Review/synthesis

Agroforestry: the new old paradigm for Asian food security

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Abstract

Rising population pressure and urbanization, coupled with land degradation, soil salinization, and global warming are causing food insufficiency in large parts of Asia. Agroforestry, or woody perennial-based mixed species production systems, has the potential to arrest land degradation and improve site productivity through interactions among trees, soil, crops, and livestock, and thus restore part, if not all, of the degraded lands. Many such practices are sited on the smallholdings of tropical Asia, characterised by sub-optimal management and subsistence farming conditions. Food production either directly (producing food grains, root crops, fruits, and vegetables) or indirectly (improving soil conditions and thereby promoting understorey crop productivity especially on degraded sites) constitutes the central theme of most smallholder agroforestry practices. Low input use and ecological security are other intrinsic attributes of this unique land use activity. Despite such advantages, agroforestry as a land use option has not attracted much attention from the planners and extension community. Reasons for this include inconsistencies in understorey crop productivity (positive, negative, or neutral effects depending on species, site, and management) and lack of public policy support. Conscious efforts on system management and policy adjustments are therefore imperative to promote agroforestry adoption by the farming community.

Keywords: Food diversity, Land degradation, Nutritional security, Species mixtures, Sustainable production, Understorey productivity.

Introduction: Uncertainties about food availability in Asia and the role of agroforestry

Asia is the "continent of the current century", according to many; yet, some analysts have shown that many Asian countries may not be able to feed their projected populations in the 21st century (e.g., Rosegrant et al., 2001). On the one hand, there is less land per person in Asia today than in other parts of the world (Beinroth et al., 2001), and on the other, productive land is progressively being displaced by urbanization (Smil, 1998; Scherr, 1999). Historically, food production in the overall Asian context increased at the same rate as that of human population (Fig. 1; FAO, 2003a). However, population growth has outmanoeuvred the food production trends in the past decade, implying the need to augment food production. According to FAO (2003b), there are about 800 million people in the developing world who suffer from hunger. And most of this (*ca*. 60%) is in Asia with South Asia accounting for about 36% (Fig. 2). To make matters worse, increases in cereal yields are slowing down in all regions of the world due to the so-called 'technology fatigue', and Asia is no exception (Fig. 3).

Yet another characteristic feature of Asian food production is that it is mostly done by the smallholders. For example, in South Asia, about 80% of the holdings are less than 0.6 ha in extent (Gulati, 2002) and one or more forms of mixed species gardens are present on these smallholdings. These units function at low levels of productivity and the diminishing soil fertility regimes cause a particularly grim scenario (De Costa and Sangakkara, 2006). Soil salinization and water logging,

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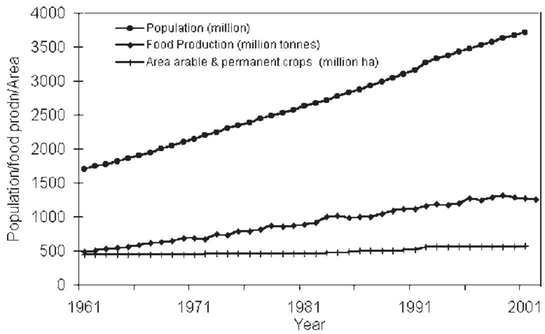

Figure 1. Changes in human population, food production (measured as sum of cereals, millets and root crops) and area under arable and permanent crops during the last four decades in Asia (source: FAO 2003a).

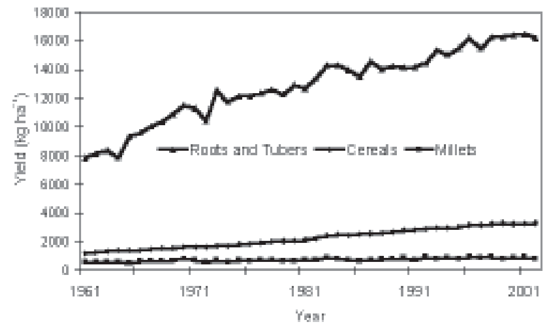

Figure 3. Changes in the productivity of Asian food crops during the last four decades (Source: FAO 2003a).

which render arable lands unproductive, also continue unabated in most parts of Asia (van Lynden and Oldeman, 1997; Scherr, 1999; Eswaran et al., 2001; Lal, 2001). Indeed, out of the world's 1900 million ha of land affected by soil degradation, the largest area (around 747 million ha) is in Asia (Oldeman, 1994). Most countries of the region also lack the capital resources to make the financial investments required to reclaim degraded lands. These, coupled with the limited ability to extend agricultural areas because of high population density, are major challenges facing the agricultural policy planners of the region. Deforestation and forest degradation are also critical parameters threatening ecosystem stability and depleting the natural resource base. FAO (2001) figures suggest that within Asia annual deforestation rates were highest in South East Asia (*ca* 2.3 million ha per year).

