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Teak in Mixed Plantations: An Appraisal of Productivity, Compatibility and Ecological Sustainability

Sanjay Singh* • Rameshwar Das • Ravindra Krishnamurty

Botany, Silviculture and NWFP Division, Institute of Forest Productivity, Aranyodaya, NH-23, Lalgutwa, Ranchi- 835303, India

Corresponding author: * sanjaysingh@lycos.com

ABSTRACT

Timber yield is generally the primary objective of monoculture plantation of forest trees, which leads to imbalance in natural resource depletion from the sites, renewed risk of productivity loss resulting from some catastrophic events such as disease epidemics or insect-pest outbreak and reduction in biodiversity. Although plantations do not fully match with goods and services provided by natural forests, a judicious mixture of species might supplement them to a great extent. Hence, it is possible to design mixed stands of compatible species having highest possible yield and vegetation/ environment stability, low risk of total crop loss and improved landscape aesthetics. The benefits accrued by mixed plantations can further be multiplied several folds by deployment of superior clonal material. Teak is one of the most valuable timber species of the tropics accounting for about 15% of all forest plantations. Mixed plantations of teak have been tried throughout the tropics with varying degrees of success. Promising combinations of teak include *Swietenia macrophylla* (Fiji, Sri Lanka), *Schleichera oleosa* and *Dalbergia latifolia* (Indonesia), *Leucaena leucocephala* (Malaysia, Sri Lanka), *Pterocarpus macrocarpus* (Myanmar), *Khaya grandifolia* and *Cassia siamea* (Nigeria). However, teak plantations mixed with *Swietenia macrophylla* (Indonesia), *K. grandiflora* and *K. senegalensis* (Nigeria) and *Copaifera officinalis* (Trinidad) met with limited success. In India, successful mixed plantations with teak have been those of *Artocarpus hirsuta*, *Dalbergia latifolia*, *D. sissoo*, *Xylia dolobriformis* and some bamboos (e.g. *Melocanna bambusoides*, *Cephalostachym pergracyle*). But inclusion of *Gmelina arborea*, *Acacia catechu*, *Pterocarpus marsupium* and *Bambusa tulda* with teak suppressed growth of each other. The present paper is a critical ecological appraisal of growing mix plantations consisting of various species with teak as the major component.

Keywords: associates, competition, growth, monocultures, silviculture, species-mixtures

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INTRODUCTION

Teak (*Tectona grandis* L.f.; Verbenaceae family) is one of the world's premier hardwood timbers, famous for its mellow colour, fine grain and durability with a wide range of uses, including both heavy and light construction work, house building carpentry, furniture and wood carvings (Katwal 2004). It is a large, deciduous tree with open crown with many small branches, reaching over 30 m in height in favourable conditions (Troup 1921). The species is diploid, 2n=36 (Gill *et al.* 1983), monoecious and insect pollinated (Bryndum and Hedegart 1969; Mathew *et al.* 1987). Teak occurs naturally in India, Myanmar, Cambodia, northwest Laos, north Thailand and Vietnam but has been widely planted outside its natural range since the 14th century (Behaghel 1999). It has performed well in plantations, not only in its Southeast Asian range of origin, but also in other parts of Asia, as well as in Africa and Latin America (Varmola and Carle 2002). Teak's fine performance in plantations under favourable conditions is in contrasts with some of the more commercially known and valuable tropical hardwood species (e.g. species of the Family Meliaceae and African mahoganies) which have proved unamenable growing in plantations for reasons such as exceedingly slow growth, mortality in establishment on cleared land (being climax rather than pioneer species) or vulnerability to pests and diseases (Pandey and Brown 2000). Although teak is not devoid of silvicultural and management difficulties, it is a timber species which has been found to be relatively benign and successful in plantation environments in the tropics. Today, teak ranks among the top five tropical hardwood species in terms of plantations area established world-

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wide with the estimated total area under teak plantations at three millions ha of which more than 90% is located in Asia (Pandey and Brown 2000).

