Multifunctional Agroforestry Systems in India for Livelihoods: Current Knowledge and Future Challenges

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Land-use options that increase resilience and reduce vulnerability of contemporary societies are fundamental to livelihoods improvement and adaptation to environmental change. Agroforestry as a traditional land-use adaptation may potentially support livelihoods improvement through simultaneous production of food, fodder and firewood as well as mitigation of the impact of climate change. Drawing on the representative literature, Here, I critically review the contribution of agroforestry systems in India to: (i) biodiversity conservation; (ii) yield of goods and services to society; (iii) augmentation of the carbon storage in agroecosystems; (iv) enhancing the fertility of the soils; and (v) providing social and economic well-being to people. Agroforestry systems in India contribute variously to ecological, social and economic functions, but they are only complementary—and not as alternative—to natural ecosystems. To promote well-being of the society, management of multifunctional agroforestry need to be strengthened by domestication of useful species and crafting market regimes for the products derived from agroforestry systems. Future research is required to remove many of the uncertainties that remain, and also carefully test the main functions attributed to agroforestry against alternative land-use options in order to know unequivocally to what extent agroforestry served these purposes.

Key words: Biodiversity Conservation, Biological Pest Control, Carbon Sequestration, Ethnoforestry, Food Security, Global Climate Change, Soil Fertility Enhancement

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1. Introduction

Land-use options that increase livelihood security and reduce vulnerability to climate and environmental change are necessary. Traditional resource management adaptations, such as agroforestry systems may potentially provide options for improvement in livelihoods through simultaneous production of food, fodder and firewood as well as mitigation of the impact of climate change.

A livelihood is a means of deriving a just and dignified living by the society, family and individuals. It comprises of the assets available to households (human, financial, physical, natural, and social capital), the activities, and the access to these (mediated by institutions and social relations) that together determine the living gained by the society, households or individual[1,2]. A livelihood can be urban or rural depending upon the context in which families derive their living. A livelihood can be sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural capital[3,4]. The livelihoods improvement through natural resource management seeks to understand individual or household strategies through which they make long-term progress towards a better quality of life[5,6].

Livelihoods improvement is not just about the positive change towards better quality of life and human well-being but it takes into account the local and global change which determines livelihoods[7]. The adverse impact of climate change may be more severely felt by poor people who are more vulnerable than rich. Appropriate policy responses combining the agroecosystems as key assets can strengthen adaptation and help build the resilience of communities and households to local and global change[8]. Steps to promote the mainstreaming of adaptation into livelihoods improvement may potentially deliver better results when combined with adaptive management of natural resources and agroecosystems.

There is, thus, a need for intensified conservation efforts and resort to *in situ* and *ex situ* conservation as well as growing products and generating services in agroecosystems[9]. Tree growing in combination to agriculture (agroforestry systems) as well as numerous vegetation management regimes in cultural landscape (ethnoforestry systems) may improve nutrient availability and efficiency of use and may reduce erosion, provide firewood and store carbon. Management practices in landscape continuum that include individual farms, watersheds and regional landscape can be integrated to take advantage of services provided by adjacent natural, semi-natural or restored ecosystems. Trees and shrubs planted in buffer strips surrounding farmlands may decrease soil erosion and can take up nutrients that otherwise would enter surface or ground waters. Insects and other animals living in nearby habitats can provide crop pollination services. Agroforestry systems can also be managed to reduce inputs of weeds and other agricultural pests[10].

In order to craft strategies for livelihoods improvement and adaptation to local and global change land-use options are necessary that increase livelihood security and reduce vulnerability. Such adaptations are possible when combined with traditional resource management systems. Agroforestry as an adaptive system, therefore, is a promising area of interest[11-14].

This review examines the multifunctional agroforestry systems in India as a potential option for livelihoods improvement, climate change mitigation, biodiversity conservation in agroecosystems as well as yield of goods and services to the society. The synthesis of the available literature also helps to identify remaining uncertainties and thus the future directions for research.

2. Trees in Agroecosystems and Cultural Landscapes in India

Trees have a very special role in the ethos of the people of India. There are several sacred trees and sacred groves valued by the people. India also has a long historical tradition of tree growing on farm and around home. These long traditions and indigenous ethics had and continue to have the impact and implications for the tree growing and ecological, economic and social well-being of the people. Sacred elements in cultural landscape of India also have a substantial conservation value[15-22].

