decreased with decreasing spacings of bamboo. The oleoresin percent in turmeric, ginger and chittaratha significantly varied over the spacings, implying that, oleoresin content is perhaps dependent on spacings of bamboo. But the previous studies conducted by Latha (1994) reported that oleoresin and shade were independent. Similar observation also recorded by Kumar *et al.* (2001) in ginger. Other workers have revealed that, the ginger grown under shade have better quality oleoresin and essential oil concentrations over the open (Babu and Jayachandran, 1994 and Kumar *et al.*, 2005). Other factors like time of harvest, varieties, genetic factors etc. may be contributing to the oleoresin content and superiority (FAO, 2002).

The growth and development of understorey crops may depend on overstorey species, soil condition and in turn the uptake of nutrients from the soil. Several studies reveal that understorey crop nutrient uptake is strongly correlated with overstorey stand density, root length, understorey photosynthetically active radiations and the amount of plant nutrient demand (Rowe *et al.*, 2001; Zhang, 1999 and Gao *et al.*, 2013). The uptake of N, P and K increased accordingly over the spacings due to decreasing belowground competition and more PAR availability. Higher uptake of N:P:K may be due to higher root growth and biomass of understorey crops in wide spacings of bamboo (10x10 and 12x12 m). Ingestad and Agren (1988) noted that root growth has a large effect on nutrient uptake leading to strong plant-soil interaction. Kattge *et al.* (2009) also reported that relationship between maximum photosynthetic capacity and uptake of nutrient content by understorey crops are highly correlating. Livesley *et al.* (2000) revealed that maize production was decreased with greater proximity to *Grevellia robusta* tree rows due to competitive interactions. This may be the reason for better growth performance of turmeric and ginger in wider spacings of 12x12 and 10x10 m and the chittaratha in the open plot.

Further, understorey growth is regulated by overstorey bamboo. Bamboo being a deciduous crop, close spacings add more litter to the ground which may hinder the understorey crop growth. But in wide spacings (10x10 and 12x12 m) the net surface area to crown cover of bamboo may be more which lead to lesser litter accumulation. Chander *et al.* (1998) reported that litter and soil organic matter increased in closer spacings of wheat-*Dalbergia sisoo* based agroforestry system which resulted into reduction in wheat production. Possibly other reasons are due release of chemical constituents from the leaves of bamboo which may hinder the understorey crops growth. Eyini *et al.* (1989) revealed that, the aqueous leaf extract of fallen leaves of bamboo contains phenolic acids namely, chlorogenic, ferulic, coumaric, protocatechuic, vanillic and caffeic which inhibited the growth and development of groundnut seedlings. The similar conclusion was also made by Sahoo (2013).

The study of distribution of tree and crop root systems is vital to minimise competition for resources while maximizing resource use in agroforestry systems. With a fibrous root system, maximum roots are confined to 0-50 cm depth in bamboo (Divakara, 2001). When beds are prepared, the bamboo roots are cut-down leading to better growth of understorey crops during initial stage. Subsequently bamboo roots reoccupy available space over turmeric, ginger and chittaratha beds leading to more competition for belowground resources. While in wide spacings (10x10 and 12x12 m), the beds are so distant that, bamboo roots merely reach the beds and may lead to minimum competition. The decline in lateral root spread with distance has been observed by many researchers. Odhiambo *et al.* (2001) reported that, there might be temporal separation of root activity between species, but tree root length declined with increasing distances from rows of trees and with depth in the soil profile. Several studies revealed certain degree of niche partitioning in terms of rooting depth and placing of roots, root dynamics and resource acquisition strategies in plants (Nobel, 1997; Fargione and Tilman, 2005 and Livesley *et al.*, 2000). Therefore, root competitiveness in polyculture system involving bamboo is a function of the proximity of bamboo, which in turn decides the associated crop productivity (Divakara, 2001). The further detailed study on root interactions are discussed below by application of ^{32}P radioisotope.

5.1.5 Rhizosphere competition

The radioisotope technique are used for studying the root activity patterns of woody perennials and root competition in multi-species cropping systems. ^{32}P soil-injection is by far the most widely used method (Wahid, 2001). The method is unique as it enables one to delineate the lateral and vertical spread of the active roots (Bohm, 1979). In the present study turmeric foliar ^{32}P counts were directly related to bamboo spacings. Lowest absorption of ^{32}P by turmeric was reported under closest (4x4 m) spacing of bamboo and the highest in widest (12x12 m) spacing. ^{32}P absorption by adjacent untreated turmeric plants from the treated plants was, however decreased. This decrease was possibly because of reduced lateral root spread. The bamboo clumps closer to turmeric bed recovered ^{32}P from the treated turmeric crop. The recovery of ^{32}P by bamboo decreased while the distance between treated turmeric and bamboo clumps increased. Rowe *et al.* (2001) observed that more ^{15}N was recovered by maize and *Gliricidia* from placements at 5 cm depth than from placements at 45 or 65 cm depth. Lesser ^{32}P counts by treated turmeric under closest spacing of bamboo (4x4 m) and in turn higher recovery of ^{32}P by bamboo in closest spacing (4x4) reveal that turmeric and bamboo exerted competitive interactions. This interaction decreased significantly when bamboo distance from the turmeric beds increased. This might be due to nature of fibrous root systems in bamboo. George *et al.* (1996) reported that, sever reduction in the nutrient uptake and yield of the associated crop can be expected if the tree component of the system has a shallow spreading root system. Presumably the root overlapping between bamboo and understorey crop is the one factor for reduced growth in close spacings, which may compete for the unambiguous site resources. Kunhamu *et al.* (2008) reported competitive interaction in *Acacia mangium*-ginger and Thomas *et al.* (1998) in *Ailanthus triphysa*-ginger based cropping system. Though direct measurement of rooting intensity would be desirable to make positive conclusions in this regard, several workers (Nye and Tinker, 1977 and Vose, 1980) suggested that, ^{32}P technique would be a precise method for characterising root interactions. In intercropping, stratification of roots of different species at different depths is therefore desirable.

5.2 Logarithmic spiral trenching

Trench analysis provides a relatively quick and detailed quantitative distribution of roots. Knowledge of root distribution in tree is very crucial in selection, design and management of stand. In the present study the rooting intensity and spread was steadily increased with increasing spacings of bamboo. The higher root intensity in wide spacings (12x12 m) may probably be due to large isolated clumps. The rooting intensity in closest spacing (4x4 m) at 0.75 m away from the clump recorded 387 roots m^{-2} while at same distance in 12x12 m spacings found 494 roots m^{-2}. Bhol and Nayak (2014) found that bamboo root intensity decreased with increase of distance from clump. They also reported that at 1 m distance the rooting intensity was 330 m^{-2} while at 4 m distance it was 222 roots m^{2}.