Establishment of teak plantations commenced in India in 1842 and the area under teak plantation in now > 1.00 million ha (Katwal 2004). In Myanmar, the teak plantations, the first of which were established in the year 1700 A.D., made an important supplement to supplies from native forests (Pandey and Brown 2000). In Thailand, pioneer plantations of teak were established from 1906, and teak plantations currently cover approximately 0.16 million ha. Teak plantations in Indonesia are largely located in Java and currently exceed 0.70 million ha (Bhat and Hwan 2004). Elsewhere in Asia, teak has been established in Bangladesh, Sri Lanka, China, Philippines, Laos, Nepal and Vietnam (Tewari 1992). In Africa, teak has been established in plantations in Nigeria, Cote-d'Ivoire, Sierra Leone, Tanzania and Togo (Kadambi 1993; Pandey and Brown 2000). Plantations of teak are also widespread in tropical America, where it was introduced early in the 20th century (Ball *et al.* 2000). Teak plantations now cover an estimated 33,000 ha, spread mainly across Costa Rica, Trinidad and Tobago, Panama, El Salvador, Columbia, Guatemala, Venezuela and Ecuador (Bhat and Hwan 2004). In the pacific region, the Germans introduced teak to Papua New Guinea in the early 1900s and some 3500 ha of plantations were subsequently established (Pandey and Brown 2000). Teak was also introduced to plantations in Fiji and the Solomon islands and planted in northern Australia at trial levels. Although it is widely planted, plantation–grown teak does not show a significant impact on supplies of industrial roundwood in the global timber trade, except some short-term log exports from Papua New Guinea and Ecuador (Krishnapillay 2000).

Both within and outside its natural range, teak is primarily cultivated in artificial established pure stands. Modest growth rates are reported for teak plantations. Under favourable conditions in early life, a plantation may exhibit a growth rate between 10 and 20 m^3 per ha per year. However, growth falls to the generally reported level of 4 to 8 m^3 per ha per year as the plantations ages (Cao 1999; Htwe 1999). On the best sites in Myanmar and India, 50-year old plantations exhibit an average height of 30 m and diameter at breast height (DBH) of 60 cm (Krishnapillay 2000). Pure teak stands have often been associated with the deterioration of the soil quality and erosion (Ball *et al.* 2000). Pure teak plantations are often prone to attack of defoliators, especially when planted on unsuitable soils, poor in nutrients. The management of pure stands laid with a protective understorey tends to avoid the deterioration of the soil, particularly when the undergrowth contributes to the fixation of nitrogen. On the best sites, where healthy growth is present, attack by defoliators is less frequent and intense, and can be further reduced with the maintenance of a suitable understorey (Centeno 1997). Lamprecht (1989) has demonstrated that teak grows well with soil enriching tree species. Hence, the present paper makes a critical appraisal of growing teak as the major component in the mixed plantations in relation to productivity, compatibility and ecological sustainability.

RATIONALE OF MIXED PLANTATIONS

There is a long-standing concern about the ecosystem stability of single species plantations. In particular, the risk of yield reduction is severe due to deterioration in site quality arising from repeated crops of a single species or catastrophic insect outbreaks and disease epidemics. A mixed plantation promotes ecological stability in stands and reduces the risk or massive failures (Brünig 1991). The ecological stability of a stand may be defined in two terms: *resistance* to change against external stress, and *resilience* to bounce back to its former dynamic state after removal of natural or anthropogenic perturbations (Larsen 1995). Both properties of ecological stability arise from dynamic interactions among species growing as community in an ecosystem. A mixed plantation tends to emulate the properties of a community, which develops a sustainable ecosystem. Although plantations do not fully match with goods and services provided by natural forest, a judicious mixture of species might supplement them to a great extent. Hence, it is possible to design mixed stands of compatible species having highest possible yield and vegetation/environment stability, low risk of total crop loss and improved landscape aesthetics.