During the recent years, concern also has been growing among scientists and the general public about the possible impacts of climate change on terrestrial ecosystems, especially with respect to plant growth, changes in biodiversity, and the overall effect on carbon storage in the biosphere (Rosenzweig and Hillel, 1998). The impact of global warming on food production in South Asia is particularly alarming as the predicted shifts in monsoonal rainfall patterns (Lal et al., 2001) may render large areas unproductive. Woody perennial-based production systems, such as agroforestry, have the potential to sequester large quantities of CO_2 and thereby partially offset the global warming process (FAO, 2004; Kumar, 2006). Many of these are sustainable production systems and despite the prevailing dogma that the subsistence farmers depend more on annual crops, the small and marginal farmers in the tropics have long been practicing agroforestry – to meet their food, fodder and fuel requirements.

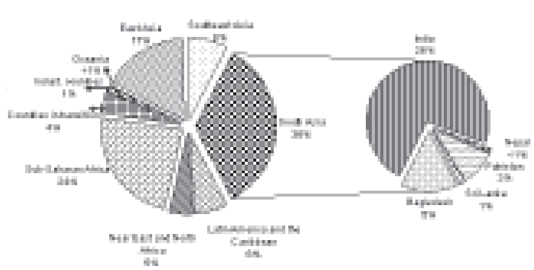

Figure 2. Relative proportion of the food insecure population in developing countries (based on FAO 2003b).

Apart from ensuring food production, such systems also would enhance economic returns to the growers. Consistent with this, Rasul and Thapa (2006) in a case study of the degraded agricultural lands of Chittagong Hill Tracts (Bangladesh) reported that economic returns from agroforestry were greater than that from *jhum.* The higher cash incomes provide greater "buying power" with respect to food, especially when agriculture is not practiced, or when the crops fail. Moreover, diversified production is a form of risk avoidance, which is of special relevance in the context of the current agricultural crises that many countries in South and Southeast Asia are experiencing. The potential of agroforestry to provide alternate sources of income and employment to the rural poor also has been highligted (Balooni, 2003; Puri and Nair, 2004; Samra et al., 2005).

The diverse products (fruits, vegetables, spices etc.), which are available year-round in systems such as homegardens not only contribute to food security during the "lean" seasons but also ensure food diversity (Kumar and Nair, 2004). They are also sources of mineral nutrients for improving household nutritional security especially for 'at-risk populations' (e.g., women and children). In experimental studies, target families significantly increased year-round production and consumption of vitamin-rich fruits and vegetables compared to a control group without gardens (Shankar et al., 1998). This, in turn, alleviated deficiencies of iodine, vitamin A, and iron and made children of garden owners less prone to xerophthalmia. As little or no chemical inputs are used, the produce from agroforestry is also expected to be of superior quality.

Over the period when input usage in agriculture was promoted in Asian agriculture, agroforestry being less input intensive, was overlooked as a means of food production. The development community, in particular, was not fascinated by such mixed gardens with scattered and/or boundary planted trees. The woody perennial-based mixtures were also thought to be less productive and difficult to manage; instead, the "replicable models" of input intensive production practices became fashionable. The smallholder mixed tree-gardens in Asia thus represent a substantial unexploited potential for enhancing productivity and profitability. In this paper, an attempt is made to evaluate the potential of these woody perennial based production systems in easing food insecurity and averting environmental degradation in the developing world, with particular reference to the Asian tropics. The production increasing and decreasing functions will be specifically addressed using data from published sources. A limited amount of such data will also be presented to demonstrate certain concepts and managerial interventions that are discussed.

