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Review/Overview Article

Agronomic practices for agroforestry systems in India

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ABSTRACT

Of late, the importance of agroforestry is increasingly being realized from all corners owing to its multifaceted role in sustainable production, soil health, biodiversity conservation, employment generation, drought proofing, natural resource conservation and ecosystem services. Agroforestry is a unified land-use system involving all disciplines. Though the basic principles of agronomy remain the same, the agronomic practices, are slightly modified owing to presence of perennial component in agroforestry. This paper provides a brief review of all aspects of agronomic practices under agroforestry, so as to give some insights to researchers, teachers, students, farmers and planners. The issues like agroforestry situation in India; selection of agroforestry components and their establishment; management of water, nutrients, weeds and insect-pests and diseases; environmental services and natural resource conservation are highlighted here.

Key words : Agroforestry systems, Agronomic practices, Climate resilience, Productivity, Soil health, Sustainability

Agroforestry is an age-old practice, defined as a land-use system in which woody perennials (trees, shrubs, palms, bamboo etc.) are grown on the same piece of land with herbaceous plants and/or animals, either in spatial arrangement or in time sequence, and in which there are both ecological and economic interactions between the trees and non-tree components (Beets, 1989). A more recent definition embracing the global twin challenges of poverty and environmental degradation defines agroforestry as a dynamic, ecologically based, natural resource management system that, through integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels (Leakey, 2011).

The area under agroforestry in India is estimated as 25.3 million ha, which is 8.2% of the total geographical area of the country (Dhyani *et al*., 2013). There is scope of increasing the area under agroforestry in future by another 28.0 million ha, which can be brought from cultivable fallows, pastures, groves and rehabilitation of problem soils. Researchers and planners are increasingly recommending agroforestry systems as a sustainable form of land use for augmentation of biomass production from agricultural systems (Nair, 1984; DAC, GoI, New Delhi, 2000; Arunachalam, 2002), problems soils (Singh, 1995; Singh *et al.,* 1997; Sunil Kumar and Chaubey, 2008) and recently for mitigation of climate change by way of sequestering carbon in both standing biomass and soil (Ajit *et al.,* 2013; Dhyani *et al.,* 2013).

The integrated approach associated with agroforestry makes it the most self-sustaining and ecologically sound land-management system (Singh *et al.*, 1997). In agroforestry, trees, crops and animals are integrated in a long-term conservative, sustainable, productive and eco-friendly system where greater emphasis is placed on perennial multi-purpose trees (MPTs) that are planted once but yield benefits over a long period of time (Saha *et al*., 2007). It reduces the risks associated with agriculture and increases sustainability of agricultural production system besides conserving and even improving the soil. In spite of this long-standing social, ethnic and religious significance of trees in India and the practice of various traditional forms of agroforestry in different parts of the country, recognition of trees as components of farming systems (Nair, 2001) has been rather limited. This is partly because of the traditional divide between agriculture and forestry in government business – just as it is elsewhere in the world.

Prominent agroforestry systems in India

Agroforestry is practiced throughout India as way of

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life since time immemorial. Indian agriculture is facing diverse challenges and constraints due to growing demographic pressure, increasing food, feed, pulp, fodder and timber needs, natural resource degradation and climate change (Pandey, 2007; Dhyani *et al.,* 2013). Diversification of land-use system with agroforestry can address some of these challenges, and as a result, agroforestry has received greater attention in India from researchers, policy-makers and others for its perceived ability to contribute significantly to economic growth, poverty alleviation and environmental quality. Today, agroforestry is recognized as an important part of the 'evergreen revolution' movement in the country. India has been in the forefront of agroforestry research ever since organized research in agroforestry started worldwide about 40 years ago. Nair (1985) described 18 agroforestry practices followed in different parts of India, viz. improved shifting cultivation, planted tree fallows, *taungya*, alley cropping, live fences, multipurpose trees on crop lands, woodlots, protein bank, trees as shelter for crop and animals, trees for soil conservation on bunds and terraces, trees for water management, homegardens, plantation crop combinations, livestock under trees, dune fixation, aquaforestry, apiculture with forestry and irrigated forestry. Major agroforestry practices followed in India are summarized in Table 1.

On the basis of the diagnosis and design (D&D) exercises (Pathak *et al.,* 2000), the prominent agroforestry systems from different regions of the country were enumerated on priority scale (Table 2).

Tree-crop-environment interface in agroforestry

Tree–crop–environment interface is an important aspect in agroforestry and its careful management is very crucial for the success of the agroforestry systems (Lal, 1989). Tree–crop interactions occur when more than one individual are present in a biological system and when resources are limited. The positive (complementary) and negative (competitive) effects of trees in agroforestry systems have been realized by field observations. The nature and quantum of tree–crop interactions and their effects are not uniform, and depend on many factors like nature of the species grown, age and size of trees, density of components, management practices (spacing, training, pruning, irrigation, fertilization, etc) and environmental factors (Kaushal and Verma, 2003). More specifically, in case of erect growing and sociophyte plants, the extent of tree–crop interaction and the resultant effects will be less than spreading type and heliophytes. Similarly, the adverse effect will be more in case of aged and large-size-trees. Further, higher the density of components, more will be the negative effect on the under storey crop and vice-versa. The management practices like training, pruning, irrigation, fertilization and environmental factors, viz. availability of water, nutrients and light, also affect the tree–crop complementarities or antagonism.