Agroforestry systems in India include trees in farms, community forestry and a variety of local forest management and ethnoforestry practices[23]. A wider definition of agroforestry encompasses a wide variety of practices, including trees on farm boundaries, trees grown in close association with village rainwater collection ponds, crop-fallow rotations, and a variety of agroforests, silvopastoral systems, and trees within settlements (**Table 1**). These systems have been presented as a solution to rising fuelwood prices in India resulting from increase in demand and decrease in supply of fuelwood due to forest degradation[24,25].

Overall, India is estimated to have between 14,224 million[26] and 24,602 million[27] trees outside forests, spread over an equivalent area of 17 million ha[28], supplying 49% of the 201 million tonnes of fuelwood and 48% of the 64 million m^3 of timber consumed annually by the country[29].

3. Agroforestry Systems as Carbon Sinks

Land management actions that enhance the uptake of CO_2 or reduce its emissions have the potential to remove a significant amount of CO_2 from the atmosphere if the trees are harvested, accompanied by regeneration of the area, and sequestered carbon is locked through non-destructive (non-CO_2 emitting) use of such wood.

Carbon management through afforestation and reforestation in degraded natural forests are useful options but agroforestry is attractive because[30]: (i) it sequesters carbon in vegetation and possibly in soils depending on the pre-conversion soil C, (ii) the more intensive use of the land for agricultural production reduces the need for slash-and-burn or shifting cultivation, which contribute to deforestation, (iii) the wood products produced under agroforestry serve as substitute for similar products unsustainably harvested from the natural forest, (iv) to the extent that agroforestry increases the income of farmers, it reduces the incentive for further extraction from the natural forest for income augmentation.

Evidence is now emerging that agroforestry systems are promising management practices to increase aboveground and soil C stocks to mitigate greenhouse gas emissions[31]. The C sequestration potential of tropical agroforestry systems in recent studies is estimated between 12 and 228 Mg ha^{-1} with a median value of 95 Mg ha^{-1}. Therefore, based on the global estimates of the area suitable for the agroforestry (585-1215 x 10^6 ha), 1.1-2.2 Pg C could be stored in the terrestrial ecosystems over the next 50 years[32].

In India, average sequestration potential in agroforestry has been estimated to be 25tC per ha over 96 million ha[33] but there is a considerable variation in different regions depending upon the biomass production (**Table 2**). However, compared to degraded systems agroforestry may hold more carbon. For example, the above ground biomass accumulation in central Himalayan agroforestry system has been found to be 3.9 t ha^{-1} yr^{-1} compared with 1.1 t ha^{-1} yr^{-1}at the degraded forestland[34].

A major uncertainty, and therefore issue for future research, is that these estimates are mostly derived through biomass productivity and often do not take into account the carbon sequestration in soils[35]. In order to exploit the mostly unrealized potential of carbon sequestration through agroforestry in both subsistence and commercial enterprises innovative policies, based on rigorous research results, are required.

4. Enhancing Soil Fertility and Water Use Efficiency

Maintenance and enhancement of soil fertility is vital for the global food security and environmental sustainability[36-38]. Although India is self-sufficient in terms of food production currently, but for a population expected to rise further, country will need to enhance both the food production as well as tree biomass. The next green revolution and concurrent environmental protection will have to double the food production[39,40]. Maintaining and enhancing the soil fertility of farmlands to grow food grains as well as tree biomass can help meet the demand in future. Ecologically sound agroforestry systems such as intercropping and mixed arable-livestock systems can increase the sustainability of agricultural production while reducing on-site and off-site consequences and may be a road to sustainable agriculture[41].

Tree-based agroecosystems have more closed nutrient cycles that help conserve soil productivity. Planting and pruning N-fixing legumes is a feasible way to add Nitrogen to the systems[42]. As the climate change progresses, the effect of elevated CO_2 itself will have positive effect on growth and nitrogen fixation of several Australian *Acacia* species[43] that grow very well in India. Agriculturally induced successional pathways often lead to dominance by leguminous trees and therefore serve as a mechanism for increasing N oxide emissions from tropical regions[44]. In regions where green revolution has not been able make dent due to lack of soil fertility agroforestry may hold promise[45,46].

In India, various soil management practices to enhance soil organic carbon content have been suggested including reduced tillage, manuring, residue incorporation, improving soil biodiversity, and mulching[47]. However, a useful path, complementary to chemical fertilizers, to enhance soil fertility is through agroforestry. Alternate land use systems such as agroforestry, agro-horticultural, agro-pastoral, and agro-silvipasture are more effective for soil organic matter restoration[48]. Soil fertility can also be regained in shifting cultivation areas with suitable species. For instance, a field experiment to study the N_2 fixation efficiency suggests that planting of stem cuttings and flooding resulted in greater biological N_2 fixation, 307 and 209 kg N ha^{-1} by *Sesbania rostrata* and *S. cannabina*, respectively. Thus, *S. rostrata* can be used as a green manure by planting the stem cuttings under flooded conditions[49].