The rooting intensity also increased due to increase of spacings between the bamboo. The similar trend was also reported in bamboo by Divakara and Kumar (2001). The closer spacings (4x4 and 6x6 m) of bamboo recorded lesser lateral distribution of roots as compared to wide spacings (10x10 and 12x12 m). As the depth and lateral distance increased the rooting intensity decreased. The maximum rooting intensity was within 0-30 cm soil depth and up to 4.45 m lateral distance under all the spacings. However, in wider spacings (10x10 and 12x12 m) the roots were distributed beyond 30 cm depth and spread laterally up to 8.75 m. The higher rooting intensity was observed in wider spacing possibly because of more belowground space. The higher intensity of <2.5 mm diameter size roots compared to >2.5 mm diameter size roots was observed. The present results are in conjunction with Divakara *et al.* (2001) who reported that 83 per cent of the large clumps (> 4 m dia.) extended roots beyond 8 m while only 33 per cent of the small (< 2.5 m dia.) clumps extended roots up to 8 m. Niranjana and Viswanath (2008) also reported that maximum feeder roots (<2 mm) of *Grevillea robusta* were found within the 2.4 m from the tree. With increasing spacings of bamboo, more horizontal and vertical spread of roots were evident. The deeper spread of bamboo roots in wider spacings may enable clumps to capture nutrients that would otherwise be leached from the upper horizons of the soil profile (Kumar and Divakara, 2001).

5.3 Root activity in bamboo

Root activity varies spatially and temporally. It is also affected by stand density, age and soil condition. The several direct methods for measurement of roots viz., Excavation technique, Auger methods, Profile wall methods etc. fail to evaluate "physiologically active roots". So, the indirect measurement with minimal damage to the tree can be determined by ^{32}P with a reasonable accuracy (Wahid, 2001). This study quantifies root activity, maximum feeding zone and in turn helps for ideal stand density management. With this background an attempt was made for measurement of active roots in 7 year old bamboo by injection of ^{32}P solution at varying depths and lateral distances.

In general, ^{32}P recovery significantly decreased from 15th to 30th day after application. Lehman *et al.* (2001) also determined root activity patterns in an Amazonian agroforest with fruit trees by ^{32}P, ^{33}P and ^{15}N applications and found that all the applied isotopes decreased with increasing day after application. As the lateral distance and depth from base of the clump increased the ^{32}P absorption significantly decreased. This reveal that maximum bamboo roots are concentrated nearby its clump. Similar trend was also observed in bamboo by Kumar and Divakara (2001) and in *Grevillea robusta* by Samritika (2013). The increase of ^{32}P uptake by bamboo with decreasing spacings between the bamboo clearly indicate the presence of active roots in the close spacings (4x4 m). The higher ^{32}P uptake at greater depth and lateral distances was evident with increasing spacings between the bamboo; this reveal that active root spread was more at wider spacings.

'About 50 per cent of ^{32}P absorption was found within 50 cm lateral distance in closest spacings (4x4 m) and this was decreased with increasing spacings, depth and lateral distances. This reveal that bamboo having fibrous root system, maximum concentration of active roots are present within 50 cm^2 in the soil.

Similar results were also found by Isaac and Anglaaere (2013) with soil δ(18)O isotopic signature in cocoa. They reported that rooting intensity declined with depth. However, the absorption of ^{32}P at 1 m depth and 2 m lateral distances in widest spacings (12x12 m) was higher compared to closest spacings of 4x4 m. Higher root activity at wide spacings (12x12 m) in this distance (1 m x 2 m) may be attributed to more belowground space. In close spacings due to close adjacent clumps possibility of restriction of horizontal and vertical root activity exists. The lesser absorption of ^{32}P in close spacings may also be due to competitive absorption by adjacent bamboo and this absorption by treated bamboo was gradually increased with distance from the adjacent bamboo. Kumar and Divakara (2001) also revealed similar observation in mixed species systems of bamboo, teak and vateria and reported that uptake of ^{32}P by treated teak and vateria decreased with decreasing distance from the bamboo. They also reported that as clump size increases the ^{32}P absorption increased; the same trend was also found in present study.

Therefore the present study clearly found that "maximum foraging zone" in closest spacing (4x4 m) was within 50 cm^2 of the soil and this decreased gradually with increasing spacings of bamboo. However, in wide spacings (12x12 m) the lateral spread of active roots were more at greater depth (1 m); this helps "nutrient pumping mechanism" from the deeper layers. The same mechanism was also discussed by Christanty *et al.* (1996) in bamboo '*talun-kebun*' system of West Java. 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'.

5.4 Soil nutrient content

Productivity of plantations depends strongly on soil nutrient supply and in turn influenced by species and management practices (Binkley, 1997). As the bamboo spacing increased from 4x4 to 12x12 m the bulk density was increased from 1.11 to 1.52 Mg/m^3. The higher bulk density in wider spacings may be due to soil compaction. The decrease in bulk density of soil under the canopy of *Albizia lebbek* was reported by Hazra (1989). Reyes *et al.* (2014) also found greater bulk density in the open field compared to forests. The soil p^H was invariably increased with spacings of bamboo. Soil acidification in close spacings due to more leaf litter may the reason (Chander *et al.,* 1998). The concurrent changes in the soil N, P and K indicate that, the variation of these nutrients are likely driven by bamboo density. The total N (0-20 cm) in closest spacing (4x4 m) was 2109.8 kg/ha which was decreased to 1430.8 kg/ha at 10x10 m spacings of bamboo. However, the avail. P at surface soil (0-20 cm) was 20.91 kg/ha at closest spacing which decreased to 12.86 kg/ha under bambooless control plot. The decrease of K was from 269.8 kg/ha to 210.15 kg/ha due to increasing spacings of bamboo. The higher N P K in close spacings may be attributed to more organic matter addition by bamboo. Wang *et al.* (2012) also investigated soil organic matter content which decreased with decreasing densities of hybrid larch plantation in China. Chander *et al.* (1998) also reported that soil organic matter, total N, P and K increased with the decrease of spacings from 10x10 m to 5x5 m of the *D. sissoo* plantation. The others also reported that the amounts of nutrients provided by litter-fall are determined by the production rate and the nutrient concentrations, which further depends on soil type, tree species and tree density (Singh *et al.*, 1994 and Palm, 1995). However, in the present study, about 50 % of N, P and K are present within 0-20 cm soil and this was further decreased drastically beyond 20 cm depth. Warren and Ashton (2014) also found that most of the soil nutrient changes were confined within 0-10 cm depth in the forest. Rana *et al.* (2002) also found similar findings of soil organic carbon content and N P K declined with increase in soil depth under multipurpose tree plantation. However, N:P:K content up to 1 m depth recorded highest (3738:42:608 kg/ha) under closest spacings (4x4 m) of bamboo; this was decreased (456.07, 23.96 and 450 kg/ha) significantly with increasing spacings (12x12 m) of bamboo. The surface rooting activity of bamboo may be another reason for maximum concentration of nutrients within surface soil (0-20 cm). Divakara (2001) reported most of the bamboo root activity within 30 cm depth. Samritika (2013) also reported similar results for *Grevillea robusta.*

5.5 Soil C sequestration

Carbon in whole soil

The total amount of SOC within 1 m soil profile varied significantly among the spacings of bamboo. The closest spacings (4x4 m) had highest (36.51 Mg/ha) and widest spacing (12x12 m) the lowest (14.97 Mg/ha) SOC content. Higher litter production and its fast turnover, may explain the high carbon content in dense stand (4x4 and 6x6 m) compared to bambooless open plot. Gradual decrease of SOC content with increasing spacings or decreasing stand density may be the result of sparse clumps (10x10 and 121x2 m). The decrease of SOC with stand density was also reported was by Kunhamu *et al.* (2008) in *Acacia mangium*. The close spacings promote C storage, but is adversely affected by decreased girth and crown expansion in bamboo. However, utmost care is necessary in optimization of spacings. As expected, the total SOC content decreased with soil depth under all the spacings of bamboo. Furthermore, the amount of SOC in the top half of the 1 m soil profile (0-50 cm) was greater than in the lower half (50—100 cm) by 84 percent in closest spacings and 196 per cent in widest spacings of bamboo; the corresponding value was 224 per cent for bambooless control plot. These differences are likely a manifestation of the litter addition, root distribution and activity. Litton *et al.* (2004) also reported that carbon addition to the soil increased with increasing stand density of Lodgepole pines. The soil carbon accumulation vary with management practices and land use. For example, the SOC decreased with land use systems from natural forests to rubber plantation and rice field (Saha *et al.*, 2010). Furthermore, unlike forests, bamboo plantations experience disturbances like weeding, culm cutting and litter collection all of which affect the process of C deposition.