Agroforestry development in Asia

Asia is home to many traditional agroforestry systems and practices (Nair, 1989). Historically, agroforestry development in Asia involved two distinct pathways, viz., growing food crops in the forests and establishing tree-crop production systems on arable lands. Although scientific and technological developments relating to these are profoundly different, food production is a cardinal aspect of both. Just as the direct forms of production (e.g., edible fruits, nuts, grain, rhizomes and tubers, leaves, flowers, fodder, mushrooms, medicinal plants and other non-timber forest products including fuels, livestock products etc.), the indirect mechanisms that promote enhanced and/or sustained production (soil fertility improvement, soil and water conservation, hydrological benefits, microclimatic modification, etc. discussed elsewhere in this paper) are fundamental to both types. Most agroforestry systems are also complementary to other crop production enterprises, as they provide green manure, fodder, and fuel (Kumar, 2005a; Wiersum, 2006). This complementary and sustainable use of environmental resources differentiates food production through agroforestry from that through intensive arable cropping and makes agroforestry particularly attractive. Socioeconomic evaluations, albeit few, also have established agroforestry as a profitable land use option (e.g., Mohan et al., 2006; Lindara et al., 2006).

Myriad of agroforestry systems and practices

Prominent examples of Asian agroforestry include systems of historical significance such as shifting cultivation and the *taungya*, besides plantation crop-food/forage crop combinations (Fig. 4a, e; Nair, 1983), tropical homegardens (Fig. 4c; Kumar and Nair, 2006), jackfruit tree (*Artocarpus heterophyllus*) and palm-based food production systems (Nair, 1989), integrated agriculture-aquaculture systems (e.g., agrosilvofishery systems; Fig. 4b,d,f), spice-based agroforestry (Kumar et al., 1995; Lindara et al., 2006), smallholder livestock production systems, parkland agroforestry systems

Figure 4. Agroforestry systems for food production (a) Fodder crops (*Panicum maxima*) in a coconut (*Cocos nucifera*) garden, Kerala, India, (b) Integrated agriculture [coconut-areca palms (*Areca catechu*)-*Coffea* spp.]–aquaculture system in Palakkad district, Kerala, India, (c) a Kerala homegarden with many economically important species around the house such as black pepper (*Piper nigrum*), areca palm, papaya (*Carica papaya*), *Musa* spp. and the like, (d) Poplar (*Populus deltoides*)–rape (*Brassica* spp.)–wheat (*Triticum* spp.)–fish production systems in Nanjing province, China (Photo: Tang Luozhong), (e) systematic planting of coconut trees (foreground) and mixtures of coconut palms, *Mangifera indica* and *Hibiscus tilaceus* in the rear (Malo Island, Vanuatu, Melanesia; Photo: N. Lamanda), and (f) traditional aquaculture systems in Ernakulam district, Kerala, India.

(e.g., *Prosopis cineraria*-based food production systems in the Indian arid and semiarid regions; Shankarnarayan et al., 1987), as well as grass (*Cenchrus* sp.)+legume (*Stylosanthes* sp.) associations with trees (Sharma et al., 1996; Pathak, 2002) and integrated rice (*Oryza sativa*)+*Acacia nilotica* systems (Viswanath et al., 2000).

Intercropping food crops with palms (*Cocos nucifera*, *Phoenix sylvestris*, *Borasus flabellifer)*, jackfruit tree, *Acacia nilotica*, *Dalbergia sissoo*, *Paulownia* spp., *Ziziphus jujuba*, willow (*Salix* sp.), false indigo (*Amorpha fruticosa)*, white mulberry (*Morus alba*), *Aleurites fordii, Sapium sebiferum, Juglans regia, Castanea bungeana, Camellia oleifera,* tea (*Camellia sinensis*), rubber (*Hevea brasiliensis*), *Diospyros kaki*, *Baccaurea sapida, Fraxinus chinensis,* etc. (Nair, 1989; Zhaohua et al., 1991; Tejwani, 1994), growing edible fungi (*Auricularia, Tremella, Dictyophora indusiata, Lentinus edodes,* and *Pleurotus ostreatus*) and the traditional Chinese medicinal plants (*Panax ginseng*, *Coptis chinensis* var. *brevisepala*, *Amomum villosum,* and *Gastrodia elata*) in bamboo forests, and intercropping rubber with tea, or rubber and camphor trees (*Cinnamomum camphora*) with tea, and fodder crops with *Elaeagnus angustifolia, Lycium furcomanicum, Populus sp., Hippophae rhamnoides* and *Astragalus adsurgens* and *Medicago* sp. (Zhaohua et al., 1991) are also popular in one or more regions of Asia.