Mixed plantations have been established to be more productive than monospecific plantations (Smith 1986; Burkhart and Tham 1992; Wormald 1992). Stratified mixtures, that combine rapidly growing overstorey species with slow starting but high growth performing species, are likely to exhibit higher productivity than pure stands of shade tolerant species (Smith 1986). When mixtures combine tree species of variable requirements for growth and production, they tend to reduce interspecific competition and out yield monospecific stands (Kelty 1992) and produce a greater amount of biomass per unit area due to optimum utilization of site resources (Montagnini *et al.* 1995). Mixed stands also improve the survival and growth of a species in nutrient poor soils when accompanied with a suitable species (Matthews 1989; Binkley 1992). Mixed species utilize nutrients more efficiently than do pure stands because of differences among species in rooting patterns and mycorrhizal associations (Perry *et al*. 1992; Hartley 2002), shade-tolerance (Assmann 1970; Forrester *et al.* 2006), growth rate (Smith 1986; Piotto 2008), form (Menalled *et al*. 1998; Erskine *et al.* 2005), phenology (Keenan *et al*. 1995), nutrients demands (Kelty 1992; Stanley and Montagnini 1999), soil mineralization rates (Matthews 1989; Boley *et al.* 2009), litter fall and ability to fix nitrogen (Morgan *et al*. 1992; Bauhus *et al.* 2000; Forrester *et al.* 2006). Mixed plantations of teak with other species have been reported to have a positive influence on floristic regeneration of native understory and management of invasive species. Kaewkrom *et al.* (2005) showed that plantations consisting of mixture of teak with several species especially those of *T. grandis* and *Gmelina arborea*; and *T. grandis*, *Tamarindus indica* and *Anacardium occidentale* in the overstorey had a higher diversity of native forest species in the understorey than the single-species plantation in northern Thailand. Mixed plantations of teak with native species of Panama viz., *Albizia adinocephala*, *Colubrina glandulosa*, *Dalbergia retusa*, *Pochota quinata*, *Tabebuia rosea* and *Terminalia amazonia* were found to be effective for control of invasive Asian grass species *Saccharum spontaneum* which inhibits the establishment of woody species due to the its deep and extensive root system (Wishnie *et al.* 2002).

In many studies, tree species mixtures have been reported to produce higher yields than monocultures of individual species (Cannell *et al*. 1992; Kerr 1992; Wormold 1992; Khanna 1997; Menalled *et al*. 1998; Piotto *et al.* 2004; Nichols *et al.* 2006; Redondo-Brenes and Montagnini 2006). Beneficial species mixtures in these studies include N-fixing *Inga edulis* with *Terminalia Amazonia* (Cannell *et al*. 1992), *Eucalyptus globulus* and *Acacia mearnsii* (Khanna 1997), mixtures of *Cedrela odorata*, *Cordia alliodora* and *Hyeronima alchorneoides* (Menalled *et al*. 1998) and 46 tropical and temperate species (Piotto *et al.* 2004). Mixes of species that differ in height (rather than diameter) growth, form, shade-tolerance and phenology are most likely to increase site productivity (Kelty 1992; Piotto 2008). In an extensive review of temperate and boreal regions, Burkhart and Tham (1992) showed that species mixes usually had equal or higher yields than did pure stands. Mixtures tend to outperform monocultures on poor sites (Binkley 1992; Montagnini *et al*. 1995) whereas pure stands of a highly productive species can have higher merchantable yields on high quality sites (Burkhart and Tham 1992; Kelty 1992) but are more vulnerable and susceptible to pest outbreaks (Lugo 1997; Bragança *et al*. 1998).

Species mixtures often include retention of mature overstorey nurse trees, chosen for its beneficial effects on the main crop species. In addition to nutrient synergisms (Kelty

1992) and pest resistance (Stiell and Berry 1985), these trees are used to protect crop species from frost (Nilsson 1990; Groot and Carlson 1996) and drought (Nilsson 1990; Marsden *et al.* 1996); provide side shelter for training tree form (Smith 1986) and increase wind stability (Kerr 1992; Lugo 1997). Polycultures also reduce risks associated with the uncertainty of future economic markets (Kerr 1999) and sometimes provide high returns (Ball *et al.* 1995). Planting polycultures also avoids risks associated with lack of site suitability, establishment failure and nutrient depletion (Evans 1992; Kerr 1999). In addition, most studies support the public view that polycultures have abundant and diverse flora and fauna in comparison to monocultures, especially where native species are planted (Bibby *et al.* 1989; Donald *et al.* 1997; Bragança *et al.* 1998; Donald *et al.* 1998). Although some experimentation will be necessary to optimize the species mix and ratio, plantation mixtures show much promise and should be seriously considered by managers (Stanley and Montagnini 1999).