Through a combination mulching and water conservation, trees in agroecosystems may directly enhance the crop yields of coarse grains. For instance, in the arid region of Haryana, the effect of *Prosopis cineraria*, *Tecomella undulata*, *Acacia albida* and *Azadirachta indica* on the productivity of *Hordeum vulgare* (barley) was found to be positive. *P. cineraria* enhanced the grain yield by 86.0%, *T. undulata* by 48.8%, *A. albida* by 57.9% and *A, indica* by 16.8% over the control. Biological yield was also higher under the trees than that in the open area. The soils under different tree canopies were rich in organic carbon content, moisture availability and nutrient status[50].

Recent studies[51] have found that multiple-use species such as *Bambusa nutans* has potential to help in soil nutrient binding during restoration of abandoned shifting agricultural lands (jhum fallows) in north-eastern India under the *B. nutans*. A Comparison of jhum cultivation and agroforestry suggests that agroforestry is an option to address the challenges of slash-and-burn[52].

A study of nutrient cycling, nutrient use efficiency and nitrogen fixation in *Alnus*–cardamom plantations in the eastern Himalaya found that nutrient standing stock, uptake and return were highest in the 15-year-old stand. Annual N fixation increased from the 5-year-old stand (52 kg ha^{-1}) to the 15-year-old stand (155 kg ha^{-1}) and then declined with advancing age. Thus, *Alnus*–cardamom plantations performed sustainably up to 15–20 years[53].

There is robust evidence that agroforestry systems have potential for improving water use efficiency by reducing the unproductive components of the water balance (run-off, soil evaporation and drainage)[54]. Examples from India and elsewhere show that simultaneous agroforestry systems could double rainwater utilisation compared to annual cropping systems, mainly due to temporal complementarity and use of runoff in arid monsoon regions[55-57]. For instance, under the experimental conditions, the root system of the alley cropped *Acacia* and *Sorghum* exploited larger soil volume utilizing soil resources more efficiently than the respective monocultures. Combination of crop and trees used the soil water between the hedgerows more efficiently than the sole cropped trees or crops, as water uptake of the trees reached deeper and started earlier after the flood irrigation than of the *Sorghum* crop, whereas the crop could better utilize topsoil water[58]. Integration of persistent perennial species with traditional agriculture also provides satisfactory drainage control to ameliorate existing outbreaks of salinity[59].

Agroforestry systems can be useful for utilization of sewage-contaminated wastewater from urban systems. For instance, availability of permanent streams of sewage-contaminated wastewater from the twin city of Hubli-Dharwad in southern Indian State, Karnataka has enabled small-scale farmers to diversify their cropping practices such as increasing production from fruit trees in agroforestry systems[60].

It must be pointed out that agroforestry systems may reduce crop yield for a variety of reasons. But, there may be a trade-off. For instance, studies on traditional agroforestry system in central India[61] found that effect of residual nitrogen on the yield of rice crop after removal of 15-year old *Acacia nilotica* trees resulted in increase in the crop yield (12.5 t ha^{-1}) that was almost equal to the reduction in the crop yield suffered during 15 years of the tree growth in agroforestry system.

Yield reductions may also be compensated in the long run by microclimate modification. For instance, statistically similar wheat harvest indices in all the treatments despite lower total biological yields in agroforestry treatments suggest that microclimatic conditions under agroforestry systems may be more favorable for wheat growth due to reduction in heat load during the post anthesis period[62].

Even when trees are not removed through total harvest, the species combination may be designed for nutrient release that benefits crops. Chemical characteristics and decomposition patterns of six multipurpose tree species, viz., *Alnus nepalensis, Albizzia lebbek, Boehmeria rugulosa, Dalbergia sissoo, Ficus glomerata* and *F. roxburghii* in a mixed plantation established on an abandoned agricultural land in a village at 1200 m altitude in Central Himalaya[63] is a case in point. These species gave the highest rates of N and P release during the rainy season. Thus, *kharif* crops (rainy season crops) are unlikely to be nutrient stressed even if leaf litter is the sole source of nutrients to crops in mixed agroforestry. A diverse multipurpose tree community provides not only diverse products but may also render stable nutrient cycling[63].