The total amount of SOC (11.50 kg/ha) within the top 1 m of soil in closest spacing (4x4 m) was 1434 per cent lower than that of widest spacing. However, the SOC values under widest spacing of bamboo (12x12 m) and bambooless control plot was somewhat similar. Overall, these differences between the widest spacing and bambooless control plot evened out with soil depth such that SOC from all soil depths yielded similar SOC value.

Soil organic carbon in aggregate fraction classes

The per cent distribution of various aggregate classes under spacings of bamboo showed marked difference. The 4x4, 6x6, and 8x8 m spacings of bamboo (0-50 cm) recorded higher SOC in silt and clay (<53 μm) aggregate class. However, greater amount of macro-aggregate fraction in lower depths (50-100 cm) was observed irrespective of spacings of bamboo. Among the soil aggregate classes, the SOC accumulation was maximum in silt and clay fraction, followed by micro and macro-aggregates. The SOC accumulation in silt and clay-aggregates up to 1 m depth varied from 47.57 Mg/ha in closest spacing (4x4 m) to 19.11 Mg/ha in widest spacings (12x12 m) of bamboo. In micro-aggregate SOC accumulation ranged from 39.79 Mg/ha in closest spacings to 16.19 Mg/ha in widest spacings. Whereas in macro aggregate class SOC accumulation varied from 22.17 Mg/ha to 9.62 Mg/ha in closest to widest spacings of bamboo.

The macro-aggregate class (250-2000 μm) roughly represents the macroaggegates that contain the more active pool of C, which is influenced by the land-use and soil management (Six *et al.*, 2002). This pool contains the recent C depositions in soil (Carter, 1996); therefore it is sensitive to changes in organic matter and in soil with time course. The micro-aggregate class (53-250 μm) is the building block of soil structure and more stable in storing C (Tiessen and Stewart 1983). In other words, SOC in silt and clay aggregates is usually more stable (Haile *et al.*, 2008). Different factors may contribute to the high amount of C in the fine aggregates (<53 μm) in bamboo systems and open plot; such factors include low decomposition rates of organic matter (Hassink, 1997), root distribution and turnover. The differences in SOC across the spacings of bamboo could be the stand density effect. The SOC content in silt and clay-aggregate class (<53 μm) showed a trend of increasing amount with decreasing spacings of bamboo from 4x4 m to 12x12 m, with highest value in 4x4 m and lowest in 12x12 m spacing. It could be because of relative higher silt and clay content in the close spacings (4x4 and 6x6 m) compared to wide spacings (10x10 and 12x12 m) including bambooless control. The depth also significantly affected the carbon accumulation. As the depth increased the SOC also decreased, this trend was observed in all the spacings of bamboo. Numerous studies (Nzila *et al.*, 2002; Bronick and Lal, 2005 and Arevalo *et al.*, 2009) have indicated that dense stand contain higher soil C in the fine fraction (<53 μm) than the open field. However, in silt and clay aggregate fraction at surface soil (0-20 cm depth) about 114.56 per cent in closest spacing and at widest spacing about 98.64 per cent higher SOC content in as compared to macro-aggregate class. The higher percent in silt and clay aggregate was due to higher stand density of bamboo and more litter addition.

5.6 Aboveground biomass production in bamboo

5.6.1 Growth parameters of bamboo

Stand density reflects the degree of crowding of stems within the area (Gingrich, 1967). The growth attributes of trees in a stand are greatly affected by stand density. The height growth is much influenced by stocking. Several researchers have revealed that height growth decreases with decreasing stand density. Menzies *et al.* (1989) noted an increase in height growth with increasing spacings of radiata pine from 200 to 800 stems/ha. Mason (1992) also found a reduction in height growth with decreasing stocking below 2000 stems/ha in Nelder experiments. The present study also showed a wide variation in the bamboo height and clump diameter increment with spacings. Due to decreasing bamboo spacings from 12x12 to 4x4 m, the clump height of bamboo increased from 6.81 to 8.86 m and the clump DBH decreased from 1.61 to 1.06 m. The similar growth observations was observed by Kibwage *et al.* (2008) in the bamboo-tobacco growing regions of Kenya. The ability of the tree to grow taller in denser stands and larger girth in less denser stands was evident; this is in confirmation with Hummel (2000). The number of live culms and crown spread of bamboo also increased with increasing spacings of bamboo. The decrease in number of culms and crown spread in close spacings may be attributed to less available growing space and more crown competition. Fisher and Binkley (1999) reported that competition for light in mixed plantations result in decreasing crown diameter. The higher MAI in wider spacing

(12x12 m) may be attributed to higher clump diameter and volume. Taylor and Zishing (1987) also reported that bamboo (*Fargesia spathacea*) mean annual increment increased with increasing culm diameter. More number of culms in wider spacings may be due to less crown competition and more aboveground space for culm expansion. Bhol and Nayak (2014) also reported that more number of culms and crown expansion in 12x10 m spacing compared to 10x10 m spacings of bamboo.

5.6.2 Biomass production

The underlying mechanisms of plant biomass partitioning are of great importance in the study of plantation productivity. For higher biomass allocation in tree component the spacing/density is most important. The density stress followed by competition alters the biomass distribution among components (Harper, 1977). In the present study biomass production show wide variation depending on spacings, which in turn is determined by the number of culms and their biomass accumulation. The aboveground component biomass viz. culm wood, twigs, leaf and dried culm biomass increased with increasing spacings. Invariably culm wood constituted the highest (60-70 per cent) to the total biomass in all the spacings of bamboo. Previously, Kumar *et al.* (2005) also reported that about 80% of the biomass was contributed by culm wood. The twig biomass ranged from 21.65 kg/clump (4x4 m) to 64.04 kg/clump (12x12 m). The dried culm contribution varies from 5 per cent (12x12 m) to 7 per cent (4x4 m). However, total aboveground biomass ranged between 112.3 kg/clump in 4x4 m spacings to 271.79 kg/clump in 12x12 m spacings of bamboo. The comparatively more dried culm share in closest spacings may be attributed to higher competition for resource sharing. Conversely, variation in tree spacing or an increase in tree spacing with tree age or size is an evidence of competitive mortality (Druckenbrod *et al.*, (2005) and Das *et al.*, (2011)).