There are many more examples of land use activities that either integrate trees at the landscape or plot level with other life forms, a full coverage of which is beyond the scope of the present article. As mentioned earlier, these traditional land-use practices were neglected when organized research endeavours in agriculture and forestry developed along strict disciplinary lines (Puri and Nair, 2004). Consequently, even area estimates of many agroforestry practices are either not available, or the available information is barely complete (Nair and Kumar, 2006). Likewise, system management of mixed tree-herbaceous crop production system is an unresolved issue (e.g., homegardens; see Kumar and Nair, 2004). Despite the considerable advances made in the agronomic arena, the picture concerning productivity of field crops in the subcanopy of trees is particularly hazy.

Productivity of tree-herbaceous crop mixtures

In an effort to provide a comparative account on the performance of food, fodder and beverage crops, 14 research papers reporting rigorous scientific data on arable crop productivity in agroforestry combinations and monospecific systems from South and Southeast Asia were compiled (Table 1). It involved 48 disparate combinations of 23 understorey crops and 21 woody perennials. These 14 experimental studies, however, do not reflect the full spectrum of agroforestry practices across the region and Table 1 is only an attempt to compare systems on which comparative data are available. The results, therefore, can be generalized only within the limits of the data presented.

Although many studies have reported mixed species production (involving different trees, field crops, and/or their management), in certain cases the data reported in the literature could not be included in the comparative analysis. This is because some authors have reported crop yields on per plant basis with considerable variations between plants of different rows around the trees, making it difficult to arrive at "area-based productivity estimates". Yet another problem encountered in this respect is the profound inter-annual variations in crop productivity, which were not reconciled by appropriate multivariate data analysis techniques. Some trials lacked proper treeless control plots in the experimental design; and in a few cases where such control plots were included, due to constraints in the plot layout plan, statistical comparisons were impossible. Variations in the population of intercrops (compared to sole crops) owing to the presence of tree components in the system is a potential confounding factor in this respect. This calls for further and more careful field experimentation on aspects relating to the productivity of field crops in tree-crop combinations, besides the need for having more refined statistical approaches (see Moser et al., 1990) so that cause-effect perspectives on mixed species production could be deduced.

Table 1. Case studies representing the productivity of food, beverage, and medicinal plants in agroforestry systems and practices from South and Southeast Asia.

Systems/practices and parameters evaluated	System description	Productivity (kg ha^{-1})	Source	Effects on productivity
Coconut (*Cocos nucifera*)+ intercrops (occupying 70 to 75% of the net area) in Kerala, India (inter crop yield)	cassava (*Manihot esculenta*)	60 to 75% of open area yield	Nair (1983)	0
	elephant foot yam (*Amorphophalus companulatus*)			0
	sweet potato (*Ipomoea batatas*)			0
	greater yam (*Dioscorea alata*)			0
	lesser yam (*Dioscorea esculenta*)			0
	Chinese potato (*Coleus parviflorus*)			0
	ginger (*Zingiber officinale*)			0
	turmeric (*Curcuma longa*)			0
Acacia tortilis-silvopastoralism in Rajasthan, India (fodder yield)	*Cenchrus ciliaris* +trees planted at 10 x 10 m spacing	5580	Shankarnarayan et al. (1987)	+
	Cenchrus ciliaris +trees planted at 5 x 10 m spacing	5290		+
	Cenchrus ciliaris alone	4600		
Sorghum-nitrogen fixing tree mixtures in semiarid central India (grain yield; tree age= 8 years)	Sole crop	1154	Suresh and Rao (1999)	
	Faidherbia albida	1013*		–
	Acaica ferruginea	890*		–
	Albizia lebbeck	720*		–
Acacia nilotica + rice, Chattisgarh, India (rice grain yield)	year 1	2000	Viswanath et al. (2000)	+
	year 10	3400		
Subsistence farming systems in the mid-hills of Nepal (pooled rice, maize, wheat and millet grain yields)	uplands: Agroforestry[1]	5686[a]	Neupane and Thapa (2001)	+
	no Agroforestry	3036[b]		
	lowlands: Agroforestry[1]	6853[a]		+
	no Agroforestry	4002[b]		
Forage grasses in association with fast growing multipurpose trees in Kerala, India (Cumulative annual biomass yield for tree+grass combinations; dry weight comparisons at age year 6 yr)	*Pennisetum purpureum* (sole crop)[2]	1257[b]	Kumar et al. (2001a)	
	Leucaena leucocephala + P. purpureum	540[a]		–
	Casuarina equisetifolia + P. purpureum	355[a]		–
	Ailanthus triphysa + P. purpureum	630[a]		–
	Acacia auriculiformis + P. purpureum	510[a]		–
	Panicum maximum (sole crop)	1020[a]		
	Leucaena leucocephala + P. maximum	583[a]		–
	Casuarina equisetifolia + P. maximum	1350[b]		+
	Ailanthus triphysa + P. maximum	973[a]		0
	Acacia auriculiformis + P. maximum	535[a]		–
	Brachiaria ruziziensis (sole crop)	830[b]		
	Leucaena leucocephala + B. ruziziensis	480[a]		–
	Casuarina equisetifolia + B. ruziziensis	645[a]		–
	Ailanthus triphysa + B. ruziziensis	410[a]		–
	Acacia auriculiformis + B. ruziziensis	393[a]		–
	Zea mexicana (sole crop)	507[a]		
	Leucaena leucocephala + Z. mexicana	710[a]		+
	Casuarina equisetifolia + Z. mexicana	663[a]		+
	Ailanthus triphysa + Z. mexicana	417[a]		–
	Acacia auriculiformis + Z. mexicana	305[a]		–
Ailanthus triphysa trees + *Zingiber officinale* at different densities in Kerala, India (ginger rhizome dry weight at five years of tree age).	sole ginger	3500	Kumar et al. (2001b)	
	Ailanthus density 3333 trees ha^{-1}	3700[a]		+
	Ailanthus density 2500 trees ha^{-1}	5000[b]		+
	Ailanthus density 1660 trees ha^{-1}	3600[a]		+
	Ailanthus density 1111 trees ha^{-1}	4000[a]		+