5. Biodiversity Conservation

Society needs to craft synergies among sustainable livelihoods, the Kyoto Protocol, the Convention on Biological Diversity, and other international instruments[64]. Genetic diversity of landraces and trees in agroecosystems is particularly of immediate concern as there is a danger of erosion in ethnocultivars as well as knowledge that has generated such diversity[65]. Using agroforestry systems as carbon sinks, to sequester and store atmospheric carbon dioxide, and by designing a suitable emissions trading system, the Kyoto Protocol provides a new source of financial support for protection and management of biological diversity[66].

Continued deforestation is a major challenge before the society[67-72]. Although agroforestry may not entirely reduce deforestation[73], but in many cases it acts as effective buffer to deforestation. Trees in agroecosystems in Rajasthan and Uttranchal have been found to support threatened cavity nesting birds, and offer forage and habitat to many species of birds[74]. These systems also act as refuge to biodiversity after catastrophic events such as fire[75]. Agroforestry also leads to a more diversified and sustainable rural production system than many treeless farming alternatives and provides increased social, economic, and environmental benefits for land users at all levels[76]. What constitutes enough biodiversity in agroecosystems depends upon the goal in question and will differ depending on whether the aim is to increase yields to support livelihoods improvement or deal with salinity, ground water levels, soil erosion, leaching of nutrients or weed control[77].

If we are concerned about conserving important biodiversity, then protected areas are the preferred choice, and biodiversity conservation may not be a primary goal of agroforestry systems. Nevertheless, agroforestry systems, in some cases, do support as high as 50-80% of biodiversity of comparable natural systems[78], and also act as buffers to parks and protected areas. The landscape mosaics created by the interplay of rainwater harvesting as an adaptation to climate change and consequent growth of vegetation in agroforestry systems[79,80] acts as corridor providing avenues for dispersal and gene flow in wildlife population[81,82,]. An example of buffer is provided by agroforestry around Hyderabad-Secunderabad. Biomass assessment within 100 km radius of twin cities suggests that annual increment of trees and forests in the region approximately equals with the estimated annual wood and fuelwood intake of the cities and villages[83]. This supply has acted to buffer the pressure on natural forests.

Tree diversity indeed can be large in some Indian village ecosystems. Study in Sirsimakki village of Karnataka by Shastri et al.[84] found 952 individuals belonging to 93 species in just 1.7 ha of agroecosystem. An additional 44 species on non-agricultural lands in the village ecosystem that included *soppina bett*a, minor forest and reserve forest were found. The overall agroecosystem had more trees (556 trees/ha) and diversity (diversity index 3.5) compared to the non-agro ecosystem that had 354 trees/ha and a species diversity of 3.87. The overall village ecosystem tree density of 418.8 per ha, with 144 species in 2238 individuals in the sampled area of 5.34 ha is a useful resource. Furthermore, home-gardens, with tree species varying between 20 and 40 on each unit with an average area of 376 m^2, support in all 93 tree species counted in just 1.7 ha.

Thus, although not a substitute for continuous and intact natural systems, fragments of all sizes and shapes, nonetheless, have conservation relevance. Local farmers who plant trees on their small farms are often surprised later by the number of birds and small mammals that begin to populate the area.

6. Biological Pest Control

Agroforestry systems create landscape structure that is important for the biological pest control. In small-scale, subsistence agriculture in the tropics, traditional farming practices have evolved that provide a sustainable means of reducing the incidence and damage caused by pests including nematodes. The biodiversity inherent in multiple cropping and multiple cultivar traditional farming systems increases the available resistance or tolerance to nematodes[85]. In structurally complex landscapes, parasitism is higher and crop damage lower than in simple landscapes with a high percentage of agricultural use[86].

7. Breaking the Poverty and Food Insecurity Circle

Agroforestry could contribute to livelihoods improvement in India where people have a very long history and accumulated local knowledge. India is particularly notable for ethnoforestry practices[23] and indigenous knowledge systems on tree-growing[87,88]. In terms of household income central Indian upland ricefields provide an illuminating economics[89]. The farms often have an average of 20 *Acacia nilotica* trees per ha. of 1 to 12 years of age. Small farms have more tree-density. At a 10 years rotation, these trees provide a variety of products including fuelwood (30 kg/tree), brushwood for fencing (4 kg/tree), small timber for farm implements and furniture (0.2 m^3), and non-timber forest products such as gum and seeds. Thus, trees account for nearly 10% of the annual farm income—distributed uniformly throughout the year than in rice monoculture—of smallholder farmers with less than 2 ha farm holding. The combination of Acacia and rice traditional agroforestry system has a benefit/cost (B/C) ratio of 1.47 and an internal rate of return (IRR) of 33% at 12% annual discount rate during a ten- year period (see also **Table 3**).

