Review/Synthesis

Quarter century of agroforestry research in Kerala: an overview

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Abstract

Kerala with many woody perennial-based land use practices is one of the "Meccas" of agroforestry. Twenty-five years of research has demonstrated the potential of agroforestry as a sustainable production system in the state. Aspects such as system inventory and dynamics, species richness, belowground interactions, nutrient cycling, tree and stand management, carbon sequestration potential, timber and fuelwood properties, and socioeconomic aspects were the major themes investigated. Considering the state's unique land use, demographic, political, and sociocultural characteristics, Kerala's experience in agroforestry research is important to agroforestry development, especially in the humid tropical regions. Although agroforestry has received much attention from researchers, for its perceived ability to contribute to environmental quality, agrobiodiversity conservation, and nutrient cycling, the policy makers are yet to fully recognize such benefits and agroforestry extension is either weak or non-existent in the state. This calls for more process-oriented research and policy initiatives to promote agroforestry among the farmers of Kerala.

Keywords: Agrobiodiversity, Agroecosystem management, Carbon sequestration potential, Nutrient cycling, Woody perennials.

Introduction

Agroforestry systems and practices abound in Kerala since time immemorial. The long history of agroforestry (although the term *agroforestry* was not introduced until the late 1970s) is evident from the early literature. For example, the travelogue of the Persian traveler Ibn Battuta (1325–1354) mentions that in the densely populated and intensively cultivated landscapes of the Malabar Coast, coconut (*Cocos nucifera* L.) and black pepper (*Piper nigrum* L.) were prominent around the houses (Randhawa, 1980). The contents of the over 300 year-old book of agricultural verses, *Krishi Gita* (Kumar, 2008a), also reflect the importance of maintaining tree cover on the landscape, planting fruit trees on cleared forests, gardens, and other leftover lands, avenue planting, as well as leaving vestiges of forests in the midst of cultivated landscape—presumably for agrobiodiversity conservation and agroecological balance. The writings of the colonial period (Mateer, 1883; Logan, 1906; Nagam, 1906) that provide evidences of homegardening is another example in this respect. Contemporary studies too highlight the importance of agroforestry in Kerala (Kumar, 1994; 1999; 2005; 2006a; 2007; Guillerme et al., 2011).

Trees and shrubs are present on most agricultural lands in Kerala except in the paddy (*Oryza sativa* L.) fields. Examples include, the tropical homegardens, shaded commercial crop production systems involving cacao (*Theobroma cacao* L.), coffee (*Coffea* spp.), tea (*Camellia sinensis* (L.) Kuntze.), and spices, silvopastoral systems with fodder grasses in association with commercial trees, trees on farm boundaries, and woodlots (Figs 1–6; Kumar et al., 1995a; Chandrasekhara, 2009). Homegardens that offer food and nutritional security to the subsistence farmers, are, however, a distinguishing feature of the state. Multifunctionality is a characteristic feature of

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Figure 1. A mixed species homegarden in Kerala.

Figure 2. Tea+*Grevillea robusta* (silver oak) system in Munnar, Kerala.

Figure 3. Pineapple (*Ananas comosus*) intercropped along with young rubber (*Hevea brasiliensis*) saplings.

Figure 4. Areca palm (*Areca catechu*) + cacao (*Theobroma cacao*) system in Wayanad, Kerala.

Figure 5. Shaded coffee (*Coffea* spp.) production system in the Western Ghats.

Figure 6. Black pepper (*Piper nigrum*) + support tree system in the Western Ghats.

Photos: BM Kumar

the agroforestry practices in Kerala, as it is elsewhere. Most agroforestry systems have the intrinsic potential to provide food, fuel, fodder, green manure, and timber resources. Furthermore, there is an accumulation of scientific evidence about the environmental functions of agroforestry, such as their role in the regulation of physical and chemical fluxes in ecosystems, and mitigation of environmental pollution (Nair, 2008). Despite these positive traits and the efforts to promote agroforestry (e.g., National Agriculture Policy of 2000; http://www.incg.org.in/Agriculture/Policies/National Agriculture Policy.htm), 'modern' agroforestry technologies involving either improvement of traditional practices or introduction of new ones (Nair, 1993) have not been widely adopted in the state. In this paper, I will assess the extent to which the past 25 years of research and experience have contributed to the science and practice of agroforestry in Kerala and highlight some issues that have relevance for adopting mixed species production systems involving woody perennials and herbaceous crops.

Agroforestry Research in Kerala

Organized research in agroforestry started in Kerala with the establishment of All India Coordinated Research Project on Agroforestry at the Livestock Research Station, Thiruvazhamkunnu, Palakkad in June 1983—almost at the same time when similar initiatives were made elsewhere in the country (ICAR, 1981). The research initiatives on agroforestry in Kerala, however, gained momentum only after the establishment of the College/Faculty of Forestry at the Kerala Agricultural University (KAU) on 2 July 1986. This paper focuses on the research done during the past 25 years. The reference here is to research under the name 'Agroforestry'. Although research of this nature was conducted earlier, it was not known as agroforestry (e.g., crop combinations with coconuts and other perennial plantation crops: Nair, 1979).