Morus alba-Phaseolus mungo production in subtropical India (grain yield; 5 year old trees spaced at 5 x 8 m)	Open	435	Thakur and Singh (2002)	
	no crown removal	251*		–
	25% crown removal	299*		–
	50% crown removal	337*		–
	75% crown removal	354*		–
Alley cropping (upland rice with *Gliricidia sepium* and *Cassia spectabilis*), northern Mindanao, Philippines[3] (upland rice grain yield)	control (no inputs)	90 to 830	MacLean et al. (2003)	–
	mulched (10 Mg ha^{-1} of *C. spectabilis* fresh materials)	310 to 1040		–
	incorporation of 10 Mg ha^{-1} of *G. sepium* fresh materials	910 to 1510		+
	incorporation of 10 Mg ha^{-1} *G. sepium* fresh materials + mulching (5 Mg ha^{-1} *G. sepium* green manure + 5 Mg ha^{-1} of *C. spectabilis* mulch)	1270 to 1480		+
	farmer's practice + hedgerows	230 to 1150		
Poplar (*Populus deltoides*)- soybean (*Glycine max*) agrisilviculture systems in Chattisgarh, India (grain yield)	sole crop	1450	Mishra et al. (2004)	–
	mixed with poplar at 4 x 5 m spacing (year 6)	970 to 1420*		
Agrisilviculture involving rice (*Oryza sativa*) and fast growing multipurpose trees planted at different spacing in Konkan region, Maharashtra, India (grain yield)	sole crop	4900	Thaware et al. (2004)	
	Casuarina equisetifolia (year 6) 5 x 2 m	3300*		–
	10 x 2 m	3500*		–
	15 x 2 m	4000*		–
	Acacia auriculiformis (year 6) 5 x 2 m	3600*		–
	10 x 2 m	3900*		–
	15 x 2 m	4200*		–
Poplar-mungbean (*Vigna radiata*) agroforestry system in Uttaranchal, India (grain yield)	sole crop	1054	Pandey and Tewari (2004)	
	in association with 6 year-old trees	864*		–
Kaempferia galanga in multistrata systems involving *Cocos nucifera*, *Vateria indica*, *Ailanthus triphysa* or *Grevillea robusta* in Kerala, India (dry weight of rhizomes)[4] when coconut palms were 17 years and dicot trees three-year-old)	no over canopy	1619[a]	Kumar et al. (2005)	
	single strata (coconut canopy; palms at 7.5 x 7.5 m spacing)	1696[a]		0
	multistrata (coconut+one row of multipurpose trees in the middle of two rows of coconut in both directions)	1477[a]		0
	multistrata (coconut+two rows of multipurpose trees in the middle of two rows of coconut in one direction only)	1641[a]		0
Tea (*Camellia sinensis*)-hedgerow system in the sloping lands of Sri Lanka (made tea yield for 36 months)	control	7404	De Costa and Surenthran (2005)	
	Calliandra calothyrsus Mulched	5540*		–
	Unmulched	4949*		–
	Senna spectabilis Mulched	5178*		–
	Unmulched	4681*		–
	Euphatorium innulifolium Mulched	9092*		+
	Unmulched	7576		+
	Flemingia congesta Mulched	5764*		–
	Unmulched	5113*		–
	Gliricidia sepium Mulched	5290*		–
	Unmulched	4482*		–
	Tithonia diversifolia Mulched	5096*		–
	Unmulched	4432*		–

