Role of agroforestry in achieving food and nutritional security, climate change mitigation and environmental resilience: a review

HTJ Seneviratne
Environmental Studies and Services Division, NBRO

VDW Sumanasekara
Environmental Studies and Services Division, NBRO

DMMR Dissanayake
Environmental Studies and Services Division, NBRO

ABSTRACT: Against the backdrop of rapid acceleration of changing land uses, increasing climate uncertainties, variabilities and extremes, it is necessary to focus more on environmental sustainability while combating the food and nutritional insecurities. To achieve environmental sustainability, food and nutritional insecurities while successfully mitigating impacts of climate change, it is necessary to revoke the long neglected crucial role of the plants rather than highly domesticated crop varieties. More than 1.2 million people practice agroforestry worldwide by integrating plants with annual crop cultivation, livestock production and other farm activities ranging from close imitation of tropical rain forests with dense tree cover to polycultures with only few plant species. Climate stability, reduction of biodiversity loss and restoration and maintenance of above ground and below ground biomass and biodiversity, creation of biological corridors between protected forest fragments, safeguarding ecosystem services, regulation of biogeochemical cycles including water, maintenance of watershed hydrology, soil conservation, reduction of pressure on natural forests, contribute to food security and range of environmental benefits, provision of products and social co benefits such as increased income. However, numerous challenges strongly impede achieving optimal benefits from agroforestry. However, with the application of suitable solutions these challenges can be faced successfully.

1 INTRODUCTION

Currently practiced by 1.2 million people worldwide, agroforestry is defined as a collective name for land use systems and technologies where woody perennials are deliberately used on same land management units as agricultural crops and /or animals in some form of spatial arrangement or temporal sequence (Leakey, 2010; Lundgren and Raintree, 1982). Many agroforestry systems in the world integrate various intensities of traditional agricultural practices in combination with modern assessable low-cost technologies and know-how. These sub categories include agro-silviculture (growing trees with crops), agrosilvopastrure (growing trees with pasture), agro-horticulture, shifting cultivation and home gardens which manage trees, crops and animals (Lundgren and Raintree, 1982; Nair, 1993). The trees used in agroforestry are utilized mainly as fuelwood, and for timber, fodder, shade, windbreak, fruits, shelter, medicine, soil improvement, supports for climber crops, and other ecological services. (Bélair, 2010; Nair, 1998; Richard, 2013).

Agroforestry systems with its promotion of positive ecological interactions between species and management options with limited environmental losses, aim to provide an array of environmental, social and economical benefits to the communities. Agroforestry systems provide the income to the practitioner, improve soil fertility, enhance the local climate conditions, and reduces the anthropogenic pressure on the soil and biodiversity. Most of these benefits; ecosystem services are direct benefits while others such as Carbon sequestration, micro-climate modification, etc. contribute to mitigate global issues such as climate change.

Low income countries rely on agriculture as the main income source. However, in developing countries the agriculture is adversely affecting the food production due to reduced productivity resulted by severe land degradation, climate change, etc. Most of the countries focuses on reforestation and forest protection initiatives to mitigate climate change and these efforts are conflicting with the requirement of expanding the agricultural production to feed the growing population (Mbow et al, 2014 b). Sustainable intensification of agriculture through agroforestry by integrating trees into intensive agricultural land uses underlies the importance of achieving sustainable agricultural and biodiversity conversational goals simultaneously.

This paper investigates the potential of using agroforestry to provide financial assets for farmers, combined with opportunities for climate change mitigation, to promote sustainable agricultural

production by increasing biodiversity and environmental resilience by critically reviewing recent scientific findings.

2 ACHIEVING FOOD AND NUTRITIONAL SECURITY

Reaching food and nutritional security requires a range of interconnected approaches from increasing the crop yield and soil fertility, bio-fortification of staple foods to cultivating wide range of plants which provide edible fruits, vegetables, nuts and diversify the diets of the people (Jamnadaas et al, 2013). However, farming communities around the world use more exotic crop varieties and lesser indigenous varieties which are often richer in nutrients, fiber and protein sources than the conventional staple crops. These indigenous verities have been harvested from forests by local communities as NTFPs (Non Timber Forest Products). However, the use of these food sources are threatened due to rising deforestation and fragmentation of forests.