In northeast Indian state of Meghalaya the guava and Assam lemon based agrihorticultural agroforestry systems (i.e. farming systems that combine domesticated fruit trees and forest trees) gave 2.96 and 1.98-fold higher net return respectively in comparison to farmlands without trees. Average net monetary benefit to guava based agroforestry systems was Rs. 20,610/ha (US$ 448.00) and (Rs. 13,787.60/ha or US$ 300.00 to Assam lemon based agroforestry systems. Such systems are most useful livelihoods improvement strategies in the rainfed agriculture of Meghalaya[90]. Similarly, The net present value for the different agroforestry models on six years rotation in Haryana varied from Rs. 26626 to Rs. 72705 ha^{-1} yr^{-1} whereas the benefit:cost ratio and the internal rate of return varied from 2.35 to 3.73 and 94 to

389%, respectively. Thus, agroforestry has not only uplifted the socioeconomic status of the farmers but also contributed towards the overall development of the region[91].

There are numerous non-timber forest products collected from the wilderness for subsistence and cash income[92]. Often, harvesting is unsustainable because of a lack of knowledge about silviculture of species and destructive exploitation strategies driven by market forces. Domestication of such species aimed at commercialisation and production of valued products can reduce the pressure on natural ecosystems[93].

Domestication of fruit trees and other species grown in agroforestry systems offer significant opportunity for livelihoods improvement through the nutritional and economic security of poor people in tropics[94-96]. The wild edible plants form an important constituent of traditional diets in the Sikkim Himalaya where about 190 species are eaten and almost 47 species are traded in local market. Wild edible fruit species have high carbohydrate content ranging between 32 and 88%[97]. Some prominently used fruit species include *Baccaurea sapida*, *Diploknema butyracea*, *Eriolobus indica*, *Spondias axillaris*, *Machilus edulis* and *Elaeagnus latifolia*. Densities of these species are low in natural forests due to unsustainable fruit-collection. Such fruit trees can be taken up for domestication in agroecosystems on priority action[98]. These are the most promising candidates for domestication in Himalayas.

Trees in agroforestry systems can provide host to globally valued products, and thus, support livelihoods locally. A study of 8 year old agroforestry intervention in Palamau District of Jharkhand found that community dependent solely on rainfed farming and animal husbandry definitely gains positively by agroforestry interventions[99]. Suitable programmes that design the plantations of non-timber forest products in tribal areas such as Jharkhand can serve dual purpose of conserving the useful species as well as livelihoods improvement of local people[100]. Such programmes in tribal areas have more chances of success as communities are heavily dependent on the wild resources for livelihoods[101]. In Jharkhand, trees in agroecosystems are particularly valued as host to insects that yield marketable products such as silk[102], lac products[103], honey[104].

Woodcarving industry is emerging as an important source of income to local artisans worldwide[105]. Promotion of species used in woodcarving industry facilitates long term locking-up of carbon in carved wood and supports local knowledge, therefore, strengthens livelihoods. For example, Jodhpur in Rajasthan has emerged as a major centre of woodcarving exporting the woodcrafts worth Rs. 60 million annually facilitated by the traditional knowledge and skills, and growing tourism. Suitable agroforestry programmes may enhance the availability of wood in agroecosystems thereby improved ability of developing countries to participate in the growing global economy.

8. Caveats and Clarifications

All nature-society interactions have trade-offs and agroforestry systems are no exception. Although agroforestry is a useful land use management option, it requires some careful planning and studies on the remaining challenges such as farm yield decline under agroforestry systems.

There may not be an entirely convincing rationale for the argument that agroforestry systems are the answer for livelihoods improvement. Nevertheless, this review does provide some pointers in that direction. Although, over the last twenty-five years of research in India has demonstrated the potential of agroforestry, and some practices have been widely adopted, but the vast potential is yet to be fully exploited[106] (**Table 4**). Research is needed to further refine the key points of agreement and also to fill the crucial knowledge gaps. There is, evidently, a major gap in our understanding of how agroforestry systems contribute to/fit into rural livelihoods improvement. Future research is required to remove many of the uncertainties that remain, and also carefully test the main functions attributed to agroforestry against alternative land-use options in order to know unequivocally to what extent agroforestry served these purposes.