As part of the agroforestry initiatives, the KAU organized an Indo-US Workshop-cum Training in Tree Nursery Technology and Management in Agroforestry at the College of Forestry (6 to 18 May 1991). Professors William H. Emmingham and Robert W. Rose of the Department of Forest Science, Oregon State University, Corvallis, Oregon, U.S.A. participated in this workshop as key resource persons. This workshop dealt with tree nursery production ranging from seed collection up to and including out-planting. It was concluded that improvement in regeneration of forests, degraded lands, desertified areas, and agroforestry planting must be approached as an integrated project in which the nursery production is part of a well-coordinated chain of events to attain success in the field. Another landmark agroforestry event in Kerala has been the Annual Work Group Meeting and Symposium on Agroforestry (5 to 7 February 1998) to review the ongoing programmes of the All India Coordinated Research Project on Agroforestry (AICRPAF) and to formulate strategies for future research. The KAU also organized the 'National workshop on natural resource management: changing scenarios and shifting paradigms' (21 to 24 February 2003) and the National Workshop of AICRPAF (21 to 23 May 2011) – to take stock of the natural resource management scenario in the state (Kumar et al., 2003) and to review the status of agroforestry research in the country, respectively.

Major Research Themes

Systems Inventory and Dynamics

A major component of the research programmes under the AICRPAF was *Diagnosis and Design* of Kerala's traditional farming systems. Homegardens, which represent an intimate, multistorey combination of various trees and crops, sometimes in association with domestic animals, around the homestead, have been recognized as the flagship agroforestry practice of Kerala (Kumar et al., 1994; Kumar, 2003; Kumar and Nair, 2004). There are about 6.3 million predominantly small operational holdings in Kerala (average size 0.24 ha in 2000–01) covering a total area of 1.2 million ha (MoA, 2001), of which about 80% are homegardens (Kumar, 2006a). They function as the loci for experimentation with new tree species and cultivation techniques, and thus have the potential to contribute to the development of other agroforestry systems, and to extension efforts that seek alternatives for agricultural development (Kumar and Nair, 2006; Kumar, 2008b).

Border trees, scattered trees on farmlands, live fences, supports for commercial crops such as black pepper, farm woodlots, and commercial crops growing under the shade of trees in the natural forests are also popular in the state. The coconut tree forms the nub of the cropping systems in Kerala. Due to its height, narrow crowns, rooting pattern and wide spacing adopted, this tree is amenable to growing a variety of annual, biennial, and perennial crops under it. As a result, intercropping coconut with cacao, black pepper, betel vine (*Piper betle* L.), yams (*Dioscorea* spp.), cassava (*Manihot esculenta* Crantz), turmeric (*Curcuma longa* L.), mango (*Mangifera indica* L.), pineapple (*Ananas comosus* (L.) Merr.), and banana (*Musa* spp.) abounds (Ghosh et al., 1989; Kumar, 1999; 2007; Reddy and Biddappa, 2000). The smallholder farmers who practice multiple cropping often depend on their farms for most of the food needs of the family and the farm operations are also based on the family's manual labour.

Cardamom hill reserves (CHR) constitute a traditional agroforestry system in the high altitude regions of Kerala. It involves growing small cardamom (*Elettaria cardamomum* (L.) Maton Engl.), a sciophytic commercial crop, under the shade of trees in the natural forest. Dominant trees in the evergreen and semi-evergreen forests selectively retained by the growers provide shade to the cardamom crop in this age-old cultural system. Shade trees also vary from place to place depending on local preferences (Kumar et al., 1995a).

Taungya, a system of establishing commercial forest plantation in which agricultural crops are grown on a temporary basis between regularly arranged rows of trees, has been widely practiced in Kerala till the l990s. The greatest disadvantage of taungya and other systems established on the sloping lands of Kerala, however, has been soil erosion caused by land preparation for planting crops (Alexander et al., 1980; Moench, 1991). Gopinathan and Sreedharan (1989) reported that in cassava + *Eucalyptus* system, substituting 10% cassava with grass strips reduced soil erosion by 41%. Although for long, taungya was thought as a harmful practice, the State Forest Department, of late, is re-evaluating the pros and cons of this practice.

With increasing emphasis on industrial models of agricultural development [e.g., rubber (*Hevea brasiliensis* H.B.K. M.-Arg.)], fragmentation of land holdings due to demographic pressures driving land use intensification and, to some extent, decreasing appreciation, the traditional agroforestry systems have declined and monocultures of commercial crops became dominant in Kerala (Jose and Shanmugaratnam, 1993; Kumar and Nair, 2004; Peyre et al., 2006; Guillerme et al., 2011). Natural forests and cardamom (planted under forest canopy) also have been widely replaced by smallholder cultivation involving an array of arable crops (Monech, 1991).

Agrobiodiversity

Most agroforestry systems in Kerala harbour disparate and intricate species mixes (Depommier, 2003; Kumar and Takeuchi, 2009). The tropical homegardens are a case in point. Both naturally occurring wild flora and deliberately introduced plants occur in the homegardens (Kumar et al., 1994). A new species may be introduced because of its properties, i.e., food, wood, medicinal, religious, ornamental, and based on self-instinct or information passed on by neighbours and relatives. Many attempts were made to characterize the floristic richness and species diversity of Kerala homegardens (Nair and Sreedharan, 1986; John and Nair, 1999; Mohan et al., 2007). Such studies generally report high floristic diversity and richness (e.g., Kumar and Nair, 2004). Indeed, the Simpson's floristic diversity index (0.64, 0.41, and 0.46 for small, medium, and large homegardens respectively), floristic richness, and tree density were the highest for the smallholdings (Kumar et al., 1994; Kumar, 2011a). Holding size, geographical location, gardeners' socioeconomic status, and managerial interventions are major determinants of this.