Average fruit consumption is often less than the minimum recommended daily intake (400g per person) in most developing countries as they strongly focus on purchasing cheap sources of staple foods to meet their basic energy requirements as the family budgets limits the purchase of more nutritious food products. However, expenditure analysis have indicated the increase of nutritious food purchase with the increase of household income. Hence, the agroforestry can help attain both increase of income and the provision of direct access to edible nutritious products for the households (Bélair, 2010; Jamnadaas et al, 2013; Nair, 1998).

Also relying on the income received from a single commodity crop leads to food insecurity as the payments will be one-off, delayed or unpredictable (Jamnadaas et al, 2013). On the other hand, agroforestry systems with multiple crops will help to avoid risks of food insecurities as they provide not only variety of tree commodities but also local food trees, vegetables and even edible fungi and mostly profits gained are superior than monoculture systems (Kumar, 2006; Pushpakumara et al, 2012). Such systems are even encouraged by international markets through certification systems.

Fuelwood and charcoal also plays a significant role in the food and nutritional security as they produce energy and generate high income in spite of introduction of modern energy sources. Often low income families are forced to use low quality fuelwood or traditionally avoided wood species. It is also noted that agroforestry practitioners spent less on fuelwood, rely less on natural fuelwood sources, and they require less time for fuelwood collection. Adequate access to cooking fuel will make people more flexible in their diets preferably better nutritional foods which require more energy to prepare (Bélair, 2010; Jamnadaas et al, 2013).

3 ENHANCING AGRICULTURAL PERFORMANCE

Although, the primary crop is grown under relatively intensive form, agroforestry systems are highly structural complex entities. Hence, agroforestry has the potential to improve soil quality by increasing Soil Organic Matter, altering soil structure and biological Nitrogen fixation using leguminous species, etc. (Mbow et al, 2014 b). It was found that subjected to soil type and technology used, average yields of maize in Africa have increased by planting of N Nitrogen fixing plants, (Jamnadaas et al, 2013). In addition, plant species integrated in the agroforestry systems provide shade and support to the staple food crops, occupation and creation of complementary niches and interconnections among them.

Nitrogen cycle of the agroforestry land uses is much effective than the monocultural land uses (Kumar, 2006; Mbow et al, 2014 b). N mineralization potential was observed to be higher in agricultural systems which had windbreakers and also in tree based intercropping systems compared to other conventional agricultural systems. (Richard, 2013). Intercropped trees enhance soil nutrient pools such as extractable Phosphorus, total Nitrogen and mineralizable Nitrogen in agroforestry systems (Rivest et al, 2013). The trees are also an effective trap for atmospheric dust and they are act as focal points for attracting soil micro and macro fauna, further contributing to the enhanced local nutrient cycle. With these positive interactions and processes in nutrient cycle, need of inorganic fertilizer may be reduced in agroforestry systems.

Use of legumes as fertilizer trees have provided about 50-200 kg N ha^{-1} N inputs to the associated crops with a yield increase of 2-3 times and the planting of those species can be a tradeoff between natural diversification and nutrient input independent management (Garitty, 2004; Tscharntke et al, 2011). In southern Africa, the incorporation of Nitrogen fixers in cultivations have stabilize the crop production in drought periods while improving the efficiency of rainwater usage whereas monocultures reduce resilience to extreme climate conditions and outbreaks of pest and

diseases (Jamnadaas et al, 2013, Oxfam International, 2011, Rivest et al, 2013). As the African continent is subjected to climate change induced extreme climate events agroforestry will aid in achieving food security.