Agroforestry practices are strongly dependent on access to land within the community. Households that do not have ownership to lands may not be able to benefit from the agroforestry interventions for livelihoods improvement, unless market regimes permit their inclusion through value addition services.

Trees in agroforestry systems contribute to food security, rural income generation through diversity of products and services, and can enhance nutrient cycling, improve soil productivity, soil conservation and soil faunal activities. Nonetheless, trees in simultaneous agroforestry systems can also cause competition with the associated food crops[107]. Agroforestry may, thus, reduce the yield of the agricultural produce in farmlands. For instance, in Haryana, *Azadirachta indica* and *Prosopis cineraria* did not produce any significant difference in the wheat yield while the other two species (*Dalbergia sissoo* and *Acacia nilotica*) gave a reduction in yield. *A. nilotica* had a more prominent effect with a reduction of 40 to 60 % wheat yield and *Dalbergia sissoo* reduced yield by 4 to 30 % but the reduction effect was only up to a distance of 3 meters[108]. Interestingly, the species that did not negatively affect the yield, are indigenous trees occurring in traditional agroforestry systems, and they are economically more useful for providing multiple benefits. Selection of such species to enrich agroforestry systems shall be useful for local and national food security.

Not all species desirable for livelihoods improvement through agroforestry systems can be grown without designing an optimum combination. Many forest tree and fruit species are suitable to tolerate highly alkali soil (pH > 10) but susceptible to water logging. Their otherwise desirability for agroforestry systems due to high potential for livelihoods improvement requires special techniques for planting. For example, pomegranate (*Punica granatum*) trees are unable to tolerate water stagnation. To avoid mortality due to water stagnation during the monsoon the raised and sunken bed technique may be necessary for agroforestry practices on highly alkali soil[109].

Designing a sustainable tree mixture for agroforestry systems is another challenge. In agroforestry differences in functional group composition do have a larger effect on ecosystem processes than does functional group richness alone. Thus, much time and expense need to be invested in finding species or genetic varieties that combine in more diverse agroecosystems to improve total yield[110]. For instance, a five year field experiment of tree mixtures for agroforestry system in tropical alfisol of southern India involving mango (*Mangifera indica*), sapota (*Achrus sapota*), eucalyptus (*Eucalyptus tereticornis*), casuarina (*Casuarina equisetifolia*) and leucaena (*Leucaena leucocephala* found that growth of sapota can be enhanced by 17% when grown in mixture with leucaena. But a reduction of 12% in the growth of mango may occur when co-planted with casuarina or leucaena[111]. Eucalyptus is incompatible with mango and sapota because these species suffer due to Eucalyptus. Furthermore, because many species suffer from root competition and thus selection of tree species with either low root competitiveness or trees with complementary root interaction is of strategic importance in agroforestry systems[112].

With increasing possibility of an emerging market for carbon, fast growing trees may become the norm. The emission of isoprene from fast growing agroforestry species represents a considerable unintended consequence of agroforestry cultivation. Unlike other trees, almost all fast-growing agriforest species, including *Acacia* (tropical), *Eucalyptus* (tropical) and *Populus* (temperate) emit significant quantities of isoprene (2-methyl-1,3-butadiene) affecting the species-dependent ecosystem services. This is a highly reactive hydrocarbon that increases regional ozone pollution and enhances the lifetime of methane. But this challenge may get resolved as a recent study by Rosenstiel et al.[113] confirm experimentally in an intact *Populus* ecosystem that increased CO_2 not only enhance biomass accumulation in a short-rotation agriforest, but also reduce net ecosystem isoprene production. Thus, the negative air-quality impacts due to isoprene emission from growing agriforests may be partially offset by increases in global atmospheric CO_2. But under the ambient CO_2 concentrations the challenge of isoprene remains.

9. The Future

Although numerous issues are involved with the livelihoods improvement, agroforestry systems are one option with multifunctional value. In India and other developing countries the path to sustainable development could be a decentralized planning and implementation of strategies that promote local biomass production in agroforestry systems. Such decentralized systems in India can provide critical inputs for livelihoods improvement and sustainable development. Along with mitigating the climate change agroforestry systems can at least partially meet the energy needs of 1 billion people in India through bioenergy options by a prudent use of agricultural residues and biomass generated in agroforestry systems. Biomass energy-based supply options can create rural wealth and employment necessary for livelihoods improvement and sequester large amount of carbon in a decentralized manner. Such a strategy would also ensure ecological, economic and social well-being. Thus, energy and food self-sufficient taluka (a small administrative unit) can be a new model of rural development in India[114].