Tree–crop interactions may also be as above-ground and below-ground interaction. In a legume and non-legume-based intercropping system, part of the N_2 fixed in the root nodule of the legume may become available to the non-legume component is an example of complementarity. Further, the complementarities in resource capture and sharing under mixed cropping/intercropping system may be spatial or temporal (Ghosh *et al*., 2009). Multi-storied cropping in coconut and planting shade trees in cocoa and tea plantation uses this principle. In similar manner under agroforestry system, exploitation of different layers of soil

Table 1. Major agroforestry practices followed in India

Practice	Agroecological region/states
Fodder trees	Throughout the country
Intercropping/grasses with fruit trees	Sub-tropical and tropical; orchards in hilly regions
Seasonal forest grazing	Semi-arid and mountainous ecosystem
Tree planting for reclamation of saline soils and wastelands	Semi-arid and canal-irrigated regions, mostly in the northern and north-western regions
Taungya	Eastern region
Woodlots for soil conservation	In hilly areas, along sea coast and ravine lands
Boundary planting and live hedges	In all regions
Farm woodlots	Throughout the country
Homegardens	Mainly tropical west coast region, Kerala, southern Karnataka, Andaman and Nicobar Islands
Industrial plantations with crops	Intensively cropped areas in northern and north-western regions: Haryana, Himachal Pradesh, Punjab, Uttar Pradesh; also in southern states (Andhra Pradesh, Karnataka, Kerala, and Tamil Nadu)
Scattered trees on farms, parklands	All regions, especially semi-arid and arid regions
Shelterbelts and windbreaks	In wind-prone areas, especially coastal, arid and alpine regions
Shaded perennial systems with plantation crops	Mainly humid tropical region in the southern region; also Asom, West Bengal

Table 2. Agro-forestry systems priority in different agro-climatic zones of India

Agroclimatic zone	Agroforestry system					
	Agri-silvi culture	Agri-horti-silvi culture	Agri-horti-culture	Hortipasture	Silvipasture	Specialized
WesternHimalaya	4	4	5	4	4	-
Eastern Himalaya	5	3	5	4	3	Jhum
Lower Gangetic Plains	5	-	3	2	2	Energy plantation
Middle Gangetic Plains	4	-	2	-	-	Homestead
Upper Gangetic Plains	5	-	5	-	-	Agri-horti-silvi culture
Trans-Gangetic Plains	5	-	5	-	-	Agri-horti-silvi culture
Eastern Plateau and Hills	5	-	4	3	4	Block plantation
Central Plateau and Hills	4	-	5	4	4	Block plantation
Western Plateau and Hills	4	-	5	2	4	-
Southern Plateau and Hills	5	-	3	2	4	-
East Coast Plains and Hills	4	5	4	2	2	Homegarden/Shelterbelt
West Coast Plains and Ghats	4	5	4	2	2	Homegarden
Gujarat Plains and Hills	4	2	4	3	5	Block plantation
Western Dry Zone	5	3	4	-	5	Shelterbelt
The Islands	4	5	4	1	2	Homegarden

No. 1-5 indicate the priority practiced model (1 for least and 5 for highest practiced)
Source: Pathak *et al.* (2000)

by the root-systems of trees and crops may lead to better utilization of resources with much less competition. In temporal complementarily, the yield advantages provided by the mixture cannot always be explained by more effective use of growth resources at specific times.

Tree–crop interaction may be manifested in terms of effects on growth, yield and productivity, quality, intercultural operations and other agronomic practices of the components of the agroforestry (Ralhan *et al.*, 1992). Further, the complementary effects may be manifested in terms of increased productivity, soil fertility (organic matter addition and N_2-fixation), nutrient recycling, soil and water conservation, microclimate improvement, anchorage to climber crops, crop protection from cold and heat waves and frost (wind break and shelterbelt), bio-amelioration, phyto-remediation and sustainability while the competitive effects may be manifested in terms of competition for light, water, nutrients, space and CO_2 (above-and below-ground), allelopathy (+ve and –ve), insects-pests and diseases incidence and birds (+ve and –ve). Therefore, effective planning and management of agroforestry systems is very much essential for taking full advantage of tree-crop interactions.

Agro-techniques for agroforestry production

Selection of agroforestry components

Selection of components (perennials, annual crops and livestock) for agroforestry systems has a great significance and their selection requires a judgment based on knowledge of the crops, adaptations, productivity, utility, family needs and marketing opportunities.

The local agroclimate, soil type, human and animal preference, nutritional value, digestibility, specific equipment needed for cultivation and species compatibility should also be given due consideration while selecting components for agroforestry (Singh *et al.,*1997; Pathak *et al*., 2000).

Components of agroforestry should be less competitive for space, light, water and nutrients and have strong synergy. Select and use trees, crops and planting/harvesting patterns that are suitable for the site, compatible with planned practices and provide desired economic and environmental returns. Further, the recycling and efficient use of residues, by-products and wastes from different components need to be given priority while deciding components for agroforestry (FAO, 1998). The selection of species should be from the homologous zones with similar eco-climatological areas or bioclimates as the plant life is very selective for their habitat. Suitable MPTs and crops are listed for different regions of India in Table 3 (Palsaniya *et al*., 2013).

Agroforestry establishment

Quality seed and/or planting material of perennial component is pre-requisite of successful agroforestry establishment. In case of trees, seeds need to be collected at proper maturity stage and time for good germination (Bisht and Ahlawat, 1999) and planted in advance in nursery for establishing agroforestry. Tree seeds having dormancy need to be treated with chemicals or scarified before sowing (Roy and Pathak, 1990; Sundriyal and Sundriyal, 2005; Sharma *et al.,* 2008). Seed treatments with agrochemicals