Many researchers reported density dependent changes in biomass accumulation and component sharing within the tree (Kunhamu *et al.*, 2005; Fang *et al.*, 2007 and Douglas *et al.*, 2013). The densest stand (625 clumps/ha) have culm wood biomass of 49 Mg/ha which decreased to 11.94 Mg/ha at least dense stand (69 clumps/ ha). The leaf biomass was 2.89 Mg/ha at a density of 625 clump/ha and 1.35 Mg/ha under density of 69 clumps/ha. The dried culm biomass was significantly high (4.79 Mg/ha) at densest bamboo (625 clump/ha) and less in other densities of bamboo. The biomass pattern of *Dendrocalamus strictus* in the present study were compared with other studies. Many studies reveal that biomass accumulation pattern varies with the genus and species age and stocking level. For example, *Dendrocalamus strictus* recorded clump weight of 24 and 38 Mg/ha at the age of 3 and 5 years, *Bambusa bambos* have 243 (at age 8) reported by Shamnughavel and Francis (1996). Isagi *et al.* (1997) recorded leaf biomass to the tune of 5.9 Mg/ha in *Phyllostachys pubescens*. Yiming *et al.* (2000) found leaf biomass of 3.37 Mg/ha in *Dendrocalamus latiflorus.*

The biological measure is often considered in selecting an optimum planting spacing. Too many trees over-utilize site resource, too few under-utilize the site. One such measure of site occupancy is "Stand Density Index[2]" (Reineke, 1933). However, in the present study too dense (625 clump/ha) stand though recorded maximum biomass at stand basis (hectare), the eventual clump-wise biomass was highest in widest spacing (12x12 m). However, the total aboveground biomass (70.22 Mg/ha) was increased by 274.50 per cent in 625 clumps/ha as compared to bamboo at 69 clumps/ha (18.75 Mg/ha). In earlier studies, Isagi *et al.* (1997) quoted bamboo biomass of 114.8 t/ha for *Sasa kurilensis* and 143 t/ha for *Bambusa blumeana.* Christianty *et al.* (1996) reported 43.2 t/ha biomass in *Phyllostachys pubescens* in Taiwan. Therefore, in the present study as the spacings increased aboveground component biomass increased, while increasing stand density the aboveground biomass were increased.

5.7 Nutrient accumulation in aboveground biomass

Nutrient removal at harvest from the site depends on both nutrient concentration of different tissue types and biomass yield. Among various components, leaf had the highest concentration of all nutrients, followed by twig, clump wood and dried culm. Higher nutrient concentration in leaves was also reported for many species (Aneesh, 2013 and Mohsin *et al.*, 2005). Leaf being the centre of maximum photosynthetic activity; it is logical that the highest nutrient concentration was always found in the leaves (Sreemannarayanan *et al.*, 1994 and Kumar *et al.*, 2009). The concentration of N, P and K increased with increasing spacings of bamboo. Among the nutrients potassium was highest, followed by nitrogen and phosphorus in all tissue types of bamboo except leaf tissue. The higher nitrogen concentration in leaves also recorded by Shanmughavel and Francis (1996) and Singh and Kochhar (2005).

The N, P and K uptake decreased with decreasing spacings of bamboo. Occurrences of such pattern of nutrient uptake was attributed to differences in dry matter production in different parts of plant, which in turn is influenced by different planting pattern. All the nutrient concentration (N, P and K) were increased with increasing spacings of bamboo. The nutrient (N, P and K) uptake and storage at stand basis (ha) in clump wood was 221.98, 97.13 and 240.64 kg/ha in densest stand (625 clumps/ha) and in less dense stand of 69 clumps/ha was 69.29, 33.62 and 100.48 kg/ha respectively. However the nutrients drain after harvest was to the tune of 108.42 to 323.68 kg/ha of N, 59.97 to 157.11 kg/ha P and 157.59 to 354.76 kg/ha of K in densest stand (625 clumps/ha) and least dense stand (69 clumps/ha) respectively. The twigs accounted N, P and K at the rate of 66.13, 36.05 and 71.14 kg/ha whereas, leaf contributed 16.24, 16.01 19.96 kg/ha in densest stand (625 clump/ha). Decrease in uptake of nutrients with decreasing stand density was also observed by Singh and Kochhar (2005). Conversely about 10% of the nutrients present in the standing biomass was reported to be recycled to the soil through floor litters in *B. bambos* (Shanmughavel and Francis, 1996). The others reported that the uptake of total nutrient was faster and storage of essential nutrients in standing, as well as harvested biomass was always larger than returned to the soils (Roa and Ramakrishna, 1990). However huge amount of nutrient retained is primarily in the clump wood mass. Therefore bamboo can play an important role of nutrient conservation in its plantation and forest ecosystems.

5.8 C accumulation in aboveground biomass

Bamboos can be a significant sink of atmospheric carbon (C) due to their fast growth and high productivity (Nath and Das, 2012). The estimates of C content exhibited higher proportions in leaf components (54-55%) than twigs (48-50%), clump wood (44-46%) and dried culm (40-43%) in all the spacings. The carbon partitioning among the aboveground parts in bamboo showed that almost 57-68 % was in clump wood, whereas twigs, leaf and dried culm stored 20-30%, 4-8% and 3-6 % in all the spacings of bamboo. The consistent increase in aboveground C stock with increasing spacings of bamboo might be due to more number of culms and intern higher dry matter production. Wu *et al.* (2005) also reported the ratio of above/below-ground biomass increased with increasing density of bamboo. The C in clump wood at closest spacing (4x4 m) varies from 35.21 kg/clump to 79.12 kg/clump in 12x12 m spacings of bamboo. However the twig and leaf accounted 10.46 and 2.56 kg/clump in 4x4 m spacings to 32.15 and 10.75 kg/clump in 12x12 m spacings. Higher carbon accumulation in wider spacings (10x10 and 12x12 m) may be attributed to more number of clumps per clump and higher clump girth.

The total aboveground C accumulation at stand level was highest (32.24 Mg/ha) in densest stand (625 clumps/ha) and lowest (8.85 Mg/ha) in least dense stand of 69 clumps/ha. The majority of C was accumulated in clump wood (5.45 to 22 Mg/ha), followed by twig (2.21 to 6.54 Mg/ha) and leaf (0.74 to 1.60 Mg/ha) components. Nath *et al.* (2009) also reported that in *B. cacharensis* the allocation of C was more in culm component (53.05 t ha^{-1}) than in branch (5.81 t ha^{-1}) and leaf (2.19 t ha^{-1}). The dried culm was also added C accumulation ranged from 0.43 to 2.08 Mg/ha to the total biomass C. The total C accumulation in the aboveground biomass was invariably high (32.24 Mg/ha) in densest bamboo stands of 625 clumps/ha compared to 8.85 Mg/ha in 69 clumps/ha, this decrease was upto 264.29 per cent compared to densest stand of 625 clumps/ha. Higher C accumulation in dense stand was probably due to more biomass and dry matter production. Singh and Kochhar (2005) also reported higher biomass (341 t/ha) and dry matter production in dense stand (278 clumps/ha) compared to least dense (234 t/ha) stand of 156 clumps/ha. Agarwal and Purwar (2012) also estimated 19 Mg/ha of carbon has been sequestered by *Dendrocalamus strictus* in the Mid-Himalayan region of India.