In addition to the aboveground diversity, greater organic matter flux and/or favourable soil moisture relations (Isaac, 2001) stimulate drilosphere systems (associations between earthworms and soil bacteria), implying higher belowground diversity. Consistent with this, Rahman et al. (2011) found that earthworms, millipedes, and other soil invertebrates were more abundant in agroforestry than in the arable crop production systems. Intraspecific variations also abound among the homegarden tree components (Muthulakshmi et al., 1999; Anila and Radha, 2003; Resmi et al., 2005; Abraham et al., 2006; Kumar 2008b; Nayar, 2011). Due to commercialization, however, many of these traditional fruit tree cultivars are disappearing, which calls for urgent steps to conserve the indigenous germplasm.

Lower floristic diversity of the CHRs compared to undisturbed evergreen forests and a truncated vegetation structure for shade trees (Kumar et al., 1995a) also signify erosion of species from managed ecosystems. Such losses generally represent major ecological and production constraints in the traditional small cardamom growing areas. The truncated stand structure of CHRs denote systematic removal of the lower size classes. Overall, replacement of species-rich traditional land use practices with industrial models of agricultural development is resulting in a serious erosion of biodiversity both at the species and genotypic levels.

Plant Interactions

The forced integration of trees into the agricultural production systems constructs diverse interspecific interactions. Both positive (e.g., nutrient cycling and microclimatic changes) and negative (e.g., competition, allelopathic, pest and disease vectors) effects are plausible. An important hypothesis of agroforestry, however, is resource complementarity. A series of experiments were conducted at KAU to assess the potential of agroforestry for nutrient sharing and conservation as well as to evaluate the competitive interactions among the components, using ^{32}P. The systems studied include combinations of multipurpose trees (MPTs) with fodder grasses, ginger (*Zingiber officinale* Roscoe), galangal (*Kaempferia galanga* L.), and commercial tree crops such as coconut, besides fast growing trees (*Acacia mangium* Willd. and *Ailanthus triphysa* (Dennst.) Alston.) under different thinning, pruning, fertilizing, and spacing regimes. Root interactions in mixed species systems and root distribution of woody perennials such as wild jack (*Artocarpus heterophyllus* Lamk.), cacao, and cashew *(Anacardium occidentale* L.) also were focal themes of such research.

Results of ^{32}P soil injection experiments involving interplanted dicot MPTs (*Vateria indica* L., *A. triphysa,* or *Grevillea robusta* A. Cunn. at 3 and 8 years of age) in coconut plantations (Kumar et al., 1999; Gowda and Kumar, 2008) and binary mixtures of bamboo (*Bambusa bambos* (L.) Voss) with teak (*Tectona grandis* L.f.) and Malabar white pine (*V. indica*) (Divakara et al., 2001; Kumar and Divakara, 2001) demonstrated complementary resource use. In the coconut+dicot tree system, closer the associated tree components were located greater was the subsoil root activity and greater was the potential for capturing the lower leaching nutrient ions (Gowda and Kumar, 2008). Likewise, in mixtures involving bamboo and dicot trees lower teak and Malabar white pine root activity was observed in the surface horizons (0–25 cm) and higher activity in the deeper layers (25–50cm), when the bamboo clumps were nearby, and vice versa when they were farther apart (Kumar and Divakara, 2001).

High stem density in monospecific stands of *A. mangium* also favoured restricted spread of absorbing roots and facilitated competitive downward displacement of roots (Kunhamu et al., 2010). Overall, the root systems of dicot trees become laterally compressed when individuals of the same species or other tree species occur at proximal ranges. Such plastic responses in tree root growth can be expected even when intercropped with herbaceous and other crops. For instance, cassava intercropping restricted spread and mean length of lateral roots of *Eucalyptus* and *Leucaena* (Ghosh et al., 1989).

The competitive downward displacement of tree roots, facilitating deep penetration and vertical stratification, is suggestive of a 'safety-net' mechanism to intercept the lower leaching nutrients. This is of particular relevance in the high rainfall zones of Kerala, where the potential for nutrient leaching is high. Deep-rooted trees can also make available subsoil resources to associated plants with shallower root systems through 'nutrient pumping' and hydraulic lift (Gowda and Kumar, 2008). Horizontal transfer/sharing of nutrient ions between the rhizospheres of the neighbouring plants is yet another possibility. Evidences suggest a considerable intermingling of the root systems of coconut palms and herbaceous components (e.g., galangal), which in turn is suggestive of a 'soil pool pathway' for nutrient cycling (Kumar et al., 1999). Root grafts and/or mycorrhizal connections too act as multipliers of the 'root systems' reach', facilitating interplant transfer of nutrients.

Yet another positive aspect of mixed species production systems is the "scavenging effect" of the trees. Interplanted dicot trees in coconut gardens absorbed substantial radio-label applied to the coconut palm, which otherwise would have remained unutilized by the main crop (Gowda and Kumar, 2008), implying greater nutrient use efficiency for mixed species production systems than monospecific systems (Kumar, 2006a). Thus, when the tree components are closely integrated, there is a substantial potential for "capturing" the lower leaching nutrient ions.