Agroforestry options for carbon sequestration are although attractive, as discussed earlier, they presents critical challenges for carbon and cost accounting due to dispersed nature of farmlands and dependence of people on the multiple benefits from agroforestry. Additionally, important concerns regarding monitoring, verification, leakage and the establishment of credible baselines also need to be addressed[30].

Another challenge is incentives that promote tree-growing by rural people. Not everyone is willing to adopt agroforestry. We shall need effective communication strategy to spread the among the people to adopt agroforestry further to supply fuelwood and other products[115,116]. The likelihood of adoption depends on the availability of lands, progressive attitude of farmers, supportive village institutions, their wealth status and their perceived risk concerning agricultural production[117].

In order to use agroforestry systems as an important option for livelihoods improvement, climate change mitigation and sustainable development in India, research, policy and practice will have to progress towards: (i) effective communication with people in order to enhance the agroforestry practices with primacy to multifunctional values; (ii) maintenance of the traditional agroforestry systems and strategic creation of new systems; (iii) enhancing the size and diversity of agroforestry systems by selectively growing trees more useful for livelihoods improvement; (iv) designing context-specific silvicultural and farming systems to optimize food production, carbon sequestration, biodiversity conservation; (v) maintaining a continuous cycle of regeneration-harvest-regeneration as well as locking the wood in non-emitting uses such as woodcarving and durable furniture; (vi) participatory domestication of useful fruit tree species currently growing in the wilderness to provide more options for livelihoods improvement; and (vii) strengthening the markets for non-timber forest products. Prevalence of agroforestry systems in India offers opportunity worth consideration not only for carbon sequestration but also for livelihoods improvement, biodiversity conservation, soil fertility enhancement, and poverty reduction.

Table 1: Diversity of tree management practices in Indian agroecosystems and cultural landscapes

Practices	Examples	Average range of area (ha)
Sacred and sanctified Landscapes	Temple forests	5-10 ha.
	Sacred Corridors	10-200 ha. (1-2 km. long
	Sacred Groves	0.1 to 70 ha.
	Sacred Trees/Taboo trees	Isolated and sanctified trees
	Ethnoforestry Refugia	1-5 ha. (modern variants)
	Keshar-chhanta (saffron-sprinkled and sanctified) forests	50-500 ha. large forests
	Panchwati (tree grove)	0.1-0.5 ha.
Family and Village Forests	Rari (Village Woodlots)	20-150 ha.
	Family Farm Groves	0.5-1 ha.
	Charnot (wooded grazing lands)	1-50 ha.
	Kankad (village boundary forests)	2-5 ha. Strips
	Rundh (closed royal woodlands)	10-500 ha.
	Baugh (silvi-horti-gardens)	5-50 ha.
	Home gardens/dooryard garden	0.01 ha. 0.5 ha.
	Inhabited village groves	5-40 ha.
	Lakheta (wooded islands amidst traditional village ponds)	A grove of 10 to 50 trees
	Beed/Bir (traditional woodlot)	5-200 ha.
Agroforests	Variety of forms	Extreme variation in area

Table 2: Regional examples of soil fertility enhancement in multifunctional agroforestry systems in India