* significant at 0.05 level compared to the control. Values with the same superscripts under a source category do not differ significantly.

[1]Agroforestry with exotic fodder and grass species such as *Leucaena leucocepaha*, *Calliandra calothyrsus*, *Flemingia congesta*, *Morus alba*, *Gauzuma ulmifolia*, *Pennisetum* spp and *Stylosanthes guianensis*.

[2]difference between tree-grass combinations and year after planting were significant ($p<0.01$).

[3]The range of values represents grain yield at two sites over two consecutive years for which the treatment differences were statistically significant ($p<0.01$).

[4]differences not statistically significant. '+' indicates strong positive effect, '0' means neutral effect and '–' signifies strong negative effect (comparison is made with respect to sole crops, farmer's practices, wherever relevant).

A comparison of the data in Table 1, nevertheless, indicates that crops such as upland rice, ginger (*Zingiber officinale*), and *Kaempferia galanga* showed higher productivity in certain agroforestry combinations (over sole crops), while fodder plants and many other grain crops showed relatively lower yields. That is, of the 67 cases (48 species combinations, some in more than one management situations), 16 showed positive effects, 12 depicted neutral effects, and another 39 illustrated negative trends. The relative superiority is probably dependent on species/circumstances, and is not amenable to sweeping generalizations; i.e., the effect may be positive, negative, or neutral. A further discrimination of the dataset (Table 1) and other similar studies, however, reveals that yield reductions occur when shade intolerant crops [e.g., many fodder species, cereals, legumes such as soybean (*Glycine max*)] are grown in association with tree species especially after canopy closure (note the large number of combinations in Table 1 exhibiting production decreases).

Competitive interactions

Asymmetric competition (i.e., resource acquisition at differential rates) and thereby resource pre-emption by the dominant component is a major cause of production decrease in competing mixtures (George et al., 1996; Kumar et al., 1999; 2001a and many others). Differences in resource acquisition capabilities (e.g., crown spread and rooting characteristics) are also magnified during the course of competitive interactions. Consequently, understorey yield declines are more probable in denser and older stands of trees compared to poorly stocked young stands. Likewise, nutrient-rich sites generally hasten tree canopy closure and aggravate interspecific competition. It is, therefore, hypothesised that reductions in understorey crop yield in tree-crop mixtures may be more probable on good sites, especially with high input usage. Conversely, degraded sites and shade tolerant crops (e.g., ginger) may show better subcanopy productivity or that productivity may be at par with that of open grown crops (e.g., *Kaempferia galanga*; Table 1).

Understorey crop yield is also a function of the nature and extent of crown spread and the distance from the tree at which measurement of the associated herbaceous crops has been made (e.g., Singh et al., 2002). Few studies, however, have reported such information, which makes further generalizations on this difficult. The following section summarises the promotional roles of trees in the smallholder production systems, which could help in the design and management of location-specific agroforestry practices.

Facilitative production principle

The implicit assumption in those studies reporting the positive “mixture effects” is that one or more of the components improve the environment and/or share site resources harmoniously. Many mechanisms and processes have been proposed and extensive reviews published (e.g., Young, 1989; Sanchez et al., 1997; Rao et al., 1998). Briefly summarised, these include the return of considerable quantities of organic matter and nutrients to the soil either naturally through litterfall and root turnover, or deliberately through pruning. For example, Jensen (1993) estimated that the nutrients circulated internally in a Javanese homegarden were as much as 223 kg N, 38 kg P, 373 kg K, 135 kg Ca, and 50 kg Mg ha^{-1} yr^{-1}. Jamaludheen and Kumar (1999), based on a study in the humid tropical regions of Kerala on multipurpose tree woodlots, however, reported wide variations in this respect; i.e., depending on the species involved, leaf fall might appropriate about 38 to 203 kg N, 0.8 to 6 kg P and 3.4 to 15.7 kg K ha^{-1} yr^{-1}. A related feature that ensures sustainability is linked to N-fixing trees that increase N availability through biological fixation. In experimental studies, soil N availability in the 0 to 20 cm layer was significantly superior when N fixing trees were interplanted (Kumar et al., 1998a).