Staple crops yields will significantly benefit from the agroforestry as it support the regeneration of natural tree and shrub communities. In Sahel region alone, farmer managed natural regeneration has improved sorghum and millet yields coupled with a positive relationship observed between dietary diversity and household income. In Niger, encouragement of leguminous trees on dryland agroforests have has led to re-greening of about 5 million hectares (Jamnadaas et al, 2013). But planting monocultures will result in displacing natural forests with rich sources of nutritious edibles to farmlands.

Most of crop species have shallow root activity whereas the non-crop trees such as citrus, mango, etc. have deep sub-soil activity. And their deeper interlocking roots act as safety nets which minimize nutrient leaching and also as nutrient pumps drawing nutrients from deep horizons by scavenging nutrients that have leached below the agricultural crop rooting zone (Kumar, 2006; Rivest et al, 2013; Tscharntke et al, 2011).

Non-crop shade trees also protect soil from adverse insolation, maintain Soil Organic Matter, reduce evaporation from soil, retain soil productivity, protect soil against rain drop impact, reduce runoff velocity by increasing the surface roughness and increase water infiltration by provision of litter layers and root systems which create channels on soil. High moisture levels in soil benefit soil biota and the increase decomposition process of Soil Organic Matter. Crop tree and shade tree combination of leaf litter positively affects the decomposer community structure, litter decay and associated nutrient fluxes to the soil (Kumar, 2006; Rivest, 2013; Tscharntke et al, 2011).

Microbial biomass is also observed to be higher in agricultural systems with tree based intercropping systems compared to other conventional agricultural systems (Richard et al, 2013). It has also been observed that agroforestry systems strongly alter composition of soil microbial communities due to their strong correlation with physiochemical properties of soil as they show diverse microbial and mycorrhizal communities (Fialho, 2013; Richard et al, 2013). Rivest et al (2013) provided data suggesting that soil microbial communities from man-made ecosystems with higher plant diversity are more metabolically efficient compared to others in monoculture systems and this may benefit the crop productivity.

Agroforestry systems also increase the quantity and diversity of plant residuals and rhizodepositional products due to additional deposition of tree leaves and fine roots with lower decomposition rates than the crop residues. (Richard et al, 2013; Rivest et al, 2013). Leaf litter from crop and shade tree combination increase the stability of the decomposing microbes and other microbial communities acting as critical links in Nitrogen and Phosphorus cycles. One study has observed higher rates in Nitrogen mineralization, ammonium uptake and faster turnover rate of the ammonium pool in cacao agroforestry systems compared to adjacent monoculture cultivations in Indonesia (Tscharntke et al, 2011). It is an indication of a higher Nitrogen availability in agroforestry systems.

4 CLIMATE CHANGE MITIGATION AND ADAPTATION

Agroforestry plays a significant role in two key dimensions of climate change; mitigation of greenhouse gas emissions and adoption to changing environmental conditions (Garrity, 2004; Morgan et al, 2010; Schoeneberger, 2005).

Mitigation of the adverse climate change impacts lies in the potential in soil carbon restoration and avoidance of net soil carbon emission. Global estimate potential of all Green House Gas sequestration in agricultural sector ranges from \$1500 – 4300 mt $CO_2e\ yr^{-1}$ and 70% is from the developing countries. Intergovernmental Panel for Climate Change have recognized the high potential of agroforestry in Carbon sequestration and it can be increased up to 90-150 tonnes C per ha over a potential area of 900 million ha (Garrity, 2004; Leakey, 2010; Verchot et al, 2005).

There is an immense potential for combating climate change in developing countries by building resilient agroecosystems which actively sequest carbon (Kumar, 2006; Mbow et al, 2014 b, Oxfam International, 2011; Schoeneberger et al 2012). Agroforestry systems have 3-4 times biomass than traditional treeless agricultural systems as Carbon stocks of agroforestry systems ranges from 29-228 Mg C /ha with a median of 95 Mg C /ha. (Matocha et al, 2012; Mbow et al, 2014 b). Potential for carbon sequestration of agroforestry is substantially high, as land areas suitable for agroforestry systems are high. In Africa alone the third largest Carbon sink is agroforestry eco system, after primary forests and long term fallows (Mbow et al, 2014 b). However, methods of Carbon sequestration estimation vary from simple in-situ measurements to application of different assumptions. Carbon

stocks and sequestration vary widely in different systems in different regions. Integrated land use practices such as agrosilvopastoral systems combines high Carbon stocks and high Carbon sequestration potentials (Mbow et al, 2014 b).