No.	Region	Challenge	Changes observed due to agroforestry
1.	Himalayas (Kurukshetra)[118]	Improvement of sodic soils	Increase in microbial biomass, tree biomass and soil carbon; enhanced nitrogen availability
2.	Himalayas[33]	Restoration of abandoned agricultural sites	Biomass accumulation (3.9 t ha^{-1} in agroforests as compared to 1.1 t ha^{-1} in degraded forests); improvement in soil physico-chemical characteristics; carbon sequestration
3.	Western Himalayas[119]	Reducing soil and water loss in agroecosystems in steep slopes	Contour tree-rows (hedgerows) reduced runoff and soil loss by 40% and 48% respectively (In comparision to 347 mm runoff, 39 Mg ha^{-1} soil loss per year under 1000 mm rainfall conditions)
4.	Sikkim Himalaya[120,121]	Enhancing the litter production and soil nutrient dynamics	Nitrogen-fixing trees increased N and P cycling through increased production of litter and influenced greater release of N and P; nitrogen-fixing species helped in maintenance of soil organic matter, with higher N mineralization rates in agroforestry systems
5.	Indo-Gangetic plains (UP)[122]	Biomass production and nutrient dynamics in nutrient deficient and toxic soils	Biomass production (49 t ha^{-1}/decade)
6.	Himalayas (Meghalaya)[123]	Enhancing tree survival and crop yield	Crop yield did not decrease in proximity to *Albizzia* trees
7.	Western India (Karnal)[124]	Improvement of soil fertility of moderately alkaline soils	Microbial biomass C which was low in rice-berseem crop (96.14 gg^{-1} soil) increased in soils under tree plantation (109.12 gg^{-1} soil); soil carbon increased by 11-52% due to integration of trees and crops
8.	Western India (Rajasthan)[125]	Compatibility of trees and crops	Density of 417 trees per ha was found ideal for cropping with pulses
9.	Central India (Raipur)[126]	Biomass production in N & P-stressed soils	*Azadirachta indica* trees were found to produce biomass in depleted soils.
10.	Central India[127]	Soil improvement	Decline in proportion of soil sand particles; increase in soil organic C, N, P and mineral N
11.	Southern India (Hyderabad)[128]	Optimality of fertilizer use	
12.	Southern India (Kerala)[129]	Growing commercial crops and trees	Ginger in interspaces of *Ailanthus triphysa* (2500 trees ha^{-1}) helps in getting better rhizome development of ginger, compared to solo cropping

Table 3: Income from agroforestry systems in Indian Himalayas

No	Typology of tree-growing practice	Income (ha^{-1} yr^{-1})*
1	Home gardens	Rs. 18,200
2	Simultaneous agroforestry	Rs. 25,370
3	Sequential agroforestry	Rs. 9426

Source: Nautiyal et al.[130]
* Rs. 35 equaled to US$1 at the time of study

Table 4: Unresolved challenges for future research on agroforestry in India

1. Crop yields: Increase or decrease?	Although some traditional agroforestry systems do increase crops yields near trees, there are instances where fast growing trees have reduced crop yields in the short-term. Long-term studies are required to resolve this issue.
2. Nutrients: additional supply or redistribution?	Mature and scattered agroforestry trees are associated with improved soil nutrient supply in traditional agroforestry systems, it is not known if trees additionally supply nutrients by increasing the total quantum of nutrients in agroecosystems or just redistribute the available quantity horizontally and vertically.
3. Water-Tree interaction: high water uptake or no change?	High water use by fast-growing species and therefore alleged groundwater depletion is a common concern in dry regions that remains unresolved. Do trees actually extract more groundwater or use the residual water available either through irrigation, or use the rainwater when crops have been harvested? It may be possible that rather than letting the rains be lost as runoff, agroforestry may increase the utilization of rainwater by extending the growing season. Furthermore, it is not clearly understood if trees harvest and accumulate water from surrounding area and release it during the soil-moisture stress. If this is so then, agroforestry as an adaptation to monsoon variability may actually benefit the crops.
4. Carbon sequestration in biomass and soils	Studies on the carbon sequestration potential are limited both by their location-specificity as well as uncertainty related to sequestration in biomass and soils. Often, the rate of carbon sequestration is derived from the growth of above ground biomass. Holistic insights are required on the carbon sequestration by agroforestry systems.
5. Soil amelioration and conservation	Agroforestry systems with mature trees capable of yielding enough litter are known to conserve soils and ameliorate soil nutrient status, but knowledge on the full range of species and their attributes useful for all the agro-climatic regions and problem-soils in India are required.
6. Genetically improved trees	Genetically improved trees may provide more biomass and other products valued by the society, but presently research results in this field mostly remain in the laboratory. A full mechanism starting from developing and registration of clones, decentralized certification, and mass multiplication of suitable stock to ensure availability to farmers is required.
7. Multiple-use species adapted to multiple agro-climatic conditions	Multiple-use species with a wide range of geographic and climatic adaptation can enhance the success and spread of agroforestry. This is a crucial area of research involving multi-location research in all the climatic regions in India.
8. Domestication of useful species	Many wild populations of species that yield commercially-valued products are getting depleted, research efforts are required to domesticate these species and integrate with the agroforestry systems in India.
9. Policies to promote linkages between markets and tree-growing in agroecosystems	On the one hand smallholder systems in India supply about 50% of wood and fuelwood demand, on the other here are still many restrictive regulations that potentially deter farmers from growing trees in agroecosystems and selling these in markets.
10. Value addition	Non-timber forest products have the potential to improve livelihoods of poor farmers, but efforts are needed to provide knowledge on the on-farm value addition innovation.

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