While comparing the root activity pattern of black pepper vines trailed on teak poles and *Erythrina*, Sankar et al. (1988), however, observed interspecific competition for applied ^{32}P between pepper vines and the surface feeding *Erythrina* roots. Wahid et al. (1989a) also reported a high surface concentration of active roots in cacao with about 73% of the total root activity confined to a lateral distance of 100 cm. Likewise, higher root activities in the surface soil layer compared to lower depths were noted for monospecific stands of cashew (Wahid et al., 1989b), coconut palms (Anilkumar and Wahid, 1988), and wild jack trees (Jamaludheen et al., 1997). For five year old *Acacia auriculiformis* A. Cunn. ex Benth. and *Casuarina equisetifolia* J.R. & G. Forst. trees, George et al. (1996) also found that much of the root activity was concentrated in the surface layers (within a radius of 50 cm). Trees, thus, may exert a competitive influence on associated crops in certain polycultures, the magnitude of which, however, is dependent on root system morphology and distribution of physiologically active roots.

Initial tree spacing, thinning, and pruning are silvicultural strategies to regulate root competition. ^{32}P studies in *A. mangium*-ginger intercropping system showed that belowground competition for nutrients could be reduced through thinning (Kunhamu et al., 2008). Thomas et al. (1998), however, showed a lack of significant variation in ginger ^{32}P recovery as a function of tree population density (*A. triphysa*) suggesting that tree density is probably not a strong determinant of belowground competition in well-fertilized, manured, and mulched systems (at least till four years after tree planting). High stand density also induced greater root uptake capacity close to the stem (proximal) and from the subsoil and crown pruning further stimulated root uptake capacity at proximal points (Kunhamu et al., 2010). Crown pruning and tree spacing thus can alter root spread and potentially reduce belowground competition in mixed tree and field crop production systems. As mentioned, both production decreasing and stimulating effects (i.e., competitive vs. complementary) are probable in mixed species systems. The net outcome of interactions, however, will depend on the range of traits extant in diverse species assemblages, stem density regulation, and tree management practices adopted. Mixing species with disparate crown and root architecture thus makes sense.

Tree and Stand Management

Stand density regulation through initial stocking control and subsequent thinning has been practiced in forestry for a long time and has relevance for agroforestry too, especially since the management objective often is to optimize the combined production of the tree and herbaceous crop components. The classical silvicultural trade off, however, is maximizing the individual tree growth or total system productivity, or compromising one for the other. The nature of compromise, however, will depend on the management objectives. A teak density management diagram (simple stand average models that represent dimensional relationships in a graphical form) was constructed (Kumar et al., 1995b) to help resource specialists to predict and display the consequences of stand density manipulation and translate the management objectives into practical density management regimes.

Wider tree spacing generally offers greater opportunities for understorey cropping. One of the potential problems, however, is that the widely spaced individuals are likely to develop more spreading crowns than closely spaced ones. This would not only adversely affect the prospects of intercropping but also would impair stem form and wood quality (e.g., higher taper and larger knots). Crown pruning under such situations may favour stem development, besides increasing understorey light availability. Severe pruning, nonetheless, may inhibit tree growth (Chandrasekhara, 2007; Kunhamu et al., 2010). Interactions between planting density and pruning regimes in *A. mangium* caused significant variations in plant height, radial growth, volume, crown diameter, and taper among the individual trees, implying the need to apply pruning treatments in conjunction with density regimes.

For management objectives such as maximization of timber volume production per hectare, high density stands are generally preferred. Consistent with this, in experimental studies, total stand volume was higher for dense stands (5000 *A. mangium* trees ha^{-1}); however, low density (625 trees ha^{-1}) stands had higher mean tree volume (Kunhamu et al., 2010). Likewise, higher ailanthus density (2 x 2 m spacing) stimulated stand growth but wider spacing (3 x 3 and 3 x 2 m) recorded higher mean tree biomass (Kumar et al., 2001a; Shujauddin and Kumar, 2003). Thinning is another important management tool for the production of high-quality timber. In an experimental study involving 7 year-old *A. mangium* trees, stand thinning not only increased radial growth and mean tree volume but also improved the sub-canopy photosynthetically active radiation (PAR) availability, which in turn favoured ginger productivity (Kunhamu et al., 2008). Similarly, total green fodder yield in *Leucaena leucocephala* (Lamk.) de Wit. (cv. K8) was a function of the height of cutting and the highest yield (31.35 Mg) was obtained when the plants were harvested at 1 m height (Bai et al., 1990).

Addition of fertilizers and manures is yet another silvicultural strategy to stimulate tree growth, especially on poor sites. Nonetheless, repeated application of fertilisers at 1.2, 2.25, and 5.25 years after planting had little effect on biomass and volume yields of *A. triphysa* (Shujauddin and Kumar, 2003). Competition from ground vegetation may be a plausible explanation. This, however, is a function of stocking levels; i.e., denser stands may suppress competing ground vegetation more efficiently than sparse stands, because of early crown closure, and would increase fertilizer use efficiency, especially for nitrogen. Competing ground vegetation, nevertheless, is a concern in young stands of trees.

As nitrogen losses are likely to be important in plantation and agroforestry systems, new systems of management that mimic the natural ecosystems where significant quantities of N are added via the biological fixation pathway, assume significance. In an experiment on intercropping teak with *L. leucocephala*, Kumar et al. (1998a) reported that teak growth (height and diameter) increased linearly as the proportion of *Leucaena* in the mixture increased. At 44 months after planting, teak in the 1:2 teak-*Leucaena* mixture was 45% taller and 71% larger in diameter at breast height than those in pure stands. Soil analysis of the experimental plots provided corroborative evidences, i.e., total soil N and available P increased with increasing relative proportion of *Leucaena* in the mixture. Using N_2 fixing trees (*Leucaena*, *Gliricidia*, or other woody legumes) therefore could be a viable silvicultural option for stimulating early teak growth, especially on unfertilized sites.