Table 3. Suitable crops and MPTs for different regions of India

Region	Promising MPTs	Crops
Western Himalayan region	*Ulmus wallichiana*, *Ailanthus excelsa*, *Morus alba*, *Robina pseudoacacia*, *Grewia optiva, Celtis australes, Pinus* spp.	Rice, mustard, maize, wheat, *rajma*, berseem
Eastern Himalayan region	*Acacia auriculiformis, Alnus nepalensis, Bamboos, Parasanthes falcataria, Gmelina arborea, Artocarpus heterophyllus, Parkia roxburghii*	Rice, maize, mustard, colocasia, pea, potato, cabbage, turmeric
Indo-Gangetic region	Poplar, Eucalyptus, *Dalbergia sissoo, Acacia* spp., *Anthocephalus cadamba, Prosopis chilensis, Mangifera indica, Madhuca latifolia, Psidium guajava, Citrus, etc*	Rice, wheat, oilseeds, pulses, maize, sugarcane, potato, cotton, vegetables
Arid and semi-arid region	*Dalbergia sissoo, Acacia tortilis, A. nilotica, Ailanthus excelsa, Prosopis cineraria, Leucaena leucocephala*, *Azadiracta indica,* Bamboo*, Hardwickia binata, Tectona grandis*	Pearlmillet, clusterbean, sorghum, millets, maize, pulses, oilseeds, vegetables
Humid and sub-humid region	*Albizzia* spp.*, Erythrina, Gliricidia, Acacia auriculiformis, Gmelina arborea, Dalbergia sissoo,* Bamboo	Rice, jute, sugarcane, vegetables
Coastal and island region	*Casuarina equisetifolia, Toona ciliata, Grevillea robusta, Tamarindus indica, Azadirachta indica, Ceiba pentandra, Tectona grandis, Gliricidia spp.*	Rice, cotton, sugarcane, pulses, oilseeds, vegetables

Source: Palsaniya *et al*. (2013)

or bio-priming with *Rhizobium* bio-formulations are also required for each crop and tree seed for plant protection, better germination and growth. Many pathogenic fungi are associated with seed and cause damage to seed plumule and radicle during germination. Seed treatments with fungicide and insecticide should be done just before sowing. For leguminous trees, seed should be treated with *Rhizobium* culture to ensure maximum N_2 fixation. Before transplanting in the field, tree saplings need proper hardening for better establishment (Negi *et al.,* 2005). In case of direct seed sowing in the field or also in nursery, the tree/shrubs seed should be sown at a depth of 1–3 cm (Bahuguna *et al.,* 1987; Roy and Pathak, 1990). Tree saplings can be transplanted during end of July to mid-August for better establishment.

Nutrient management

Agroforestry is supposed to promote more efficient cycling of nutrients than agriculture (Singh and Singh, 1996; Singh *et al.,* 1996, Yadav *et al.,* 2009; Saha *et al*., 2010). There exists nearly closed nutrient cycles in forest ecosystems where nutrient inputs from atmospheric deposition, biological N_2 fixation, litter fall, plant residue decay and weathering of primary soil minerals are in balance with nutrient losses due to leaching, denitrification, runoff, erosion and plant removal. Trees can provide N inputs in agroforestry systems through biological N_2 fixation (BNF) and deep nutrient capture. The presence of active nodules in roots of leguminous species indicates that BNF can supply considerable N inputs to crops via litter in soils. The non-fixing trees, such as *Cassia* accumulate more N in their leaves than N_2-fixing legumes, presumably because of their greater root volume and ability to capture nutrients which can be added to the soil as green leaf manuring. *Gliricidia* and *Sesbania* are also known for their N_2 fixation and green-manuring potential. Annual above-ground litter N content was high (256 kg/ha) with an annual release of 208 kg/ha, i.e. 81% of the total litterfall in *Leucaena* (Sandhu *et al*., 1990). Deep nutrient capture by tree roots at depths where crop roots are not present are considered as an additional nutrient input in agroforestry systems because such nutrients are otherwise leached as far as the crop is concerned. They become an input on being transferred to the soil via tree litter decomposition (Manna *et al*., 2004; Yadav *et al*., 2008, 2009).

The information on nutrient-use scenario in agroforestry systems is meagre. Agroforestry can partially provide the N requirement of crops. The degree to which this N is actually taken up by the crop depends on a variety of other factors, including the decomposition rate of organic mulches, BNF, residue management, etc. The potential for improved N management needs to be quantified in agroforestry systems by measuring processes such as mineralization, immobilization, denitrification, volatilization and leaching, along with changes in the soil organic N pools in systems combining organic and inorganic sources of N. Agroforestry, however, cannot supply most of the other nutrients required by crops. Phosphorus is often a critical nutrient in agroforestry and other low external input systems. Combinations of organic and inorganic sources of P may result in a more efficient use of nutrients. The deep capture of P is likely to be negligible because of the very low concentrations of available P in the subsoil. Many agroforestry systems do accumulate P in their biomass and return it to the soil via litter decomposition, but such cycling does not constitute an input from outside the system. However, through cycling, some less available inorganic forms of phosphorus in the soil may be converted into more available organic forms. For long-term production, agroforestry systems must include the addition of P and other nutrients and, in many cases, of N fertilizers as well in order to reverse nutrient depletion and ensure the efficient use of resources (Pathak and Sunil Kumar, 2004).

About 20% of the N released from tree prunings or litter is taken by the current crop. Much of the remaining 40–80% of the applied organic N is incorporated into soil organic matter (SOM) (Hagger *et al*., 1993). Because of the slow release of N and P from soil organic matter, organic inputs have a greater residual effect on soil fertility than do inorganic fertilizers. The rate of decomposition is mainly regulated by edaphic, climatic variables and resource quality (Singh *et al.,* 1996; Yadav *et al*., 2008). High-quality organic inputs (high N but low lignin and polyphenol contents) will release nutrients rapidly. In contrast, low-quality organic inputs (poor in N and high in polyphenol and lignin) will release nutrients slowly or even immobilize. This has practical implications for attaining synchrony between nutrient release and crop nutrient demand and, hence, for efficiency of nutrient use.

Maharudrappa (1999) reported that incubation of litter of different MPTs enhanced nutrient availability. The available N decreased slightly at 30 days of incubation compared to the control (Table 4). However, available N increased at the end of 60 days of incubation. This indicated temporary immobilization of nutrients by microorganisms. Incubation of litter also increased available K in all the treatments. The release of K to soil was more dependent on the quantity and quality of the litter. *Tectona grandis* recorded significantly higher values than other tree species. The increase in available K may be attributed to the fact that K is not strongly bound in organic structures, unlike that of N and P.