Carbon accumulation potential

The potential of culm wood C accumulation varies from 0.78 Mg/ha/year in the least dense stand (69 clumps/ha) to 3.14 Mg/ha/year in densest bamboo stand of 625 clumps/ha. The C in the twig biomass was 0.32 to 0.93 Mg/ha/year, leaf and dried culm biomass C accumulation varies from 0.11 to 0.23 Mg/ha/yr and 0.06 to 0.30 Mg/ha/yr in the densest stand to least dense stand of bamboo, respectively. Among the biomass components, the clump wood sequestered maximum C followed by twigs and leaf biomass. The C accumulation in total aboveground biomass of bamboo ranged from 1.26 to 4.61 Mg/ha/yr in the least dense (69 clumps/ha) to dense stand (625 clumps/ha) respectively. However the rate of C accumulation varies with age, site condition, species and stand density. For example, Nath and Das (2011) reported rate of C accumulation in *B. cacharensis* and *B. vulgaris* was 1.20 and 1.46 Mg ha^{-1} yr^{-1}. The smallholder agroforestry systems in the tropics, potential C accumulation rates ranged from 1.5 to 3.5 Mg C ha^{-1} yr^{-1} (Watson *et al.*, 2000). Nevertheless bamboo based land-use systems have the ability to C capture and increase C stocks if optimally spaced and regularly managed.

5.9 Allometric equations

Linear allometric equations developed to estimate AGB of bamboo clumps. The relationship between three variables viz., number of culms, clump DBH and height with total aboveground biomass indicated higher coefficient (0.89). The equations between dried culm biomass with three variable viz. number of culms, DBH and height have shown low coefficient of determination (R^2=0.65). The predicted biomass equation for dried culm was lower than equation developed for same component by Hairiah *et al.* (2001). The twig biomass of bamboo indicated higher coefficient than clump wood leaf and dried culm components.

Although equations developed for twig or leaf biomass with one variable (DBH) is statistically optimal, these equations should not be associated with other relationships that have low coefficients of determination to estimate AGB. However, to estimate total AGB, association of separate equations for foliage, branch and culm biomass would become necessary; in addition, some of components like dried culm biomass show very low coefficients of determination should be eliminated. In the observed biomass data, dispersed distribution can be seen in the equations for total AGB with combination of variables. The linear equation developed with three variables did not show difference with non-linear equation developed with one variable. Ketterings *et al.* (2001) has observed that the inclusion of variables H and DBH in the power equation gives R^2 values with negligible difference. The advantage of only DBH as independent variable is that they are simple, practical and easy to use and provide more rapid biomass estimates (Whitesell *et al.*, 1983). Several researchers have concluded that tree biomass is primarily a function of DBH and is relatively insensitive to tree height using DBH to predict biomass is a general method that has been widely applied in the bamboo forests (Naidu *et al.*, 1998; Chen*et al.*, 2009 and Yen *et al.*, 2010).

Allometric models are powerful tools that are widely applied to estimate volume, biomass and carbon storage in any vegetation (Zianis and Mencuccini, 2004; Yen *et al.*, 2008 and Yen *et al.*, 2010). The total aboveground biomass carbon prediction provided high R^2 (0.90) value than compared to biomass carbon predicted by individual component biomass variables, (clump wood (stem), twig, leaf and dried culm). However, the biomass carbon prediction with three variables is best fit. The biomass carbon prediction in twig has given R^2=0.88 which is comparatively higher than clump wood and leaf biomass carbon.

Implications to management of bamboo

Bamboo forms an important component in the traditional home garden system of Kerala. The practice of bamboo cultivation and management provides a better option for sustainable use of land. For ideal stand management of bamboo requires thorough understanding of root activity and distribution, rhizosphere competition and soil nutrients. Present study reveal that bamboo roots compete with understorey crop up to 4 m distance from the clump. However, maximum feeding area of bamboo is within 50 cm^2 distance from the clump, which decreases with increasing distance. However, providing appropriate spacing for bamboo is utmost importance. Too wide spacings may decreased the bamboonet present value (NPV) and too close spacings may distress the understorey herbaceous growth. Therefore, ideal spacing of bamboo for intercropping with turmeric is 12x12 m, for ginger 10x10 m and chittaratha grow better in open field, when intercrop with bamboo widest spacing (12x12 m) is recommended.

Stand management of bamboo for biomass and nutrient accumulation and C accumulation requires thorough root level understanding of bamboo. Generally maximum roots of bamboo found within 0-30 cm soil depth and spread up to 4.45 m lateral distance. Physiologically active roots of bamboo may spread beyond 1 m depth and 2 m lateral distance; these roots can absorb nutrients from the deeper layer of soil. However, by maintaining bamboo in the wider spacings (10x10 and 12x12 m) the roots distribute beyond 30 cm depth and spread laterally up to 8.75 m. Though planting bamboo in close spacing add higher litter and nutrient to the soil. But close spacings of bamboo invariably affect the clump diameter and biomass accumulation. The management of bamboo varies with objective. However, the objective is to produce higher biomass, nutrient deposition and C accumulation in a clump, it is recommended for wider spacings (10x10 m to 12x12 m). Study also suggest that for stand level production and C accumulation, planting and maintain of bamboo in close spacings (4x4 m to 6x6 m) is better.

Summary

6. SUMMARY

The study on "Bamboo (*Dendrocalamus strictus* (Roxb.) Nees) based agroforestry system: planting density effects on biomass accumulation, carbon accumulation, root distribution pattern and understorey crop productivity" was carried out in an experimental site attached to the College of Forestry, Vellanikkara, during 2011-2014. The project envisaged optimization of spacings of bamboo for understorey growth and productivity. During the study the understorey photosynthetically active radiations between the spacings of bamboo were measured. During the experimental trial ^{32}P was applied to the four turmeric plants lying in a row across the bed to evaluate the extent of root interaction in turmeric and bamboo+turmeric at varying spacing of bamboo.

As part of project, the physiologically active roots in bamboo were determined with ^{32}P isotope. The study also probed the root distribution pattern by employing logarithmic spiral trench. The prolonged study evaluated the impact of spacings of bamboo on soil physico-chemical properties. The soil C sequestration potential in bamboo was also assessed. As part of the study, aboveground biomass accumulation, nutrient uptake and C accumulation potential under varying spacings/density of bamboo was determined.

The salient findings of the research are summarized below.

1. The growth attributes of bamboo before understorey cropping was recorded. As spacings of bamboo increased the clump height significantly decreased. The closest spacing (4x4 m) recorded largest height (9.11 m) and widest spacing (12x12 m) recorded smallest (7.31 m). Gradual increase in clump diameter and crown width with increasing spacings of bamboo was observed. The 4x4 m spacing recorded lowest diameter (1.03 m) and highest diameter (1.58 m) was recorded at 12x12 m spacings of bamboo.

2. The physico-chemical properties of soil before understorey planting were significantly varied with spacings of bamboo. The bulk density increased

significantly with increasing spacings of bamboo. The p^H in bambooless control plot was 5.96 which was higher than 4x4 (5.83) spacing and lesser than 12x12 m spacings of bamboo (6.1).

3. The closest spacing (4x4 m) recorded highest total N (2197.7 kg/ha) and widest spacing (12x12 m) recorded 1404.97 kg/ha which was at par with (1396.41 kg/ha) bambooless control plot. The closest spacing of 4x4 m recorded highest avail. P and avail. K, which decreased with increasing spacings. The per cent decrease was 30.90 and 24.68 compared to closest spacings (4xx4 m).