Like the self-nourishing natural forest ecosystems, most agroforestry systems are also characterized by high levels of on-site nutrient conservation. For instance, the deep-reaching tree roots mobilize nutrients from zones far below the ground level for use by the field crops growing in association (nutrient pumping). Root systems of different tree components in agroforests are also expected to overlap considerably and the resultant higher root-length density may reduce nutrient leaching (safety-net hypothesis; Divakara et al. 2001). In certain cases, the proximity of trees to one another increases subsoil-nutrient recovery. For example, Kumar and Divakara (2001) found that in bamboo-based multi-strata systems of Kerala, ^{32}P uptake from the subsoil was greater when the bamboo clumps (*Bambusa arundinacea*) and dicot trees (*Tectona grandis* and *Vateria indica*) were close to one another. On-site nutrient conservation is also accomplished through interlocking roots (root grafts and/or mycorrhizal connections), which act as multipliers of the "root systems' reach." Furthermore, horizontal transfer/sharing of nutrient ions between the rhizospheres of the neighbouring plants is probable through release, leaching, and/or exudation of mineral and organic materials (Kumar et al., 1999).

It is well-known that improvements in soil structure occur when tree biomass (litter, fine roots, and green manure) is incorporated into the soil. Closely spaced trees also reduce soil erosion by acting as a multi-layer defense mechanism against the impact of falling rain drops/protection against wind erosion, and increasing the infiltration capacity. Monospecific tree stands, however, do not provide these functions until they are well established and have developed a litter layer. Agroforestry systems that include trees and crops which cover ground faster may accomplish these sooner.

As mentioned earlier, land degradation and desertification are two cardinal processes, which render agricultural lands unproductive and threaten food security in several parts of Asia. While chemical reclamation of such degraded lands is expensive, growing trees to reclaim them (e.g., sodic soils; Gill and Abrol, 1991; Dagar et al., 1994) offers a cost-effective and promising option (phytoremediation). Accordingly, salt-tolerant trees such as *Acacia nilotica, Dalbergia sissoo, Prosopis juliflora*, and *Terminalia arjuna* are now being planted extensively to reclaim large tracts of salt-affected soils in India (Singh et al., 1992; Garg, 1998) — an estimated 9 million ha (Government of India, 1992). Similarly in dry climates, windbreaks and shelterbelts moderate the effects of hot, dry winds, which increase evaporation and plant transpiration (Zhaomin and Ling, 1991).

Activities of soil organisms, which determine several key processes, are also expected to be high in agroforestry (e.g., homegardens; Kumar, 2005b). However, few data are available on the composition of soil biota or its determinants. Specifically, documentation of inter-site and/or inter-seasonal variations in soil biota, as well as other biological populations conserved and managed across the spectrum of agricultural intensification, although critical (TSBF, 2003), have not been attempted.

Implications for management

The foregoing description implies that integration of trees into the production systems may be the more rational choice as intensification of crop production may be challenging especially on the small farmsteads on degraded sites. Indeed, many positive traits are associated with agroforestry practices, which arrest soil degradation, reclaim degraded sites, and thereby promote food security. Furthermore, if planned with consideration for each species' growth characteristics, mixed systems should, theoretically, be more productive than monospecific production systems. However, such beneficial effects are not universal and in certain tree-herbaceous crop mixtures, the negative and neutral effects predominate. This, in turn, calls for appropriate management strategies to optimize the combined production of tree and field crops growing in association.

As discussed earlier, interspecific competition for site resources is the foremost production decreasing function in integrated tree-herbaceous crop production systems. Managing competitive interactions and regenerating fertility of the degraded sites, therefore, assume special significance. Ideally, in agroforestry, the components exploit different vertical layers—both above- and belowground—which signifies greater resource utilization efficiency. This pre-supposes that species with divergent growth characteristics be mixed for optimizing resource use/capture. Hence, efforts are needed to model and assess the long-term impacts of the multipurpose trees (MPTs) on site productivity/competitive interactions. Specific characteristics of the

MPTs (e.g., spreading roots/crowns/allelopathy etc.) are important in this respect. Farmers can play a lead role in the development and testing of MPT technology, assessing on-station trials, conducting researcher-designed and farmer-designed trials, and providing feedback to researchers. Nonetheless, such attempts have been made seldom and agroforesters need to develop improved technologies involving MPTs through partnerships with farmers.