Plant interactions form a major determinant of tree growth in parasitic plants such as the East Indian sandal wood tree (*Santalum album* L.), a root hemi-parasite, too. In experimental studies, tree species like *Casuarina*, *Terminalia*, *Albizia*, *Dalbergia*, and *Pongamia* formed intimate haustorial associations and facilitated translocation of nutrient ions from the host to the hemi-parasite (Taide et al., 1999). Conversely, *Emblica*, *Sweitenia*, *Delonix*, *Acacia*, *Ailanthus,* and *Leucaena* formed non-functional haustorial connections with sandal, implying that choice of host plant species may be an important design criterion for establishing sandal-based agroforestry systems.

System Productivity: Understorey Components

Many field/tree crops are grown in association with multipurpose trees in Kerala. As mentioned, competition for site resources (above-and belowground), may limit productivity. Trees with compact crown, moderate root spread, and deep rooting tendency are, however, less competitive with associated crops. Shade tolerance of the species involved is yet another determinant of productivity (Mathew et al., 1992; Kumar et al., 2001a,b). Tolerant crops are likely to maintain high understorey productivity under increasing levels of canopy closure. The results of the studies in this respect, however, are inconsistent. Experiments involving rubber clearly demonstrated the economic feasibility of growing cassava, rice, banana (*Musa* spp), ginger, turmeric, elephant yam (*Amorphophallus paeniifolius* (Dennst.) Nichols.), and pineapple as intercrops during the initial three years (Rajasekharan and Veeraputhran, 2002). Conversely, Ghosh et al. (1989) reported lower tuber yield of cassava and pod yield of the seasonal crops, when interplanted with trees. Likewise, Ravindran (1996) observed lower root yield of cassava grown under partial shade of coconut palms (68%) compared to cassava grown in the open.

The coconut-based polycultural systems often include diverse kinds of woody perennials used for fuel, timber, fodder, and green manure purposes (Reddy and Biddappa, 2000; Kumar and Kumar, 2002; Kumar, 2006a). Although presence of such trees in the coconut production system ensures more efficient resource utilization, it transforms the single-strata coconut canopy into a multistrata one. The commonest effect of this is lower understorey light availability (Kumar et al., 1999), reducing subcanopy yields. However, the negative effect on subcanopy productivity is not universal, and under certain circumstances, yields may increase ("over-yielding"), implying that productivity in multistrata systems is dependent on the growth habit/crown characteristics, planting geometry, stand leaf area index, and stocking levels of the associated tree components (Maheswarappa et al., 2000; Kumar et al., 2001b; 2005a).

In two field experiments involving multipurpose trees understorey ginger productivity, however, showed divergent trends (e.g., Kumar et al., 2001a; Kunhamu et al., 2008). While ginger in the interspaces of *A. triphysa* exhibited better growth and yield compared to tree-less systems, rhizome yields of ginger intercropped with *A. mangium* was lower than that of tree-less systems. Highest rhizome yield was observed in the 2500 trees ha^{-1} stocking level, which is presumably the optimum density for <5 year-old *A. triphysa* stands on good sites (52% mean daily PAR in the understorey). Despite showing lower productivity than sole crop, ginger yields in association with *A. mangium* increased with increasing thinning intensity (Kunhamu et al., 2008). As regards to understorey galangal rhizome yield, presence or absence of over canopy, however, had little effect; as yields under 'no over canopy', single strata, and multistrata systems were similar despite variations in understorey PAR–a function of tree species and stand LAI (Kumar et al. 2005a).

Understorey herbage productivity in combinations of four trees and grasses was monitored for seven years at Thiruvazhamkunnu (Kumar et al., 2001b). Productivity increased until three years in all tree+grass combinations, but declined thereafter, as tree crowns expanded. Overall, casuarina among the MPTs, hybrid napier (*Pennisetum purpureum* Schumach.) and guinea grass (*Panicum maximum* Jacq.) among the forage crops, were more productive than others. Pruning MPTs favoured greater subcanopy herbage production. Understorey PAR for five year-old acacia, ailanthus, casuarina and leucaena were 17, 60, 55, and 55% respectively of that in the open. Overall, careful selection of the tree and grass components is crucial for optimising herbage productivity in silvopastoral systems.

System Productivity: Woody Perennial Components

The coconut-based mixed species systems often aim at improved resource capture through incorporating several trees and field crops. Productivity of palms and the associated tree components in such mixed systems are, however, known to vary in response to the tree characteristics, planting pattern/geometry and shade tolerance of the components. The effects of three fast growing trees (*V. indica, A. triphysa*, and *G. robusta*) in association with coconut palms (18-year-old) following two planting geometries (single row and double row), on the productivity of coconuts and the growth of multipurpose trees were studied by Kumar and Kumar (2002). Shade tolerance appears to be a major determinant of the growth rates of interplanted dicot trees. Integrating shade tolerant timber trees in the coconut-based production systems, therefore, would increase overall productivity and profitability, especially in the disease affected and senile plantations. Consistent with this, Maheswarappa et al. (2003) reported that high-density multi-species gardens exerted a positive impact on system productivity of root (wilt) affected gardens. Comparing other tree+crop systems, Ghosh et al. (1989) also found that *Eucalyptus* growth was better in association with cassava and groundnut.