ECOLOGY OF MIXED PLANTATIONS

Mixed species plantations should ideally emulate natural stands of mixed species in height-growth pattern and shade tolerance characteristics of individual species, conferring a potential productivity advantage in managed forest stands (Menalled *et al.* 1998). The basis of this advantage is rooted in fundamental *niche theory*, which states that two or more species must use the resources differentially to coexist on a site (Ewel 1986; Vandermeer 1989). Differential resource use due to niche separation among species suggests that the species in a mixture must optimally utilize the resources of a site leading to greater overall productivity. Therefore, a judicious selection of species is required in mixed plantations to have important differences in characteristics, which allow them to coexist or having “ecological combining ability” (Harper 1977). The species will have this ability due to:

1. Differences in height, form or photosynthetic efficiency of foliage;
2. Differences in phenology, such as timing of foliage production and duration of photosynthetic activity;
3. Differences in root structure particularly the depth of rooting.

The prime consideration for mixed plantation is the ecological requirements of species with climate, edaphic and topographic characteristics of the proposed planting site (Dupuy and Mille 1991; Wormald 1992; Evans 1992). The foresters are expected to manage a mixed plantation in two dimensions i.e. managing distribution of different species horizontally on the ground, and vertically in the space (Dauget *et al.* 1991).

However, growth in mixed-species plantations may not be improved compared to that of monocultures when competitive interactions outweigh nutrient availability and resource capture. Careful selection of sites and species is therefore, critical for successful establishment and improved growth performance of mixed plantations. Thus, a suitable mixture should provide growth opportunity to each species to result in synergy among them. For example, planting of nitrogen fixing *Albizia falcataria* with *Eucalyptus saligna* resulted in higher yields of Eucalyptus through optimum light capture by both species, resulting in abundance of organic matter, nutrient recycling and diazotrophy (nitrogen fixation) by *A. falcataria* (De Bell *et al.* 1989; Binkley 1992). In India, a mixture of *Bombax malabaricum* and *Acacia catechu* has been noted to have synergistic growth (Indian Forest Records 1939).

The natural habitat of plantation species is a good pointer to their silvicultural flexibility. The concept of combinations of species from different stages of the secondary succession helps in deciding species in a mixed plantation (Kageyama and de Castro 1989). Three groups of species are recognized:

A. ***Pioneer*** species, rapidly provide soil cover and show little ability to tolerate competition (Aubreville 1947; Guillaumet and Adjanohoun 1971; Trochain *et al.* 1980; Favrichon 1991). These species need sufficient space and are timely thinning falling, which they do not establish themselves and disappear.
B. ***Climax*** species, appear at final stages of the succession and grow in the shade of other species.
C. ***Intermediate*** species, need neighbours to improve their growth and form.

The efficiency of mixed plantations will depend heavily on the choice of species on the basis of physiological and growth characteristics as well as successional status of the target species and planted associates. Thus, the objective of the present review is to discuss mixed plantations of which teak (*Tectona grandis*) comprises a prominent component.

ECOLOGICAL REQUIREMENTS OF TEAK

Good growth and high quality of teak are associated with deep, flat and well drained alluvial soils, rich in calcium, especially on volcanic substrata such as igneous and metamorphic soils or on alluvial soils of various origins (Tewari 1992); a mean annual temperature between 22 and 27°C with mean monthly maximum temperatures 40°C and minimum 13°C and an annual precipitation from 1270-3800 mm with a marked dry season of 3 to 5 months i.e. ≤ 50 mm rain (Krishnapillay 2000; Pandey and Brown 2000). The optimal soil pH is between 6.5 and 7.5. Calcium deficiency in the soil results in stunted growth of teak (Kaosa-ard 1981).