4. As the spacings of bamboo increased from 4x4 to 12x12 m, the PAR values were increased. The understorey PAR at 8 hours recorded lowest (6 $\mu\mu$mol/sec/m^2) in 4x4 m spacings of bamboo and the highest (76.66 $\mu\mu$mol/sec/m^2) at widest spacing (12x12 m). At 12 hours noon the understorey PAR was increased from 107.33 μmol/sec/m^2 in 4x4 m to 1019 μmol/sec/m^2 in 12x12 m against the overstorey PAR (1033 μmol/sec/m^2). Among the spacings, the widest spacing (12x12 m) recorded maximum understorey (42%) PAR and minimum in closest spacing of 4x4 m (4.44%).

5. As the spacings of bamboo increased the LAI significantly decreased. The LAI and bamboo spacings are inversely related to each other. The closest spacing (4x4 m) recorded maximum LAI (6.78) as compared to widest spacings (12x12 m, 0). The LAI in 4x4 m spacing was 678 per cent higher compared to 12x12 m spacing.

6. Due to closest spacings (4x4 and 6x6 m) the plant height, shoot length, leaves and tillers in turmeric was significantly lesser than widest spacings of bamboo (12x12 m) and bambooless control plot. The understorey ginger performed better in 10x10 m spacings of bamboo compared to closest spacings of 4x4 and 6x6 m. In case of chittaratha, control plot was found best for its growth. Among the varying spacings of bamboo+chittaratha

intercrop, widest spacing (12x12 m) of bamboo recorded better growth of chittaratha.

7. The dry matter production of understorey turmeric, ginger and chittaratha was significantly affected by spacings of bamboo. In turmeric, shoot, leaf and rhizome dry matter was maximum in widest spacings (12x12) while ginger recorded maximum dry matter production in 10x10 m spacings of bamboo. The control plot recorded largest dry matter in chittaratha followed by widest spacing (12x12 m).

8. The rhizome yield of all the intercrops was significantly influenced by spacings of bamboo. Closest (4x4 m) spacing of bamboo plot recorded least rhizome yield of 8 Mg/ha; this was 58.59 per cent less compared to widest spacing of 12x12 m (19.32 Mg/ha). The rhizome yield of ginger significantly high (19.55 Mg/ha) at 10x10 m spacings of bamboo which decreased to 3.19 Mg/ha when the spacings of bamboo decreased to 4x4 m. However, in case of chittaratha rhizome yield about 157.46 per cent decrease in rhizome yield of chittaratha was observed when chittaratha grown under closest spacing (4x4 m) of bamboo compared to bambooless control plot.

9. The N, P and K concentration and uptake by turmeric, ginger and chittaratha were significantly affected by bamboo spacings. As the spacings of bamboo increased the N, P and K concentration and uptake by all the understorey crops was significantly increased. The least (12.15:2.41:31.38 kg/ha) uptake of N: P: K by turmeric was in closest spacing (4x4 m) and highest (66.99:9.52:67.62 kg/ha) under widest spacing of bamboo (12x12 m). The maximum uptake of N: P: K by ginger recorded by 10x10 m and minimum under closest spacing of bamboo (4x4 m). However, in the case of understorey chittaratha, N and K uptake was highest (78.64 and 57.95 kg/ha) was in open plot whereas P uptake was maximum (19.30 kg/ha) in the widest spacing of bamboo (12x12 m).

10. The treated turmeric and adjacent row untreated turmeric showed competitive interaction for applied ^{32}P. At 15th day after application of ^{32}P, the absorption by treated turmeric plants in the control plot was maximum (10911 cpm); this absorption by treated turmeric decreased with decreasing spacing of bamboo. As the distance of the untreated turmeric plants increased from the treated turmeric plants its ^{32}P absorption decreased drastically. When turmeric was grown as intercrop with bamboo the ^{32}P absorption decreased significantly with decreasing spacing of bamboo. As compared to control plot, about 89.53 per cent decline in ^{32}P absorption was observed when turmeric was grown at closest spacing of bamboo (4x4 m).

11. The recovery of ^{32}P by bamboo from the treated turmeric was maximum in closest spacings which decreased with increasing distance of bamboo from the turmeric beds. The highest (48.61 per cent) recovery of ^{32}P by bamboo under closest spacing (4x4 m) at 30th DAA and 58.21 percent at 45th DAA. In the case of bamboo beyond 8x8 m spacing, the recovery of ^{32}P from the treated turmeric was nil.

12. The bamboo spacings varyingly affected root size and its distribution. As the distance from bamboo clump increased, the rooting intensity steadily decreased. As the spacings of bamboo increased the lateral spread of bamboo roots (<2.5 mm) increased. The <2.5 mm diameter size class roots are significantly higher than >2.5 mm size class under all the spacings of bamboo. The bamboo roots were not recorded at surface layer (0-20 cm) in all the spacings of bamboo beyond 4.45 m distance. However, the lateral roots were counted beyond 4.45 m distance from the clump at greater depth (beyond 20 cm) in all the spacings of bamboo except 4x4 m.

13. Under all the spacings of bamboo almost 70 per cent of roots were distributed laterally within 4.45 m distance from the clump. The total rooting intensity up to 60 cm depth in widest spacing was 193.66 roots/m^2 at 0.75 m distance, which decreased to 20.66 root/m^2 at 8.75 m lateral distance from the clump.

14. The extent of ^{32}P absorption at different depths and lateral distances significantly varied with varying spacings of bamboo. With increasing lateral distance and depth of placement, the absorption of ^{32}P by bamboo decreased significantly. At closest spacing (4x4m), ^{32}P absorption by bamboo (15th DAA) at 50 cm depth and lateral distance was significantly higher (809 cpm) which gradually decreased beyond 1 m (448 cpm) and 2 m lateral distance (196 cpm). At 30th day after application of tracer, general trend of decrease in ^{32}P absorption with increasing depths and lateral distances was observed. The widest spacing of 12x12 m was having significantly more number of active roots at 50 cm depth and 2 m lateral distance compared to 1 m depth and 2 m lateral distance.

15. The soil was analysed for physico-chemical properties at varying depths. The p^H of soil at different depth was moderately affected by spacings of bamboo. The p^H of soil was increased with increasing soil depth except 80-100 cm. The trend of increase in bulk density with increasing depth of soil was observed under all the spacings of bamboo. The bambooless control plot recorded higher bulk density than bamboo at varying spacings.

16. The closest spacing (4x4 m) recorded maximum amount (2109.8 kg/ha) of total N and 10x10 m spacings of bamboo recorded lowest (1430.8 kg/ha). Almost 56 per cent of total N was confined to surface soil (0-20 cm) under all the spacings of bamboo and bambooless control plot. The amount of N up to 1 m depth recorded highest (3738.42 kg/ha) under closest and was lowest (2954.7 kg/ha) at 10x10 m spacing of bamboo.

17. The avail. P at surface soil (0-20 cm) ranged from 20.91 kg/ha at closest spacing to 12.86 kg/ha under bambooless control plot. As the depth increased the avail. P was significantly decreased. The avail. P up to 1 m soil depth recorded highest (42 kg/ha) in closest spacing and decreased with increasing spacings of bamboo and recorded 20.31 kg/ha at control plot.