The cultural system involving pepper is unique in that it represents a commercial crop (black pepper) being trailed on a variety of support trees. An ideal support tree for trailing pepper vines may have the following traits: fast growth, ease of propagation, light crowns, and tolerance to pests and diseases. Typically, such trees should possess rough, non-exfoliating bark and deep root systems. Nitrogen fixing potential and ability to retain foliage during summer and shed the same during the rainy season are additional features in this respect. Comparative performance of black pepper trailed on exotic and indigenous tree species indicate that pepper productivity was better when the vines were trailed on trees such as *Garuga pinnata* Roxb. (Mathew et al., 1996), *A. auriculiformis,* and *A. heterophyllus* (AICRAF, 2005).

Unless the support trees are properly managed, they are likely to compete with the pepper vine for applied nutrients. Consistent with this, Cheeran et al. (1992) observed competition-related yield reduction in the vines trailed on *Erythrina indica* Lamk. and *Garuga pinnata* supports, compared to teak poles. Wahid et al. (2004) evaluating the fate of applied N in soil and its relative uptake by pepper vine and *Erythrina* support tree using ^{15}N-labelled urea also noted that both the vine and support tree absorbed N from the same pool (support trees absorbed 24 to 40% of the applied urea), implying competitive interactions.

Tree Allometry

Allometric relationships linking aboveground tree biomass with DBH and/or total height of the trees were attempted for several multipurpose trees in Kerala (Kumar et al., 1998b; Kunhamu et al. 2005). Kumar et al. (2005b) also developed allometric relationships linking clump biomass and culm number with clump diameter to predict the standing stock of bamboo biomass. Such equations, however, vary greatly with species, age, wood density, bole shape, and other factors, making determination of biomass production in agroforestry a challenging task (Kumar et al., 1998b).

Tree Biomass, Standing Stock, and Carbon Sequestration Potential

Expanding the size of the global terrestrial sink is one strategy for mitigation of CO_2 build-up in the atmosphere. As a result, there is now increasing awareness on agroforesty's potential for carbon (C) sequestration (Nair et al., 2009a,b; 2010). Summarizing the C stocks of several agroforestry systems, Nair et al. (2009a) suggest that tree growth and C sequestration potential are dependent on species, age/rotation length, site quality, and tree management. In a study of nine native and exotic taxa in the humid tropics of peninsular India, Kumar et al. (1998b) found that the aboveground C stock ranged from 9.9 to 172 Mg C ha^{-1}, with the highest for exotic species such as *A. auriculiformis,* followed by *Paraserianthes falcataria* (L.) Fosberg. In general, denser stands enhanced the vegetation C pools. However, this may create conflicts with other stand management objectives (e.g., understorey production). Excessively high stand densities also may adversely affect tree growth and productivity through competitive effects, resulting in lower vegetation C pools. In such situations, thinning may improve the growth of stands and lead to more C assimilation (Kunhamu et al., 2008). Nonetheless, thinning may result in a net release of C if the removed woods and slash are burnt, or otherwise decomposed (Nair et al., 2010).

While most agroforestry systems (e.g., MPTs, silvopasture, energy plantations, etc.) have great potential for C sequestration, homegardens are unique in this respect (Kumar, 2006b). They not only sequester C in biomass and soil, but also reduce fossil-fuel burning by promoting woodfuel production, besides conserving agrobiodiversity. In addition, they help in the conservation of C stocks in existing natural forests by alleviating the pressure on these areas (Kumar, 2006a). Moreover, there is no complete removal of biomass from the homegardens, signifying permanence of these systems. More than half of the C assimilated by woody perennials in this system is also transported belowground via root growth and organic matter turnover processes (e.g., fine root dynamics, rhizodeposition, and litter dynamics), augmenting the soil organic carbon (SOC) pool (Nair et al., 2010).

Greater agrobiodiversity of homegardens may also ensure longer term stability of C storage in fluctuating environments, apart from augmenting the biomass production potential (Kumar, 2006b). The forest-like structure and composition of the homegardens (Kumar and Nair, 2004) that tend to enhance nutrient cycling and increase SOC are particularly relevant in this respect. Homegarden size and survival strategies of the gardeners are other determinants of biomass pools (Kumar et al., 1994) and soil C (Saha et al., 2009; 2010). Average aboveground standing stocks of C ranged from 16 to 36 Mg ha^{-1}, with small homegardens having higher C stocks on unit area basis than large- and medium-sized ones (Kumar and Takeuchi, 2009; Saha et al., 2009; 2010; Kumar, 2011a).

Stand management practices would also alter litterfall fluxes, which in turn may influence the soil C sequestration (Kumar, 2008c). Kunhamu et al. (2009) reported that annual litterfall of 9 year-old *A. mangium* stands ranged from 5.73 Mg ha^{-1} in a thinned stand (remnant population density: 533 trees ha^{-1}) to 11.18 Mg ha^{-1} in an unthinned stand (1600 trees ha^{-1}), with a significant (p<0.0001) linear relationship between stand basal area and litterfall. Thinning/pruning trees also may bring about changes in understorey light-, air/soil temperature, and soil moisture regimes and accelerate detritus-turnover rates, further reducing soil carbon sequestration (SCS). For instance, high thinning intensities of 9-year-old *A. mangium* stands resulted in accelerated litter decay rates (Kunhamu et al., 2009). The highest soil organic C concentrations (0 to 15 cm soil layer) were noted in the un-thinned stands, reflecting the potential of high tree densities in promoting C retention in soil. Nevertheless, the microclimatic modifications associated with tree management practices such as thinning normally would promote understorey production, offsetting such reductions in SCS to some extent. The effects of thinning on SCS, thus, appear to be complex.