Teak is an obligate light-demanding species throughout its life cycle and requires sufficient aeration for proper development of the root system. The light requirements of teak are those of a pioneer species, unable to stand much competition from other species, or from trees of the same species. Inferior trees are readily suppressed if stand density is too high. However, over most of its range, teak occurs in moist and dry deciduous forests below 1000 m altitude and is one of the several species constituting mixed forest stands.

TEAK IN MIXED PLANTATIONS

Teak has inherent capacity of growing with other tree species as over most of its natural range teak exists in the mixed forest stands (**Table 1**). Conspicuous associates of teak include *Terminalia chebula*, *T. belerica*, *T. tomentosa*, *Dalbergia latifolia*, *D. sissoo*, *Mitragyna parvifolia*, *Boswellia serrata*, *Anogeissus latifolia*, *Ougenia dalbergiodes*, *Schleichera oleosa*, *Madhuca latifolia*, *Xylia dolabriformis*,

Table 1 Associates of teak in natural forests.

Top canopy	Second storey	Undergrowth
Adina cordifolia	*Acacia catechu*	*Bambusa arundinacea*
Anogeissus latifolia	*Bridelia retusa*	*B. hamiltonii*
Boswellia serrata	*Buchanania lanzan*	*B. polymorpha*
Chlorozylon sweitenia	*Cassia fistula*	*B. tulda*
Dalbergia latifolia	*Diospyros melanoxylon*	*Cephalastachyum pergracyle*
Lagerstroemia parviflora	*Emblica officinalis*	*D. membranaceous*
Mitragyna parviflora	*Ougenia oojeinensis*	*Dendrocalamus strictus*
Pterocarpus marsupium	*Schleichera oleosa*	*Melocanna bambusoides*
Terminalia tomentosa		*Tyrosostachys oliveri*

Gmelina arborea and *Adina cardifolia.* Bamboos also come naturally under the upperstorey of teak (Luna 1996). In fact, bamboo regrowth is a serious problem in some of the teak plantations. *Bambusa arundinacea*, *B. hamiltonii*, *B. polymorpha*, *B. tulda*, *Cephalostachyum pergracyle*, *Dendrocalamus strictus*, *D. membranaceous*, *Melocanna bamusiodes* and *Tyrosostachys oliveri* are the main bamboo species of the teak forests (Tewari 1992). Teak also has different associates in various soil conditions: *T. tomentosa* and *Stephegyne parvifolia* in deep clay with permeable sand stone soil beneath; *A. latifolia* in fine clay loam, and *Xylia xylocarpa* in red murram soil (Troup 1921). In spite of ability of teak to thrive in the presence of other species in the natural conditions, no single species has been found to form a satisfactory crown mixture with it in plantations. In mixtures with other tree species as observed in Java, teak exhibits quick crowding out of their crowns, extensive branching and sensitivity to root competition (Kadambi 1993).

In this perspective, mixed plantations of teak should be carefully designed giving ample stress to the complex ecological requirements of teak by incorporation of accompanying species complementing its growth.

Reduction in crown competition

Teak has a unique successional status. It is a pioneer species, which stays for longer durations on the sites withstanding moderate competition due to evolutionary adaptations. As it is a pronounced light demander, the reduction in crown competition will be the chief factor to be addressed in designing composition of mixed teak plantations. The clearest way of using mixtures to make more complete use of available light is by combining species that develop a stratified canopy with overstorey of teak in high light environment and understorey of a shade adapted species (**Fig. 1**). In the beginning of the twentieth century a mixture of *Swietenia macrophylla* (mahogany), *T. grandis* and jack fruit (*Artocarpus integrifolius*) was established at Sundapola in Sri Lanka. Lack of crown competition among the species has been a prime factor (along with protection of mahogany from attacks by *Hypsipyla robusta*) for its success by the 1950s as mahogany being a shade tolerant did not interfere with light demands of teak. However, a decision was made to manage the area as a selection forest favouring the more valuable mahogany and the teak and jack fruit had been reduced to about 20% of the crop by 1963 (Muttiah 1965). In contrast, crown competition in mixed plantation of two climax species with similar light requirements, viz. teak and *Xylia dolabriformis* resulted in failure with teak outgrowing the latter (Lahiri 1987).