18. The trend in decrease of avail. K with increasing depth and spacings of bamboo was evident. The closest spacing (4x4 m) recorded (0-20 cm) highest (269.8 kg/ha) and lowest (210.15 kg/ha) by widest spacing of bamboo (12x12 m). As compared to bambooless control about 21 per cent higher avail. K was found under closest spacing of bamboo. The total avail. K up to 1 m depth of soil was highest (608.97 kg/ha) in closest spacings; this was 35 per cent higher compared to widest spacings (12x12 m).

19. The amount of SOC in whole soil at 0-20 cm was highest (11.50 Mg/ha) in 4x4 m spacing and lowest (6.61 Mg/ha) in widest spacing (12x12 m) of bamboo. The SOC was significantly decreased with increasing soil depth. The total SOC upto 1 m depth in closest spacing (4x4 m) was 36.51 Mg/ha and 14.97 Mg/ha in widest spacing (12x12 m); this decline was 144 per cent compared to closest spacing.

20. The SOC in silt and clay aggregate (<53 μm) was highest (15.92 Mg/ha) in closest spacing (4x4 m) and lowest (5.20 Mg/ha) in bambooless control plot at 2050 cm soil depth. The SOC up to 1 m soil depth recorded maximum (47.57 Mg/ha) in closest spacing and minimum of 17.48 Mg/ha in bambooless control; this decrease was about 63.24 per cent. As the spacing of bamboo increased the SOC in micro aggregate (53-250 μm) was significantly decreased and 10x10 m spacing of bamboo recorded lowest (6.51 Mg/ha). The total SOC in micro aggregate up to 1 m depth in closest spacing was 39.79 Mg/ha and 16.19 Mg/ha in widest spacing.

21. The SOC in macro aggregate (>250-2000 μm) in closest (4x4 m) spacing was highest (9.23 Mg/ha) at 0-20 cm depth; this decreased to 2.27 Mg/ha at 80-100 cm depth. The SOC in widest spacing (12x12 m) recorded 4.22 Mg/ha at surface soil (0-20 cm) and decreased to 1.05 Mg/ha at lowest depth (80-100 cm). However, the SOC up to 1 m depth was highest (22.17 Mg/ha) in closest spacing (4x4 m) and lowest (9.62 Mg/ha) in widest spacing (12x12 m) of bamboo.

22. The growth attributes of bamboo was significantly affected by varying spacings / densities. The largest (8.86 m) clump height was recorded by closest spacing (4x4 m) and widest spacing (12x12 m) recorded smallest (6.81 m). The clump diameter was highest (1.61 m) in 12x12 m spacings and decreased to 1.06 m in closest spacings of bamboo (4x4 m); this decrease was 34.16 per cent compared to 12x12 m spacing. The reduction in crown width was 42.20 per cent in closest spacing (4x4 m) compared to widest spacings (12x12 m). The mean annual increment of bamboo in closest spacing (4x4 m) was 1.04 m^3/clump/year and 1.98 m^3/clump/year in widest spacing (12x12 m).

23. The number of live culms was maximum (130/clump) in the widest spacings (12x12 m) and minimum (47.66/clump) at closest spacing. About 73 per cent reduction was observed in closest spacings compared to widest spacings of bamboo. The dead culm were maximum (7/clump) under widest spacings (12x12 m) and minimum (2.66/clump) under 6x6 m spacings of bamboo. However the total number (live+dried) of culms per clump was maximum (137/clump) in the widest spacing (12x12 m) of bamboo and minimum (51.66/clump) in the closest spacing (4x4 m) of bamboo.

24. Biomass allocation to aboveground components was significantly affected by its density. Due to closest spacing (4x4 m) culm wood biomass decreased by 54.68 per cent compared to widest spacings of bamboo (12x12 m). The maximum twig biomass (28 per cent) was recorded at 6x6 m and 8x8 m spacings of bamboo and closest spacing (4x4 m) recorded minimum (19 per cent). The leaf biomass contribution to the total biomass was minimum (4 per cent) due to closest spacing and widest spacing of bamboo recorded maximum (7 per cent). The total aboveground biomass at closest spacings (4x4 m) was 112.36 kg/clump and increased to 271.79 kg/clump at 12x12 m spacing of bamboo; this increase was 141.89 per cent compared to closest spacings (4x4 m).

25. The culm wood biomass was maximum (49 Mg/ha) in densest stand (625 clumps/ha); this decreased to 11.49 Mg/ha in least dense stand (69 clumps/ha). The increase of culm wood biomass was to the tune of 310.38 per cent at densest stand compared to least dense stand. The twig and leaf biomass reduction in least dense stand (69 clumps/ha) was 207 and 114 per cent compared to densest stand (625 clumps/ha). The total aboveground biomass at densest stand was increased by 274 per cent compared 69 clumps/ha.

26. Nutrient concentration (N, P and K) in aboveground biomass was significantly affected by its density. The N, P and K concentration under all the spacings of bamboo decreased in the order of leaf>twig>clump wood>dried wood. The total N accumulation in the aboveground biomass was highest (323.69 kg/ha) in densest stand (625 clumps/ha) and lowest (108.44 kg/ha) in least dense stand (69 clumps/ha). The increase of N accumulation due to variation in stand density was up to the tune 198.49 per cent.

27. The bamboo in closest spacing (4x4 m) recorded least clump wood P concentration (0.19 per cent); this was increased to 0.28 per cent at 12x12 m spacing. The total P accumulation in the aboveground biomass of bamboo varied from 157.13 kg/ha in densest stand (625 clumps/ha) to 59.99 kg/ha in least dense stand (69 clumps/ha). Aboveground P accumulation increased in densest stand by 161.92 per cent compared to 69 clumps/ha.

28. The K concentration in all the aboveground component biomass increased with increasing spacings of bamboo. The total amount of K accumulated in aboveground bamboo biomass ranged between 354.77 kg/ha in densest stand (625 clumps/ha) and 157.60 kg/ha at the density of 69 clumps/ha. The increase of K accumulation in densest stand was 125.10 per cent.

29. The carbon partition in the aboveground biomass varied with spacing/density of bamboo. The maximum (79.12 kg/clump) C was accumulated in the clump wood at widest spacings (12x12 m) and minimum (35.21 kg/clump) at closest spacings (4x4 m). The C accumulation in twig component was 10.46 kg/clump at closest spacings (4x4 m) and 32.15 kg/clump in the widest spacings (12x12 m). The leaf and dried wood C accumulation in the widest spacings (12x12 m) was 319.92 and 88.58 per cent more compared to closest spacing (4x4 m).

30. At stand level, C accumulation in the densest stand (625 clumps/ha) recorded 22 Mg/ha and 5.45 Mg/ha in least dense stand (69 clumps/ha). The order of C accumulation was in the order of clump wood>twig>leaf>dried wood. The densest stand (625 clumps/ha) recorded 6.54 and 1.60 Mg/ha of C in the twig and leaf components which was decreased to 2.21 and 0.74 Mg/ha at 69 clumps/ha. The total C accumulation in the aboveground biomass was highest (32.24 Mg/ha) at densest bamboo stand (625 clumps/ha) compared to 8.85 Mg/ha at 69 clumps/ha.

31. The culm wood biomass (kg/clump) were best fit with R^2 value of 0.81. The quadratic equation for clump wood biomass with DBH as one variable show R^2, 0.85 which was comparatively higher than linear equation. Linear equation with highest R^2 value of 0.94 was recorded for twig biomass followed by leaf biomass ($R^2 = 0.83$). Among the component biomass carbon, the maximum R^2 (0.88) value was recorded for twig component followed by leaf (R^2, 0.84) and clump wood carbon (R^2, 0.83).