Bamboo, the 'green gold', 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. Bamboos once widely distributed in the homegardens of Kerala, however, has become a shrinking resource base (Kumar, 1997). Bamboo trade, nevertheless, has been flourishing in central Kerala (Krishnankutty, 2005). The homegardens of Palakkad, Malappuram, and Thrissur districts (central Kerala) were surveyed to assess the standing stocks of bamboo, and obtained total culm dry weight estimates of 124 389, 86 267, and 28 658 Mg respectively (Kumar et al., 2005b; Kumar, 2008d), signifying the huge potential of such traditional land use systems for C sequestration.

Nutrient Cycling and Bioelement Release

Trees in managed species mixtures have a great potential to bring about micro-site enrichment through litterfall (Jamaludheen and Kumar, 1999; Isaac and Nair, 2006; Kumar, 2008c). Tropical homegardens are excellent examples of this (John, 1997; Kumar and Nair, 2004). Yet another important pathway of enriching the soil C pool is the fine root biomass turnover. It is well known that trees allocate a large portion of gross primary production belowground for the production and maintenance of roots and mycorrhizae (Nair et al., 2009a). Indeed, more than half of the C assimilated by the plant is transported belowground via root growth and turnover, root exudates, and litter deposition. Under certain conditions, total soil organic carbon increased directly with stand basal area (BA), indicating that BA may be an important design element of agroecosystems (Russell, 2002).

The tropical agroecosystems, involve diverse kinds of trees and their impact on the nutrient cycling process is probably variable. Jamaludheen and Kumar (1999) showed that exotic N-fixing species such as *A. auriculiformis, P. falcataria,* and *C. equisetifolia* accounted for three highest litterfall rates (6.44 to 12.69 Mg ha^{-1} yr^{-1}) among the nine MPTs studied. *Pterocarpus marsupium* Roxb., another indigenous legume, however, showed the lowest litterfall (3.42 Mg ha^{-1} yr^{-1}), implying a paradox in the litter production potential of woody tropical legumes. Litter accumulation for bamboo clumps averaged 909 g m^{-2} and the associated nutrient return was 48.15, 3.67, and 42.98 of N, P and K g m^{-2} respectively (Kumar et al., 2005c).

Stand thinning generally lowers litterfall rates (Kunhamu et al., 2009). However, soon the stand would be back at the plateau of litterfall, if crown closure were quickly regained (Kumar, 2008c). Likewise, pruned trees yield less litter (excluding pruned materials). In a study involving four tropical species grown in silvopastoral system in Kerala with periodical pruning, George and Kumar (1998) indicated that annual addition of litter ranged from 1.92 to 6.25 Mg ha^{-1}, which was substantially lower than the litterfall recorded in unpruned woodlots (Jamaludheen and Kumar, 1999). Pruning also may alter the leaf fall periodicity, especially if significant quantities of foliar biomass are removed in such operations. Generally, litterfall for deciduous species is an episodic process, with conspicuous peaks corresponding either to the beginning or near the end of the dry period (e.g., unimodal litterfall pattern for most tropical species: George and Kumar, 1998; Jamaludheen and Kumar, 1999; Gopikumar, 2000; Kumar, 2008c). A plausible explanation for this episodic litterall is that water/temperature stresses activate *de novo* synthesis of abscissic acid in the foliage (Kumar and Deepu, 1992).

Litter decomposition generally follows a biphasic pattern with heavy mass loss during the early months of incubation followed by a slow decay phase (Jamaludheen and Kumar, 1999; Kumar, 2008c; Kunhamu et al., 2009). The largest changes in litter decay rates are succinctly explained by substrate chemistry; environmental factors such as temperature, moisture, and actual evapotranspiration also influence the rate and timing of nutrient release; however, species differences are overwhelming in this respect (Kumar, 2008c). Jamaludheen and Kumar (1999) found that litter from N_2 fixing species decomposed faster than litter of non-N_2 fixing species. In a previous study, Kumar and Deepu (1992) showed that detrital N content is a better predictor of decay rate, than lignin. The rising atmospheric CO_2 levels may alter litter chemistry and would influence the decomposition process (Kumar et al., 2005d). Overall, a small but predictable decline in litter N concentrations and increased lignin content, and a consequent decline in litter decay rates are probable under elevated CO_2 levels.

Although agroforestry is generally heralded as a sustainable land use system (Kumar and Nair, 2004), loss of nutrients during the harvest, especially when rotations are short, may exceed the rate of replenishment by weathering of minerals and/or by atmospheric inputs (Kumar et al., 1998b), implying that site quality deterioration is almost a cliché. Denser stands also showed greater accumulation of N, P, and K with higher potential for nutrient export through harvest (Shujauddin and Kumar, 2003). Nutrient export through bamboo harvest (NPK) varied among tissue types with the highest in live culms, followed by leaves+twigs and dead culms (Kumar et al., 2005c). Overall, the nutrient recycling characteristics of a species should form an important design criterion in the choice of species for agroforestry. And leaving foliage and branches at the site will reduce the associated nutrient export through wood harvesting.