Based on the ecological theory of niche differentiation, different species tend obtain resources differently to reduce the competition for limited resources such as water. Accordingly, deep root systems of the non-crop trees are able to spread in a larger soil volume which will aid in exploration of water and nutrients during droughts. Due to this complementaries in resource capture, they are able to access soil nutrients and water unavailable to crops and also nutrients leached from crop rhizosphere. In addition, increased soil porosity, reduced runoff and increased soil cover increase the water infiltration and retention of water in the soil. This will significantly reduce moisture stress during low rainfall seasons (Richard, 2013). Application of Nitrogen fertilizer temporary increase availability of mineral Nitrogen concentrations in soil for nitrifying and denitrifying microbes. And this leads to increased non CO_2 Green House Gases; N_2O emissions. However, the agroforestry systems which uses legumes for their Nitrogen inputs has lesser N_2O emissions.

It was also noted that the financial cost of Carbon sequestration through agroforestry approximately range between $ 1 - 69/ Mg of C, which is appears to be much lower than other options (Verchot et al, 2005). Furthermore, agroforestry systems significantly reduce the pressure on natural forests for energy needs. Agroforestry used as a tool for sustainable fuelwood can contribute to energy substitution and important carbon offset option. Doubling the renewable energy in the global mix is also possible by increasing the energy efficiency in agriculture, even without allocating more lands for producing bioenergy (Mbow et al, 2014 a; Morgan et al, 2010; Schoeneberger et al 2012; Verchot et al, 2005).

Scientific data have demonstrated that the reduction of vegetation cover increases the rainfall decline (Mbow et al, 2014 b) also managing tree cover is also important as it directly influence the local and regional rainfall patterns. And large scale deforestration causes warmer and drier climates which leads to the reduction of cloud formation and upward shift of cloud condensation layers. Less rainfall coupled with less predictability of rainfall induce shorter farming seasons specially for farms functioning without irrigation systems. Extreme weather events cause crop destruction and damage. Impacts of the climate change not only affect rain-fed cultivations but also affect water availability which induce increased stress upon irrigational water sources. Since the available water quantity will be limited, the competition for water uses will be intensified further stressing the farming systems, specially the subsistence farmers (Richard, 2013). Hence, alternative farming systems which are less vulnerable to climate change impacts are necessary. Thus, agroforestry is increasingly considered as an effective mean of maintaining and increasing crop productivity under climate change (Rivest et al, 2013).

However, practices such as pasture maintenance by burning, use of agrochemicals, etc. involve raising Green House Gas emissions hence it is necessary to optimize agroforestry through more integrated management in order to maximize benefits and minimize negative impacts. Also, a better understating by assessing the benefits beyond the symbolic value of Carbon sequestration reached through the capacity of agroforestry for both Carbon stock and revenue generation. Additionally, farmers' needs should be highlighted as the highest priority and avoiding the clash between exclusive climate-oriented perspectives and other social benefits (Mbow et al, 2014 a).

5 ROLE IN ENVIRONMENT RESILIENCE

Resilience is reduction of sensitivity to stresses and disturbances while maintaining its capacity (Jacobi et al, 2013). Agroforestry can play a pivotal role in improving the resilience to uncertain climatic hazards through microclimate buffering and regulating and purification of water flows. Land management practices of agroforestry includes crop diversification, long rotation systems for soil conservation, home gardens, boundary planting, perennial cropping, hedgerow intercropping, live fences, improved fallows, mixed strata cropping, etc. (Mbow et al, 2014 b). In addition, management options reducing below-ground competition for water influence plants to tap deep ground water sources rather than utilizing top soil moisture. Hence, the top soil microfauna are encouraged. Such microclimate control coupled with other numerous ecosystem functions aid in conserving biodiversity through mitigating non-point pollution, reducing soil erosion, protecting wildlife habitats, etc. This facilitates the flexible responses to rapid shifts in ecological conditions, maintaining and restoring both biotic and abiotic natural resources.