Leguminous intercrops in agroforestry for nitrogen economy

Inclusion of legumes in the agroforestry systems plays a significant role in the N economy of the production sys-

Table 4. Available N, P and K status (kg/ha) of soils incubated with different litters

Treatments	N		P		K	
	30 days	60 days	30 days	60 days	30 days	60 days
Control	252.4	261.5	13.8	15.2	215.8	228.3
Eucalyptus						
2.5 t/ha	248.9	283.9	14.0	15.8	222.7	236.1
5.0 t/ha	245.8	301.1	14.2	17.1	230.2	245.8
7.5 t/ha	243.5	325.5	14.6	16.9	238.1	253.7
10.0 t/ha	242.7	343.9	14.8	17.4	247.2	261.0
Tectona						
2.5 t/ha	252.1	306.9	14.5	17.1	235.7	243.1
5.0 t/ha	249.1	345.4	14.9	17.8	258.4	265.3
7.5 t/ha	248.3	378.7	15.3	18.5	281.5	292.3
10.0 t/ha	246.9	403.8	15.8	19.3	301.4	312.4
Casuarina						
2.5 t/ha	247.1	280.0	14.1	15.7	223.2	238.1
5.0 t/ha	245.3	299.2	14.5	16.6	232.2	247.3
7.5 t/ha	242.0	318.3	14.9	17.1	240.6	255.8
10.0 t/ha	241.5	339.9	15.4	17.5	249.4	264.9
Acacia						
2.5 t/ha	251.0	302.8	14.3	16.8	225.4	241.5
5.0 t/ha	248.5	338.2	14.8	17.5	236.7	252.5
7.5 t/ha	247.9	373.5	15.2	18.1	247.9	259.6
10.0 t/ha	245.6	399.4	15.5	18.9	259.6	269.1

tem. Properly managed legumes are N self-sufficient. These plants can achieve vigorous growth without the N fertilizers that are required for grasses. This self-sufficiency is achieved through the process of BNF. Introduction of suitable legumes in rangelands, pastures, silvipastures and agroforestry has great significance. The important legumes, which are suitable for introduction in arid and semi-arid silvipastures are *Dolichos lablab, Clitoria ternatea, Atylosia scarabaeoides, Macroptilium atropurpureum* and *Stylosanthes* species, while pigeopea, greengram, blackgram, chickpea, groundnut, soybean, cowpea, pea, lucerne, berseem, etc. can be introduced under cultivated agroforestry (Suresh and Rao, 2000).

Water management

Relatively little attention has been given to water-management practices as far as agroforestry research is concerned. Inclusion of trees and shrubs on the agricultural landscape, i.e. agroforestry influences adjoining microclimate (temperature, relative humidity, light, wind), changes the surface energy balance, and alters the water requirement, actual water use, water-use efficiency and productivity of adjacent crops or intercrops. Trees impact the water relations of the crop by affecting the loss of water through evaporation, transpiration, damaged leaves and mining of water from deep soil layers. In arid and semi -arid regions where wind erosion is common, wind breaks, shelterbelts or agroforestry buffers provide significant reductions in the amount of windblown soil and subsequent abrasion of plant parts and cuticular damage.

Under irrigated condition, irrigation water applied to intercrop also partially fulfils the water requirement of the tree component. In a study carried out in Indo-Gangetic plains, widespread adoption of poplar agroforestry and other tree-based systems has created a substantial improvement in the water productivity of this intensively irrigated region (Zomer *et al*., 2007). Under rainfed condition, agroforestry or specifically silvipastures are raised without any provision of irrigation. However, irrigation is essentially required during initial establishment along with life-saving irrigations. Sprinkler and drip system of irrigation is a better option for higher crop growth, yield, profitability and water-use efficiency (Tewari *et al.,* 2012). Similarly, there is scope of adopting various i*n-situ* and *ex-situ* rain water harvesting techniques based on soil type, slope and agro-climate (Rao *et al*., 2007).

Agroforestry has also been advocated as a means of managing excess water that has accumulated in the fields in canal command areas. *Eucalyptus* as a biodrainage species has widely been recognized for managing rising saline water-tables. Integration of persistent perennial species with traditional agriculture provides satisfactory drainage control to ameliorate existing outbreaks of salinity. Agroforestry in peri-urban agriculture can also be useful for utilization of sewage-contaminated wastewater from urban systems (Bradford *et al.,* 2003) and bio-drainage to prevent waterlogging in canal-irrigated areas (Ram *et al*., 2011). Turner and Ward (2002) emphasized that agroforestry systems have potential for improving water-use efficiency by reducing the unproductive components of the water balance (runoff, soil evaporation and drainage). Examples from India and elsewhere show that simultaneous agroforestry systems could double rainwater utilization compared to annual cropping systems, mainly due to temporal complementarity and use of runoff in arid monsoon regions (Droppelmann and Berliner, 2003).

Weed management

In general, the weed infestation is less in agroforestry system but their management is difficult. Weeds badly affect the establishment of tree, particularly during initial 2–3 years. In subsequent years, weed growth gets reduces as canopy of trees restricts the amount of light reaching on ground. In addition to density, weed flora also changes and shade-loving weed species dominate in agroforestry system.

In semi-arid region of India, the dominant weeds in white siris (*Albizia procera*)-based agroforestry system are: *Cyprus iria*, *Digera arvensis*, *Cynodon dactylon*, *Phyllanthus niruri*, *Echinochloa crus-galli* and *Commelina benghalensis* in the rainy season and *Chenopodium album*, *Fumaria parviflora*, *Anagallis arvensis*, *Convolvulus arvensis*, *Melilotus species*, *Vicia sativa*, *Phalaris minor* and *Avena fatua* in the winter season, constituting > 90% of the total weed population (Ram Newaj *et al.,* 2007). Dominant weeds of wheat are: *Medicago denticulata*, *Anagallis arvensis* and *Phalaris minor*. Their intensity is greatly reduced when wheat is seeded between *shisham* (*Delbergia sissoo*) plantations, while the density of *Commelina benghalensis* increases (Tripathi *et al.,* 2001). Agroforestry systems are most often invaded by shade-loving weeds. Examples of this type of weeds are: blackberry, privet, wild tobacco bush, bitou bush, African boxthorn, mirror bush, cassia and vines such as honeysuckle, banana passion fruit and English ivy.