Timber and Fuelwood Values

Diverse kinds of multipurpose trees are integrated in the traditional land use systems of Kerala (Kumar, 2000; 2011a; Kumar and Kumar, 2002). Homegardens with a wide spectrum of trees and shrubs constitute a principal source of biofuels for most rural households (51% to 90%: Krishnankutty, 1990). Available micro-level studies indicate that standing stock of commercial timber from the Kerala homesteads is between 6.6 and 50.8 m^3 ha^{-1} (Kumar et al., 1994). Heat of combustion values and the physical and chemical properties of these trees and their tissue types were also profoundly variable (Shanavas and Kumar, 2003; 2006; Kumar, 2006c). Such information will enable choice of appropriate species for energy plantations/agroforests.

Public Policy on Tree farming in Kerala

Adoption of agroforestry practices is generally determined by interplay of the farmers' preferences (mainly economic rationale) and public policies. However, there exists no specific policy for agroforestry in Kerala and these mixed species systems are increasingly being replaced by monocultures (Guillerme et al., 2011). There is also little or no extension support or financial incentives for practicing such systems. The cumbersome procedures for getting permission for harvesting trees on private lands act as a further disincentive against tree planting by farmers (Kumar and Peter, 2002). In a study to understand why farmers do not grow timber and fuelwood trees, Ouseph (2002) observed that the Timber Transit Rules and Kerala Preservation of Trees Act are major constraints. Consistent with this, a plea was made in a Workshop on Cultivation of Bamboos, Rattans, and Timber Trees in Private and Community Lands to review and amend outdated or conflicting laws and harmonize them in view of the new challenges of rising wood requirements of the society and increasing pressures on remaining natural forests (Mohanan et al., 2002). Further, a workshop conducted at the College of Forestry (KAU) in July 2011 gave a call for establishing a state-level Department of Farm Forestry and to evolve a pro-farmer tree farming policy to sustain raw material availability to the state's sagging small scale wood-based industries, and to boost farmer incomes (see Guillerme et al., 2011 for a detailed treatment on aspects relating to tree farming policy).

Despite the recent amendments to the rules and regulations in this respect, the Kerala State Forest Department's control over extraction of sandal trees on private lands is inconsistent with the need to raise sandal wood production in the country (Dhanya et al., 2010). In order to help the small farmers prosper under increasing globalization, the governments should recognize multifunctionality and socioeconomic adaptability of the traditional agroforestry systems and avoid policies that limit their diversity (e.g., conversion to monocultural systems).

Most public policies in Kerala also do not take into account the environmental services rendered by agroforestry or even by the farmers (Kumar, 2005; 2006a). Although biodiversity losses from the Kerala landscape are often discussed (e.g., KFRI, 2005), the possible inappropriateness or counterproductive effects of public policies on it have been seldom assessed. In the global context of the challenges associated with food security, climate change mitigation, poverty alleviation, and preservation of environment and biodiversity, a re-orientation of the public policies in relation to agroforestry in Kerala is warranted as most of the small and marginal farmers in the state still rely on agroforestry for their subsistence.

Socioeconomic and Other Aspects

While many studies were conducted on the biophysical aspects of agroforestry, only few published reports exist on socioeconomic aspects. In an analysis of the tree farming scenario in Palakkad and Malappuram districts of Kerala, Kumar et al. (1992a) observed that the farmers are somewhat averse to plant many indigenous timber trees and multipurpose trees owing to the lack of institutional support mechanisms, inadequate attention to land tenure questions, non-availability of quality planting stock, and policy constraints. In homegarden systems, the intensity of profit generation was highest for the smaller gardens, indicating both adaptive management to land constraints, and the presence of other intangible benefits that might affect land management strategies (Mohan et al., 2006). Kunhamu et al. (2008) found that despite yield redctions in ginger+*A. manigum* systems compared to sole crops, ginger intercropping offered better economic returns.

Aspects like provenance evaluation (Babu et al., 1992; Jayasankar et al., 1999a,b), micropropagation of trees (Natesha and Vijayakumar, 2004), allelopathic effects of trees (John et al., 2006), and seed and nursery production (Kumar et al., 1992b; Sajeevukumar et al., 1995; Sunilkumar and Sudhakara, 1998; Sunilkumar et al., 2000) also have been focussed by the agroforestry researchers in Kerala during the past 25 years or so; a detailed treatment on all these, however, is beyond the scope of the present article.

Concluding remarks

Admittedly, the analysis presented here is not based on a comprehensive account of all aspects of agroforestry research that has happened in Kerala. But it gives a clear indication of the advances made in understanding the scientific underpinnings and the potential of agroforestry and the constraints that have caused setbacks in achievements during the past 25 years. Although agroforestry combines biophysical stability and socioeconomic adaptability which are critical for a vibrant and diversified agriculture that addresses both ecological and socioeconomic concerns, a major shortcoming is the apparent lack of clear goals, objectives, and political commitment to agroforestry. Agroforestry is perhaps somewhere at the bottom ebb of research priorities in agricultural and forestry sectors of this state. A more coordinated, focused, and resolute effort will certainly provide results that are more promising.

Kerala's experience in homegardening and other woody perennial-based mixed farming systems highlight the potential of such land use systems for agrobiodiversity conservation and for ameliorating the opposing impacts of input intensive agricultural technologies. It, however, clearly shows that the existing agricultural and forestry laws and procedures offer serious limitations and impediments to agroforestry development. Enabling policies and supportive political will at the highest levels of government are essential for the success of agroforestry. Even if the new policy proposed by the Kerala government shows some understanding of the farmer's problems, contradictions exist between the dichotomous approaches adopted in the agriculture and forestry sectors of the state.

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