In a study conducted in Canada, it was found that microbial communities of agroforestry systems showed significantly higher resilience to severe

water stress conditions than other conventional systems (Rivest et al, 2013). However, agroforestry preferentially enhance microbial resilience in heavier textured soils with higher clay content as soils with higher clay may provide a better structured profile resulting more diverse microsite conditions which accommodate wide range of niches (Fialho, 2013; Rivest et al, 2013). Microbial community diversity plays a significant role in soil microbial resilience after a periodic disturbance of chronic stress such as soil drying. Further, this ability of microbial communities to recover following a disturbance may also have important consequences for maintaining ecosystem functions and services (Richard, 2013).

Improvement of microclimate also affects crop performance as it acts as a buffer to climatic extremes which impact crop growth. The shading provided by extra trees buffer crops from large temperature fluctuations and hence keep crops closer to optimal conditions. The scattered plant cover enhance the development of undergrowth by reduction of incident solar radiation, air, soil temperature, improved water status of soil and increased humidity (Lin, 2011; Mbow et al, 2014 b, Tscharntke et al, 2011). It has been observed that increased canopy cover from shade trees has enhance eater uptake and increase of crop stem diameter and leaf area of cacao/ gliricedia agroforest systems in Sulawesi, Indonesia. Similar enhanced vegetative growth was observed in Ghana (Tscharntke et al, 2011).

In addition, with higher plant diversity in spatial and temporal distribution of crops, agroforestry systems mimic natural ecosystems and harbor high levels of biodiversity, specially the increase in functionally important taxa such as insectivorous birds, seed dispersing birds, pollinators, and amphibians providing biocontrol services (Lin, 2011). Findings of the recent case studies suggest high levels of species diversity facilitates a higher overall ecosystem resilience in agroforestry systems (Bélair, 2010; Steffan-Dewenter et al, 2007). Kandyan home gardens in Sri Lanka, typically found in sloping mid-altitudinal areas is an agroforestry system which maintain the unique agricultural biodiversity of the island and enhance ecological integrity of important catchment areas contributing to water quality (Bélair, 2010).

Agroforestry systems can also be considered as important buffer zones around reserves reducing edge effects and increasing connectivity among forests. It has also revealed that the shaded cacao agroforestry suffers less in terms of insect and pest problems and the diseases has significantly reduced levels under the natural shade grown conditions compared to monocultures (Tscharntke et al, 2011).

Trees are also identified as stored capital and these tree banks greatly reduce the vulnerability not only to environmental shocks but also economic and social shocks as well. Income from the shade trees and other intercrops have average 7% of the total revenue in cacao agroforestry systems in Central Sulaweai, Indonesia and reached up to 60% in other agroforestry systems. And in Peru, coffee growing small holder farmers derive 28% from shade trees (Tscharntke et al, 2011). Multipurpose trees in integrated approach enhance the benefits reap by agroforestry. For example sources of fodder can be converted to valuable products, wild edible fruits and other Non Timber Forest Products can serve as alternative food and income sources to local communities during non-harvesting periods.

6 OVERCOMING CHALLENGES

Beneficial effects are not universal and certain practices may predominate negative or neutral effects and the performance of agroforestry systems depends on relative influence of tree species selection and management, soil characteristics, topography, rainfall, agricultural practices, priority for food security, economic and social development options, etc. (Kumar, 2006; Mbow et al, 2014 b).