Reduction in root competition

Teak is also extremely sensitive to inter-specific as well as mutual root competition. Reduction of root competition in mixtures is thus, important. The principle that root stratification can be associated with increased total production has been demonstrated with herbaceous species (Ellern *et al.* 1970; Trenbath and Harper 1973). Different tree species also have different root structures and rooting depths (Spurr and Barnes 1980). Rooting zones of different species can effectively occupy different soil strata (Lamb and Lawrence 1993). This is why deeper rooting fir and beech are interplanted with shallow rooted spruce in Europe (Burschel and Huss 1987). A similar analogous situation is also an important consideration for mixed teak plantations. In teak mixed plantations, shallow rooted understorey species (e.g. bamboos) are more harmful to it than deep-rooted species (e. g. *Leucaena*) (Coster 1933). In a humid tropical region of central Kerala in India, intercropping with *Leucaena* promoted height and diameter growth of teak. This increase enhanced with increasing relative proportion of *Leucaena* in the mixture probably due to lack of root competition coupled with nitrogen fixing ability of *Leucaena* (Kumar *et al.* 1998). On the other hand again in Indian conditions, mixtures with shallow rooting bamboo, *B. tulda* led to suppression of the teak (Wormald 1992). Therefore, ideal associates in mixed teak plantations should have deep rooting system to minimize root competition with shallow rooting teak.

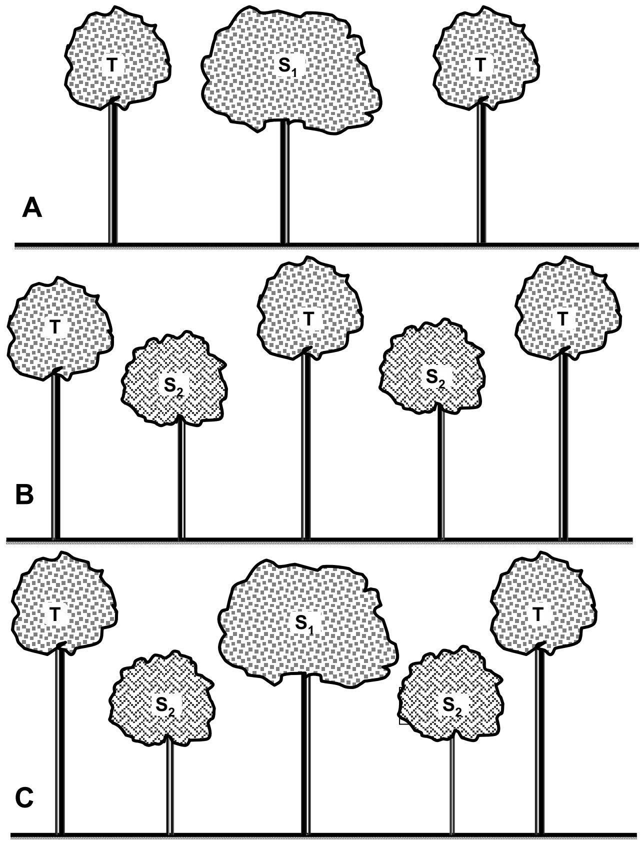

Fig. 1 Profile diagram of three types of mixed teak (T) plantations. (**A**) Sun-adapted timber species (S_1) in the upper storey. (**B**) Shade-tolerant species (S_2) in understorey. (**C**) Sun-adapted timber species in upper storey and shade-tolerant species in understorey.

Exploiting phenological differences

Differences in phenology among species in a mixed stand may reduce competition in crown or root temporally rather than spatially. Differences in timing of foliage production and duration of photosynthetic activity are important in some agricultural intercropping systems and may be important in tree plantation as well (Kelty 1992). One situation may be that one species of mixtures is deciduous (upperstorey) and the other evergreen (understorey). The combination of *D. sissoo* and teak has been highly successful in mixed plantations in India (Wormald 1992). The difference of phenological behavior provides ample niche separation to both the species for having optimal sprouting and reproductive growth as the time of leaf fall is from October to January in the *D. sissoo* and from December to march in case of teak (Egunjobi 1974; Jackson 1987). Thus, a consideration of phenological differences of the associates with teak may enhance the chances of success and productivity in mixed plantations.