Weed control in agroforestry system is complicated due to presence of more than one species at the same time and place. In most cases, trees need weed-free environment only during the first year. Weed control in the second and subsequent years is only justified where tree growth is very slow or there is extremely vigorous competition from deep-rooted grasses or perennial weeds. Since single method of weed control is not sufficient to manage weeds up to desired level, integrated weed-management approach is needed for better results. Weeds are controlled by hand and used as a mulch and green manure for perennial species in agroforestry systems. Also, leguminous species are used as live cover for weed control and for reducing the weed propagules in the soil. These weed-control methods are used until the trees in the agroforestry system control the weeds by shading. Chemical weed management in agroforestry system is somewhat difficult because two or more species of different nature are present. Therefore, apply herbicide carefully as per recommendation in sole crop but avoid the drift of spray to other species particularly on young trees (Palsaniya *et al.,* 2013).

Plant-protection practices

Limited information is available on the issues that are likely to influence disease incidence, etiology and epidemiology in agroforestry situations (Schroth *et al*., 2000). Researchers are now becoming increasingly aware of the importance of disease problems in agroforestry systems (Kumar and Shukla, 2009). There is a need to identify main diseases of crops and trees in various agroforestry systems and different interactions, which occur between them.

The microclimatic parameters like temperature, relative humdity, light intensity and duration, presence of free water on surface of inter-crop etc., are different under open field (outside tree canopy) and under tree canopy (agroforestry). In general, temperature at outside canopy is higher during the day and it is more during night under tree canopy. Reverse is the case for relative humidity. Further, the differences in magnitude of temperature and relative humidity during daytime were more as compared to night hours. Usually radiation intensity is less under the canopy than outside canopy resulting in more availability of free water on leaves of under-storey crops for longer duration under tree canopy, especially during morning hours. Data on disease incidence for multipurpose trees, horticultural plants and field crops in various agroforestry systems showed that pathogens are usually not common to component crops of a given agroforestry system (Kumar and Shukla, 2009). They made the following conclusions on disease scenario under agroforestry:

- Primary interactions, i.e. sharing of diseases among component crops of a given agroforestry systems are uncommon because of dissimilarities of plant and pathogen species involved.
- Effect of shade on incidence of certain diseases, viz. loose smut and alternaria leaf blight of wheat, *Alternaria* leaf spot of mustard, *Cercospora* leaf spot and yellow mosaic of blackgram etc., was not prominent.
- Cultivation of an inter-crop in an agroforestry system also affected the disease status of the tree species. Buildup of powdery mildew of *ber* was faster in a *ber*-based agroforestry system with wheat as compared to *ber* fields without any inter-crop.
- Changes in microclimatic parameters, brought about by introduction of trees in crop fields, generally influenced the disease severity of component crops if these operated in the cardinal range of the parameters for the disease development.

The insect-pests of agroforestry system are essentially the pests of its components, i.e., crops and woody perennials. The mechanisms governing the insect-pest situation in agroforestry systems are yet to be investigated fully and little information is available on comparing the insect-pest situation in monoculture or block plantation and in agroforestry combinations.

The presence of component plants in agroforestry that serve as host to a vulnerable stage of the insect-pest, or act as a collateral or alternate host for insect-pest, may be utilized to trap and kill these insects while keeping the main crop untreated. Agroforestry being perennial also supports the natural enemy population within and between seasons, especially during the off-season of the main crop. *Bacillus thuringiensis* (entomopathogenic bacteria) may be more effective under agroforestry, as its infection potential is greatly reduced in sunlight. Similarly, *Trichogramma* (egg parasitoid) parasitization may also be more under increased humidity in agroforestry. The increased humidity in agroforestry may be favourable for the development of disease in insect-pests. The tall woody perennial non-host plants in agroforestry may also act as a physical or biological barrier to the movement of insects and their natural enemies to, from and within the system. The proper nutrition, irrigation and other management practices also affect the insect-pest situation in the agroforestry.

Tree management

Shade is the most important growth-limiting factor under agroforestry. Shading from trees reduces crop yields, though the income from tree products compensates for the loss in yield. Shade in agroforestry can be managed through maintaining wider tree spacing, appropriate plantation geometry, plantation direction and training and pruning of tree component. It is desirable to have wider spacing of trees to have lesser shade on intercrop. The row-to-row tree spacing should be kept relatively higher than the plant to plant. The tree row direction should be east to west to avoid shading of intercrop. Training and pruning of plants is an integral activity under agroforestry. In case of trees, training is done during early stage to give the plant proper shape and size while pruning is done during bearing stage to maintain a balance between vegetative growth and fruiting. Pruning has the added benefit of raising the tree canopy which allows more light to hit the ground, thus providing higher production potential for the crop component of the system and producing an aesthetic open environment.

Generally, tree canopy is managed for 25–45% canopy for warm season crops and 40–60% canopy for cool-season crops. If canopy begins to exceed the desired amount, crop production will begin to decline. Therefore, thinning at intervals of approximately every 5–7 years is needed depending on species and site productivity to keep the canopy within the desired range. In general, the main trunk up to 1.5 m height is kept single stem to facilitate movement of tractor and implements in interspaces for intercultural operations. Tree should be maintained straight, as far as possible, to get clean bole. For fast-growing species like *Acacia nilotica* and *Albizia* species, pruning up to 75% tree height can be afforded without any adverse effect on tree growth. Pruning may be started from the second year of plantation and continued throughout rotation period either every year or alternate year. In case of timber trees like *Dalbergia sissoo* and *Tectona grandis*, pruning can be done up to 50% height of the tree. In arid regions of India, species like *Prosopis cineraria*, *Ailenthus excelsa* and *Acacia nilotica* are lopped peripherally while maintaining framework of tree. In case of evergreen species, pruning is usually done during the winter season or summer season. The best time to prune living branches is late in the dormant season (winter) or very early spring before active tree growth begins.