Firstly, to achieve desired social and environmental benefits designing the right agroforestry system by selecting the most suitable plants and management practices is a must. (Mbow et al, 2014 a). Selection of species must carefully done in response to local priorities and biophysical conditions (Mbow et al, 2014 a). Even though, the shade trees are competitors for water use, some studies have shown that by understanding the different root attributes of intercropped trees such as contrasting spatial rooting pattern, root morphology and mycorrizal status it is possible to achieve optimal use of complementary resources such as water (Tscharntke et al, 2011). For an example, use of a combination of deep rooted and shallow rooted species in agroforestry systems can improve the efficient use of soil water and nutrients. Not only the appropriate crops and trees, favorable sites, suitable management practices, it is also important to integrate those practices into local livelihood systems and communities as they act as initiators of the transformative change in land use.

As agroforestry takes relatively longer period to realize benefits than other conventional agricultural systems, farmer involvement should be

stimulated by the assuring land security and tree tenure. Land should be recognized as a common benefit while applying community inclusive stewardship principles. Continuous low returns may negatively affect the capability of farmers to improve their optimal management systems (Jamnadaas et al, 2013; Mbow et al, 2014 a; Ofori et al, 2014; Place et al, 2012). Hence, improving micro-credit at local level, appropriate and adequate financing at grass-root level and promotion of agroforestry as a potential and profitable investment is also crucial. To meet the desired address social and economic barriers, uphold social conditions such as gender synergies, development of more coordinated, structured and fair market systems with collective bargaining for both inputs and outputs of agroforestry, better transport infrastructure, involvement of lesser intermediaries in the supply chain, better investment in characterization of tree foods, provision of incentives from payment for eco system services and certification schemes should be adopted (Garitty, 2004; Leakey, 2010; Jamnadaas et al, 2013; Tscharntke et al, 2011). In addition, management of the demand side aspects such as change in diet specially in the growing urban population percentage, should also considered seriously (Mbow et al, 2014 b).

Another major challenge is to scale up successful tree domestication approaches (Ofori et al, 2014). Improving the knowledge beneficial traits of the existing indigenous plants used in agroforestry and development of new cultivars from those indigenous species, availability and ample access to high quality planting material and the safe trans-boundary transport of superior cultivars developed in different parts of the world are also important.

Furthermore, the small holder farmers play an undeniable role in the agriculture sector. In South Asia about 80% agricultural lands are less than 0.6 ha in extent (Kumar, 2006). Failure to extend advance agricultural methods hinders the small holder farmers in developing countries in achieving optimal benefits in agroforestry. Apart from the innovative limitations, small holder farmers suffers structural limitations due to the limited investment opportunities available compared to other conventional agricultural practices such as monocultures of cash crops. In general, profitability can be increased through improving and diversification of output per unit area of tree/crop/livestock and by addition of new products to enhance the financial diversity and flexibility. Hence, attention of scientific community should relate to methods and tools appropriate to gain maximum benefits from agroforestry in various human and ecological settings. Also, scientific knowledge should be translated to decision makers and the policy developers and implementers should abandon the conservative segregation of environment, agriculture and other related sectors as separate domains and embrace the need of a holistic approach to manage all the aspects under one system.

Since most ecological and economic studies are conducted separately the information is difficult to be linked and it is challenging to estimate real time financial benefits, extent and trends of agroforestry, as government inventories do not include those (Morgan et al, 2010). Even Food and Agricultural Organisation's Global Forest Assessment do not recognize agroforestry as a land use as it is categorized as agriculture or as a forest. However, available information hints the percentage of agroforestry is increasing many parts of the world (Mbow et al, 2014 a). The growing appreciation in developed countries will enhance understanding and support for its expansion in the developing countries ensuring the needed investments (Garrity, 2004).

7 CONCLUSION

Agroforestry is a provider of crucial benefits such as; food and nutritional security, enhanced agricultural productivity, mitigation of climate change impacts and resilience of environmental functions. Hence, global focus on the use of agroforestry as a tool to achieve those objectives should be increased and refined due to its ample positive social and environmental benefits. However, multifaceted analysis is needed to scrutinize in a context where basic local needs are prioritized to identify optimal management practices by giving equal opportunities to both social and environmental benefits.

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