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Bamboo (*Dendrocalamus strictus* (Roxb.) Nees) based agroforestry system: planting density effects on biomass accumulation, carbon sequestration, root distribution pattern and understorey crop productivity.

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ABSTRACT OF THE THESIS

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ABSTRACT

A field experiment was undertaken at Vellanikkara, Thrissur in a seven year old bamboo (*Dendrocalamus strictus* (Roxb.) Nees) stand planted at 4x4, 6x6, 8x8, 10x10, and 12x12 m spacings to assess rhizosphere competition and understorey (turmeric, ginger and chittaratha) productivity, to explore the root activity and distribution pattern in bamboo, to determine the understorey photosynthetically active radiation (PAR), leaf area index of bamboo (LAI) and aboveground biomass production, nutrient uptake and carbon sequestration as a function of planting density. Detailed investigation on the physico-chemical attributes of the soil was also done.

Results reveal that understorey turmeric and ginger height, shoot length, number of tiller and leaves were significantly lesser due to close spacings (4x4 and 6x6 m) of bamboo, but NPK uptake, dry matter production, rhizome yield and oleoresin content were significantly higher in wider spacings (10x10 and 12x12 m) of bamboo. The chittaratha responded better in control plot followed by widest spacing (12x12 m) of bamboo. Due to competition of bamboo about 89% decline in ^{32}P absorption by turmeric at closest spacing (4x4 m) of bamboo as compared to sole turmeric plot. The recovery of ^{32}P by bamboo from the treated turmeric was significantly decreased with increasing distance from the turmeric beds. The recovery of ^{32}P by bamboo in > 8x8 m spacings was nil. The other factors attributed to reduction in growth and yield of understorey crops may be high LAI of bamboo and low understorey PAR. The LAI of bamboo in 4x4 m spacing was 678 % higher compared to 12x12 m spacing. At 12 noon the understorey PAR increased from 107 μmol/sec per m^2 in 4x4 m to 1019 μmol/sec per m^2 in 12x12 m spacings of bamboo against the overstorey PAR (1033 μmol/sec per m^2).

The maximum rooting intensity of bamboo was within 0-30 cm soil depth and up to 4.45 m lateral distance under all the spacings. However, in wider spacings (10x10 and 12x12 m) the roots were distributed beyond 30 cm depth and spread laterally up to 8.75 m. The deeper spread of roots in wider spacings may enable clumps to capture nutrients that would otherwise be leached from the upper horizons of the soil profile. The root activity of bamboo was studied by ^{32}P at varying depths (50 cm and 1 m) and lateral distances (50 cm, 1 m and 2 m). At closest spacing (4x4 m), the ^{32}P absorption by bamboo (15th DAA) at 50x50 cm depth and lateral distance was significantly higher (809 cpm) which gradually decreased by placing ^{32}P beyond 1 m (448 cpm) and 2 m lateral distances (196 cpm). However, in wide spacings (12x12 m) the lateral spread of active roots were more at greater depth (1 m); this helps pumping of soil nutrients from the deeper layers.

The bulk density of soil increased with increasing depth of soil and spacings of bamboo. The N, P and K content of soil significantly decreased with increasing spacing of bamboo. Closest spacing (4x4 m) of bamboo recorded maximum amount (2109 kg/ha) of total N and 10x10 m spacing had lowest (1430 kg/ha). The available P at surface soil (0-20 cm) ranged from 12.86 kg/ha under bambooless control plot to 21 kg/ha at closest spacing. The available P up to 1 m soil depth was highest (42 kg/ha) in closest spacing and decreased with increasing spacing of bamboo. The total available K up to 1 m depth of soil in closest spacing was 35%

higher compared to widest spacing. The amount of soil organic carbon (SOC) in the whole soil at 0-20 cm was highest (11.50 Mg/ha) due to 4x4 m spacing and lowest (6.61 Mg/ha) due to widest spacing (12x12 m). The total SOC up to 1 m depth in closest spacing declined by 143% compared to widest spacing. The SOC in silt and clay fraction (<53 μm) was highest (16 Mg/ha) in closest spacing (4x4 m) and lowest (5.20 Mg/ha) in bambooless control plot at 20-50 cm soil depth. The SOC in macro sized fraction (>250-2000 μm) in closest spacing was 9 Mg/ha at 0-20 cm depth; this decreased to 2.27 Mg/ha at 80-100 cm depth.

Due to decrease of bamboo spacing from 12x12 to 4x4 m, the clump DBH decreased from 1.61 to 1.06 m. The crown spread, number of live culms and MAI of bamboo also increased due to increasing spacing. Due to closest spacing (4x4 m), culm wood biomass decreased by 54% compared to widest spacing (12x12 m) of bamboo. The twig biomass recorded maximum (28%) at 6x6 m and 8x8 m spacing of bamboo and minimum (19%) in closest spacing. The total aboveground biomass in closest spacing was 112 kg/clump which increased to 271 kg/clump due to 12x12 m spacing. At stand level, the culm wood biomass was maximum (49 Mg/ha) in densest stand (625 clumps/ha); this decreased to 11.49 Mg/ha due to least dense stand (69 clumps/ha). The twig and leaf biomass reduction in least dense stand was 206% and 114% compared to densest stand. The total aboveground biomass at densest stand was 274% more compared to least dense stand. Nutrient removal at harvest from the site depends on both nutrient concentration of different plant parts and biomass yield. Nutrient concentration (NPK) in aboveground biomass under all the spacings of bamboo decreased in the order of: leaf>twig>culm wood>dried wood. The total N accumulation in the aboveground biomass was highest (323 kg/ha) in densest stand and lowest (108 kg/ha) in least dense stand. Aboveground biomass P accumulation in densest stand increased by 161% than the least dense stand. The total amount of K accumulated in aboveground biomass ranged from 354 kg/ha in densest stand to 157 kg/ha in the least density of 69 clumps/ha. Higher amount of NPK was retained mainly in the culm wood followed by twig, leaf and dried wood mass. However, dense stands can store significantly higher amount of nutrients in its biomass. The carbon partitioning among the aboveground parts in bamboo show that almost 57-68% was in stem, whereas twigs, leaf and dried wood stored 20-30%, 4-8% and 3-6% in all the spacings of bamboo. The C storage in culm wood varied from 35 kg/clump at closest spacing to 79.12 kg/clump in widest spacing of bamboo. The consistent increase in aboveground C stock with increasing spacings of bamboo might be due to more number of culms per clump and in turn higher dry matter production. At stand level, the total C accumulation in the aboveground biomass was highest (32 Mg/ha) in densest bamboo stand compared to 8.85 Mg/ha in the least dense stand.

The study clearly revealed that wider spacings (10x10 and 12x12 m) of bamboo are ideal for better growth and productivity of understorey crops. Even though chittaratha perform best in open condition, among the varying spacings of bamboo, the widest spacing (12x12 m) of bamboo is best. The dense stands of bamboo had the potential of higher aboveground biomass production, nutrient storage and carbon accumulation. However, the study recommends wider spacings (12x12 m) for clump-wise biomass production/C storage and nutrient uptake.