Litter decomposition rates and nutrient cycling

Higher temperatures of tropics result in rapid litter decomposition but when the species like teak having relatively decay-resistant foliage are grown in monoculture, litter tends to accumulate on the forest floor even in tropical climate. It has been observed in teak plantations in Trinidad (Bell 1973) where the litter also enhanced fire hazard in addition to slow recycling of nutrients hampering growth. Litter decomposition may be more rapid increasing nutrient availability when a mixture of litter from different species is present on the forest floor (Simmonds and Buckley 1990). Species mixtures often have increased decomposition rates, in part because the carbon: nitrogen ratio of litter is improved and acidity is reduced. These changes stimulate microbial activity that increases nitrification and overall nutrient availability on site (Matthews 1989; Kelty 1992). Mixed species plantations can handle slow litter decomposition rates in pure teak stands. Introduction of a species with favourable litter characteristics into pure teak stands will improve nutrient recycling. Nitrogen fixing trees will be important as they fix atmospheric nitrogen and improve soil fertility. On naturally infertile or depleted soils, incorporations of such tree species generally legumes (*Acacia*, *Albizia* and *Leucaena*), which are symbiotically associated with *Rhizobium* species or *Casuarina*, associated with *Frankia* species is thus advocated (Parrotta *et al.* 1996; Kumar *et al.* 1998; Bauhus *et al.* 2000; Forrester *et al.* 2005).

Management of insect pests

A lower proportion of leaf area has been lost to herbivory in more diverse plant communities than simpler ones (Brown and Ewel 1987). Polycultures of inter-planted crop support lower density of insect pests than monocultures (Risch 1981). The major pests of teak are *Hyblaea puera* Cramer (defoliator) and *Eutectona machaeralis* Walker (leaf skeletonizer). Unless alternate host plants are available, larvae of both insect pests starve during the period of leaflessness in teak. Therefore, other tree species in mixed tree plantations should not ideally be an alternate host to these insects. Beeson (1938) considered *G. arborea* as undesirable in teak plantations on this ground. On the other hand, the species supporting insect parasites on both the major teak pests may be desirable in mixed teak plantations, for example, *X. xylocarpa* and *Morus alba*.

Use of superior clonal planting stock

Teak plantations in India are generally raised from root-shoots of unidentified and unimproved seed sources resulting in poor productivity. Employment of superior clonal planting stock for establishment of teak plantations will improve their productivity. Cloning by induction of adventitious rhizogenesis in shoot cuttings has been demonstrated for large-scale multiplication of superior clones or tested elite trees of teak (Sanjay Singh *et al.* 2005). Ansari and Sanjay Singh (2003) have also demonstrated cost effectiveness of clonal propagation of superior teak, which also confers an additional productivity gain of about 20%. Clonal trials were taken up from the parent material from a vegetative multiplication garden established through clones of selected superior trees form good teak growing regions (natural forests and plantations) of central India including states of Maharashtra, Madhya Pradesh, Chhattisgarh and Orissa. The clonal plantlets produced through shoot cuttings were employed at mixed species plantations with *D. sissoo*, *G. arborea* and *Grewia optiva* in individual strip plantings at farmers' fields. After 10 years the clones exhibited superior growth and form compared to teak plantations raised by mixed seed lots (Singh unpub.). Thus, clonal forestry can be taken up on commercial scale in mixed plantations for enhancement of quality and productivity of teak to cope up future timber demand. However, sufficient number of clones should be employed at any particular site to induce an element of diversity.

Table 2 Species planted in mixed plantations with teak and their performance.