Although trees are expected to improve soil fertility, the extent to which different agroforestry practices accomplish this depends on tree species, stocking level, growth rate and the input of litter. It should be greatest where fast growing trees are integrated at a high density and when tree prunings and litter are incorporated into the soil. Achieving synchrony in nutrient release through organic matter turnover (TSBF, 2003) is yet another challenging task. This calls for proper selection of tree/green manure species, which requires a thorough understanding of the rates and patterns of decomposition and nutrient release (Jamaludheen and Kumar, 1999; De Costa and Sangakkara, 2006).

Nutrient export from the site is another critical concern in the context of short-rotation, high-yield tree production systems on farmers' field, especially if the nutrients removed through frequent harvests exceed the inputs. Needless to mention that fast growing exotic trees such as *Acacia auriculiformis* and *Paraserianthes falcataria* often result in marked loss of nutrients from the site when whole tree harvesting is resorted to (Kumar et al., 1998b). A slight reduction in the tree parts removed from the site may, however, bring about a reduction in the magnitude of such nutrient exports. That is, returning leaves and small twigs to the site at the time of harvest may be a worthwhile management option to restrain nutrient export from the site.

Agroforestry adoption–lack of public policy support

Although smallholder agroforestry practices are of increasing importance in both sustainable food production and safeguarding environmental services such as biodiversity conservation and carbon sequestration (Kumar, 2005a; 2006), it has not attracted much attention from the planners and development professionals. Conversely, in many Asian countries, the push towards input intensive monospecific commercial production systems (e.g., rubber, coconut, oil palm and the like) has decimated many traditional agroforestry systems (Kumar and Nair, 2004). This is partly because policy instruments which promote agroforestry adoption are either lacking or inadequate. Indeed, the farmers' decision of whether or not to plant trees is primarily an economic one (Kumar et al., 1992). Policies on marketing and pricing of agroforestry produce, and land tenure can greatly influence such decisions. But many provisions of the forest-related legislations in India (e.g., the legal hurdles associated with harvesting and transporting of timber) have acted as serious disincentives to tree farming on private lands (Kumar and Peter, 2002). Likewise, the import of timber under Open General Licenses (OGL) and the inconsistencies in inter-state timber trade/transit rules in this country have nearly upset the wood production by smallholders. The situation may not be substantially different in other countries in South and South East Asia. Non-availability of quality planting stock is yet another constraint. As agroforestry extension and communication networks are choked, credit and other facilities are also limited. This calls for evolving appropriate policy packages to popularize agroforestry, covering aspects such as harvesting, processing, and utilization of farm-grown wood, as well as ensuring credit and extension services to smallholder producers. Although some beginning has been made, much more needs to be done on aspects relating to the agroforestry policies of the national governments in Asia.

Conclusions

This paper presents an overview on the food production potential of agroforestry with special reference to tropical Asia, where increasing human population pressure and mounting levels of land degradation make arable lands scarce. Land degradation and crop losses signifying poverty, hunger, and famine are pervasive, especially in the smallholder farms of tropical Asia. This, coupled with the adverse effects of enhanced atmospheric CO_2 levels increases the threat to Asian food security in the 21st century. Agroforestry emerges as a promising land use option to surmount the problem of land degradation and the imminent "food crisis". Diversified production and consequently greater food diversity and sustainability, as well as the potential for increasing the purchasing power of the rural people are intrinsic features of these traditional land use systems. Agroforestry practices are implicitly assumed to have higher productivity than monospecific systems, especially on degraded sites, because diverse assemblages have a greater likelihood of containing species with strong responses to resources compared to species-poor assemblages. However, results do not consistently support this assumption. The question, therefore, is how to optimize productivity and ensure sustainability. In particular, the practices need to be oriented towards ecologically sound and farmer-based solutions. Not all forms of agroforestry/systems of management may be of pan-Asian relevance, but the basket of options available from the traditional practices enables their modification to meet location-specific requirements. Policy and institutional support to augment food production through agroforestry research and development are, however, lacking. More focus should be placed on incentives to promote investments in agroforestry and the development of market-driven tree crop products in the near future.

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