Agroforestry as climate resilient practice

Intergovernmental Panel on Climate Change (IPCC), in its Fourth Assessment report concluded that the increasing Greenhouse Gases (GHG) have resulted in global warming by 0.74^{o} C over the last 100 years. The IPCC have predicted an increase of 1.8 to 4.0^{o} C by the end of this century. Such changes are expected to adversely affect agriculture covering crops, trees, soils, livestock and fisheries. A serious threat is being predicted in meeting the food, fibre, fuel and fodder requirements of the growing population.

Agroforestry has an important role in reducing vulnerability, increasing resilience of farming systems and buffering households against climate related risks. It also provides for ecosystem services–water, soil health and biodiversity (Dhyani *et al.,* 2009). Evidence is now emerging that agroforestry systems are promising management practices to increase above-ground and soil C stocks to mitigate GHGs. The C sequestration potential of tropical agroforestry systems in recent studies is estimated between 12 and 228 t/ha with a median value of 95 t/ha. In India, average sequestration potential in agroforestry has been estimated to be 25 t/ha C over 96 million ha but there is substantial variation in different regions depending on the biomass production. However, compared to degraded areas agroforestry may hold more C. For example, above-ground biomass accumulation in a central Himalayan agroforestry system has been found to be 3.9 t/ha/year compared with 1.1 t/ha/year in the degraded forestland. The strip plantations in Haryana sequestered 15.5 t/ha C during the first rotation of 5 years and 4 months (Ram *et al*., 2011). The role of trees outside forests in carbon balance has been considered only recently, indicating that trees outside forests in India store about 4 t C/ha, in addition, to the forests. The net annual C sequestration rates for fast growing but short-rotation agroforestry crops such as poplar and *Eucalyptus* have been reported to be 8 and 6 t C/ha/year respectively (Kaul *et al*., 2010). Poplar-based agroforestry systems in Saharanpur (Uttar Pradesh) and Yamunanagar (Haryana) stored 27–32 t/ha C in boundary system and 66–83 t/ha in agri-silviculture system at a rotation period of 7 years (Rizvi *et al*., 2011). Studies from Punjab indicate that at a rotation of 7 years, poplar timber C content could be 23.6 t/ha and an equal amount may be contributed by roots, leaves and tree bark. In smallholder bamboo farming system in Barak Valley, Assam, a traditional homegarden system, C estimate in above-ground vegetation ranged from 6.51 (2004) to 8.95 (2007) t/ha with 87, 9 and 4% of the total C stored in culm, branch and leaf, respectively, with a mean rate of C sequestration of 1.32 t/ha/year.

Currently area under agroforestry worldwide is 1,023 million ha (Nair *et. al*., 2009) and areas that could be brought under agroforestry have been estimated to be 630 million ha of unproductive croplands and grasslands, with the potential to sequester 586 Gg C/year by 2040. In fact, 5–10 kg C/ha can be sequestered in about 25 years in soils of extensive tree-intercropping systems of arid and semi-arid lands to 100–250 kg C/ha in about 10 years in species-intensive multi-strata shaded perennial systems and homegardens of humid tropics. Such estimates for India based on holistic studies are not available, and therefore research and synthesis is required. Another major uncertainty, and thus an issue for future research, is that even the estimates that are available globally, are mostly derived through biomass productivity and often do not take into account the C sequestration in soils. The potential of agroforestry systems as C sink varies depending on the species composition, age of trees and shrubs, geographic location, local climatic factors, and management regimes. The literature reviewed here indicates that agroforestry systems have the potential to sequester large amounts of above-and below-ground C compared to tree-less farming systems. In order to exploit the mostly unrealized potential of C sequestration through agroforestry in both subsistence and commercial enterprises, innovative policies based on rigorous research results are required.

Agroforestry and natural resource conservation

Agroforestry practices also help in soil and water conservation (Dhyani *et al*., 2005; Faruqui *et al*., 2006). In different agro-climatic conditions and under various land-use systems, reduction in runoff and soil loss as well as improvement in soil nutrients due to silvipasture have been observed as compared agriculture or cultivated fallow land-use systems. Studies conducted in North Eastern Hills Region on soil and water conservation at different slopes (< 50%, 50–100% and top slopes > 100%) revealed 99 and 98% reduction in runoff and soil loss, respectively, under agri-horti-silvipastoral system (Singh, 1988). In Shiwaliks, where mean annual rainfall ranges between 800–1,500 mm, due to different agroforestry system, it was observed that average soil, water and nutrients losses with runoff water were very less as compared to agricultural systems. A 3-tier silvipastoral system comprising *Leucaena leucocephala* as top canopy, *D. cinerea* as middle and *C. ciliaris + S. hamata* as lower canopy reduced the runoff and soil loss by 6 and 11 times, respectively against a bare land (Yadava and Varshney, 1997). Similarly, the loss of total soluble salts, dissolved N and K was reduced to the tune of 69, 67 and 43%, respectively, as compared to bare land. The organic C, available N and P in silvipastoral system were also improved by 53, 23 and 8%, respectively, against their initial status. Shelterbelt agroforestry, which is vegetative barriers of trees/ shrubs/ bushes, is used as protective measures to minimize hazardous effect of winds particularly in hot arid region where wind erosion is a dominant phenomenon.