Species	Country	Remarks	References
Artocarpus hirsuta	India	Successful, economically unviable	Wormald 1992
A. integrifolia (with mahogany)	Sri Lanka	Successful	Muttiah 1965
Acacia catechu	India	Tends to separate into pure groups	Wormald 1992
Anacardium occidentale	Thailand	Good for understory diversity	Kaewkrom *et al.* 2005
Antidema bunis	Indonesia	Failure	Hart 1931
Bambusa tulda	India	Suppressed teak	Wormald 1992
Casea siamea	Nigeria	Shaded out by teak	Street 1962
Cedrela toona	India	Not promising	Wormald 1992
C. pergracile	India	Successful	Wormald 1992
Cinnamomum iners	Indonesia	Failure	Hart 1931
Colubrina glandulosa	Panama	Successful	Wishnie *et al*. 2002
Copaifera officinalis	Trinidad	Shaded out by teak	Bell 1973
Dalbergia latifolia	Indonesia, India	Successful	Wormald 1992; Balooni 2000
D. sissoo	India	Done well	Wormald 1992; Singh unpublished
Diospyros celebica	Indonesia	Successful	Alrasyid 1985
Eugenia subglauca	Indonesia	Not successful	Wormald 1992
Gluta renghas	Indonesia	Failure	Hart 1931
Gmelina arborea	India	Failure; each suppressing the other	Wormald 1992
Gmelina arborea	Thailand	Good for understory diversity	Kaewkrom *et al.* 2005
Khaya grandifolia	Nigeria	Heavy borer damage in khaya	Street 1962
K. senegalensis	Nigeria	Not successful	Street 1962
L. leucocephala	Malaysia, Sri Lanka	Successful	Perera 1962; Hg 1982
L. leucocephala	Philippines	Shaded out by teak	Grenert and Rarlai 1980
L. glauca	India	Good mixture	Kumar *et al.* 1998
Lophira alata	Nigeria	Successful	Henry 1960
M. bambusoides	India	Successful	Wormald 1992
Pterocarpus indiensis	Indonesia	Not much success	Hart 1931
P. macrocarpus	Myanmar	A good mixture	Oo *et al.* 2008
P. marsupium	India	Discouraging results	Wormald 1992
Schleichera oleosa	Indonesia	Successful	Deventer 1913
Schoutenia ovata	Indonesia	Not much success	Wormald 1992
Swietenia macrophylla	Fiji, Sri Lanka	Successful	Street 1962; Muttiah 1965
S. macrophylla	India, Indonesia	Failure; each suppressing the other	Wormald 1992
Tamarindus indica	Thailand	Good for understory diversity	Kaewkrom *et al.* 2005
Tephrosia candida	India	Efficient (interplanted in III year)	Wormald 1992
Xylia dolabriformis	India	Failure; out grown by teak	Lahiri 1987

CONCLUDING REMARKS

Mixed plantations of teak have been tried throughout the tropics with varying degrees of success (**Table 2**). It is evident that growing of teak in mixed plantation deserves a careful consideration of various factors including crown and root characteristics, phenology and growth patterns of associates. However, some of the promising mixtures have been provided below:

1. **Mixed crops for timber production**
   Usually single layered mixtures of teak with medium rotation timber species such as *D. latifolia*, *M. parvifolia*, *T. tomentosa*, *A. latifolia*, *O. dalbergiodes* and *D. sissoo* is recommended.
2. **Mixed production crops (timber, useful wood and fuelwood)**
   Two-layer mixed crops are suggested. The principal species, teak is dominant and the secondary or co-dominant, usually a short rotation (5-10 years) species producing less valuable wood or fuelwood, e.g. *A. catechu*, *A. mangium*, *B. serrata*, *S. oleosa*, *T. belerica*, *T. chebulia.*
3. **Mixed crops combining productive and protective functions**
   In this type of mixed plantations, teak is associated with a species whose function is that of soil-improving ground cover. Examples are teak with *A. auriculiformis*, *L. glauca*, *Melia azadirachta* and bamboos such as *M. bambusoides*, *C. pergracile.* Leguminous species are often used with the advantage of combining good physical soil protection vis-à-vis an improvement in the availability of mineral elements, particularly nitrogen.

However, all these above mentioned mixtures need to be rigorous tested on experimental level before opting for large-scale plantations.

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