Problem soils, landslide, mine spoils and torrents may also be effectively checked and rehabilitated through silvipastoral system along with mechanical measures (Dadhwal and Katiyar, 1996). At Nalota Nala, about 4 ha landslide area on Dehradun-Mussoorie road has been successfully stabilized by bio-engineering measures including plantation of *Ipomoea carnea, Vitex negundo* and napier grass with *Erythrina suberssa, D. sissoo* and *A. catechu.* The area was completely rehabilitated within a period of 10 years. The sediment load which was 320 t/ha/year before treatment reduced to 5.5 t/ha/year with the improvement of vegetation cover from <5 to 95% (Sastry *et al.,* 1981). The significance of all these measures was reflected on the dry weather flow, which used to last hardly for 100 days after the cessation of monsoon, increased to 250 days after the treatments (based on 30 years of observation). Hazra and Singh (1994) reported that in a total of 418.8 ha of highly degraded wastelands of Gaharwara village, an area of 83.75 ha barren hill was treated with appropriate soil-and water-conservation measures and planted with suitable agroforestry systems. The soil-and water-conservation treatments helped in reducing soil loss from 41 to 9.5 t/ha from barren hillocks and from 20.5 to 5.5 t/ha from wastelands. This has also helped in reducing silt deposition from 0.28 to 0.40 m to 0.05 to 0.1 m and reduced runoff from 70 to 30% with rise in water table from 1 to 4 m. Srivastava *et al.* (2003) reported that silvipasture along with staggered contour trenching in Kangra watersheds reduced the soil erosion and improved productivity, survival of plants and output from silvipastoral system. Treatment with staggered contour trenching at 1 m vertical interval retained 227–424 m^3/ha runoff and trapped 37 t/ha/ year silt in the watershed.

Agroforestry in salt-affected soils

Salt-affected soils are very low in organic matter and biological activity. Tree growth provides a green cover and improves soil environment for enhanced biological activity, better water relations and increased organic matter and fertility status. Tree roots increase the CO_2 levels in the soil which help in mobilizing soil $CaCO_3$ and the releasing Ca exchange with Na on soil-exchange complex. Further, the litter produced also hastens the process of reclamation. In an experiment, growth and biomass production of *Prosopis juliflora* was compared in 10-year old plantations with that of *Acacia nilotica*, *Casuarina equisetifolia* and *Eucalyptus tereticornis* in an abandoned sodic soil having pH_2 of 10.4 (Singh, 1995). The biomass production in 10 years was in order: *Prosopis*>*Acacia*>*Casuarina*> *Eucalyptus.* In addition to biomass production, *Prosopis* litter when falls on ground adds to the humus content of degraded lands and increases the fertility status. Continuous growth of *Prosopis* on alkali lands reclaim these soils to such an extent that agricultural crops like wheat and oats can be grown without amendment application. Singh *et al.* (1997) evaluated agriculture, forestry and agroforestry practices in a moderately alkali soils in north-western India over a period of 6 years at the Central Soil Salinity Research Institute (CSSRI), Karnal. The soil conditions were much improved in terms of the soil buildup of soil organic matter, N, P and K when trees were associated with agricultural crops (Table 5). The improvement in soil condition with different trees was in the order: *Acacia*-based system >poplar>*Eucalyptus*> agriculture (sole crops). The higher fertility status under *Acacia* and poplar trees results from higher annual litter yields and a better quality of the added material.

Table 5. Changes in some properties of 30 cm soil in 5 years as affected by land-use practices at Karnal, India

Land-use system	Initial soil properties					
	pH	EC (dS/m)	OC (%)	Available nutrients(kg/ ha)		
				N	P	K
Sole crops	9.26	0.56	0.22	65	14.3	238
Eucalyptus-based system	9.32	0.61	0.25	65	13.8	224
Acacia-based system	9.34	0.67	0.28	72	13.6	212
Poplar-based system	9.27	0.60	0.26	68	14.4	237
After 5 years						
Sole crops	8.81	0.45	0.29	75	13.6	208
Eucalyptus-based system	8.65	0.32	0.37	86	18.5	259
Acacia-based system	8.71	0.41	0.48	103	31.0	286
Poplar-based system	8.47	0.35	0.43	93	21.7	321

Eucalyptus based agroforestry system

Eucalyptus is one of the trees which can be grown with crops. This tree is the most popular choice to be planted along the edges or bunds of agricultural fields, and appears to be well incorporated and accepted in agroforestry in India. Silvicultural properties including straightness, narrow crown, self–pruning, high growth rates, adaptability to a wide range of soils and climates, coppicing ability, a tendency not to spread as weed and wide utility of wood are some of the main features of *Eucalyptus* clones making it popular among the farmers for raising as block plantations. *Eucalyptus* has more than 600 species, among which *Eucalyptus camaldulensis* and *Eucalyptus tereticornis* are cultivated more among the farming community. These species are drought-tolerant and also capable of withstanding under irrigation and saturation, very hot summer temperatures and suitable for a wide range of sites. Spacing of 3.0 m × 1.5 m is recommended for producing poles and pulpwood, and larger spacing is desirable for production of timber from clonal *Eucalyptus* plantations. For block plantation, the distance between the trees has to be 3 m and within rows 1.5 m which hold 2,222 plants/ ha and allow raising of intercrops in first 2 years in the cycle of 4-year rotation period. Intercrops such as chillies, cotton, tobacco, blackgram, greengram are widely grown with *Eucalyptus* during the initial years (Lal and Kulkarni, 1992).

Prasad *et al*. (2010) found that different spatial arrangements evaluated at a constant density of 1,666 trees/ha did not affect *Eucalyptus* growth in terms of height, dbh and total biomass because of the compensatory growth of the trees. So row spacing for *Eucalyptus* can be increased from the current practice of 3–6 m or even 7–11 m by grouping 2 or 3 rows. Wide-row arrangements permit intercropping with economical yields all through the 4-year period of the short rotation *Eucalyptus* grown for pulpwood. Intercropping in widely-spaced *Eucalyptus* is more economical than intercropping in the farmers' spacing of 3 m × 2 m, sole woodlot or sole annual cropping. *Eucalyptus*-based agroforestry using wide-row arrangement is an important strategy for integrating wood and annual crop production for smallholders and to overcome the concerns of declining food production due to shift in acreage from crops to woodlots.

Acacia-based agroforestry system

Acacia species has been recognized worldwide as a multipurpose tree. The main advantage of this genus is that its fast biological N_2 fixation, ability to establish on N deficient and drought- prone soils and suitable for agroforestry systems and thus can be used in rehabilitation of drylands (Bargali and Bargali, 2009). In the central plains of Indian sub-continent, *A. nilotica* grows naturally in the agricultural fields and farms (Pandey *et al.,*1999). In an agri-silviculture experiment, it was found that crop production depends on distance from the tree trunk and tree canopy size. Reduction in grain yield was maximum (30%) under the large tree canopy and lowest (12%) under the small tree canopy due to decreased availability of light by 44–62% under the canopy that resulted in slow photosynthetic rates and growth (Pandey *et al.,*2000).The gradient of the incident light was the principal factor governing the gradient of grass biomass under developing canopies of all tree plantations. However, when the tree is felled after the completion of rotation cycle (>12 years), grain yield increased 126% for the first cropping season and 30% for the fifth cropping season at 1 m distance from the tree stump and declined with distance (Pandey and Sharma, 2005). These results indicate that the crop may exploit the greater amount of nutrients to increase productivity, if the tree canopy is open to facilitate greater light availability.

El-khawas and Shehata (2005) reported that leaf leachates of *A. nilotica* inhibited the germination and growth of *Zea mays* and *Phaseolus vulgaris.* These results indicated that the inhibitory effect of *A. nilotica* on seed germination and seedling growth is related to the presence of allelochemicals including tannins, flavonoids and phenolic acids. Moreover, the toxicity is caused due to synergistic effect rather than single effect of allelochemicals. The results of some agronomical interventions recorded higher seed yield of blackgram in treatment receiving trenching (730 kg/ha), which was statistically on par with treatments receiving 50% branch pruning (715 kg/ha) (Patil and Channabasappa, 2008). *Acacia auriculiformis* is one of the fast-growing multi-purpose tree species, which is being promoted for cultivation by the wood-based industries in Karnataka state.

Poplar-based agroforestry system

Poplar (*Populus deltoidus*)-based agroforestry systems are economically viable and more sustainable than many other crop rotation prevalent in northern India. Poplar has a winter-deciduous nature, its leaf fall starts at the end of September and continues till January. Intercropped poplar stands produce higher quantity of litter, higher N, P and K content in litter than pure stands, and litter fall production increases with trees age (Mohsin *et al.*,1996). Macro- and micronutrients return through poplar litterfall followed the order: Ca > N > K > S > P and Fe > Mn > Zn > Cu, respectively. Crops like wheat, turmeric, colocasia, sugarcane, oats, berseem, pearlmillet (*bajra*), sweet potato, mustard are being grown by the farmers in block plantations of poplar. Fruit tree species (mango, citrus, lichi, jujube or *ber*, guava, etc.) are also becoming popular, as the poplar is harvested by the time the fruit yield is available. Dhillon *et al.* (2001) reported annual net return of ₹ 55,390 and 73,300/ha without intercropping and with intercropping, respectively, over the entire rotation. Winter cereals are well-suited to deciduous trees like poplar and grow profusely in autumn and early spring. By the time popular develops foliage, the cereals crops virtually mature. The decrease in grain yield under 1 year old poplar is mainly due to reduction in space for crop on unit basis. Ralhan *et al.* (1992) reported 23.3% decline in wheat grain yield with poplar (clone G-3) at three years age, whereas reduction in grain yield during first year was 9 % only.

CONCLUSION

Based on the review following conclusions are drawn:

1. Agroforestry as a land-use system is gaining importance for diversification of agriculture and addressing issues of resource conservation, farm income and environmental quality.
2. Selection of agroforestry components is location specific but diagnosis and design approach indicates agri-silvi/horti-pastures are much adopted. Block plantations are practised in areas with market opportunities.
3. In agroforestry, quality seed and planting material of perennial component is very important. All care is required for proper germination and establishment of seedlings.
4. Agroforestry with different nature of crops (seasonal and perennial, cereals and leguminous) have great potential for recycling of nutrients and improvement of rhizosphere. The potential for improved management needs to be quantified in term of nutrient dynamics and C stocking rate.
5. Water use in agroforestry system has been found better than sole cropped area, and it can be further improved by reducing runoff, soil evapo-transpiration (ET) loss and drainage.
6. Weed control and plant protection in agroforestry is tedious. Integrated approach of weed management should be adopted allowing proper establishment of perennial plants, whereas mechanical and chemical methods are better for growth of intercrops. Microclimate has great influence on pest status in agroforestry, hence management of soil and crops should be attempted to reduce the pest build up.
7. Tree management is important in agroforestry to have better combined effect of perennial and annual components. Pruning intensity depends upon tree species, soil and climate and focus of agroforestry. Intensity of pruning varies from 50 to 75 % in silvi-pasture and 40 to 50 % in timber species.
8. Agroforestry has great potential in reducing vulnerability and increasing resilience of farming systems against climate related risks. The potential of agroforestry in C sequestration is enormous but systematic quantification with innovative policies is required.
9. Problem soils can be utilized for agroforestry system involving *Prosopis, Acia, Casuarina, Eucalyptus* and other suitable species for enhanced soil productivity and economic gains from such unproductive lands.

FUTURE THRUST

Agroforestry seems to be the only pragmatic alternative to meet the national target of increasing forest cover to 33% from the present level of 20.7%. However, it will require appropriate research interventions, adequate investment, suitable extension strategies, post-harvest processing and value-addition, market infrastructure, convergence and strong policy support. A major role for agroforestry in near future will emerge in the domain of ecosystem services. In view of changing scenario, the following thrust areas have been identified:

- There is need to evolve an effective mechanism for synergistically linking and managing the linkages among the various agroforestry research and development programmes.

- Genetic improvement of identified potential MPTs and ensuring quality planting material.
- In-depth studies on tree–crop–environment interactions for different agroforestry systems under varying environments.
- Developing contract and organic farming in relation to agroforestry.
- Developing integrated approaches like integrated nutrient, pest, water management (INM, IPM, IWM) etc. under agroforestry systems.
- Developing decision-support systems for replication of successful agroforestry systems/ practices.
- Exploring unexploited and under-exploited species of high economic value, such as medicinal, aromatic, oil-yielding plants, etc. and their improvement and value-addition.
- Agroforestry strategies under problem soils such as salt-affected, ravines and acidic soils.
- Environmental amelioration through C sequestration, bioremediation and resource conservation.
- Technology transfer and capacity building in agroforestry.

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