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Potential of agroforestry systems in carbon sequestration in India

S K DHYANI[1], ASHA RAM[2] and INDER DEV[3]

ICAR–Central Agroforestry Research Institute, Jhansi, Uttar Pradesh 284 003

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ABSTRACT

Various institutions are working for lowering the CO_2 concentration through different strategies like reduction in energy use, developing low or no-carbon fuel technologies, CO_2 sequestration by forestry/agroforestry and engineering techniques. Among all the techniques, agroforestry was recognized as one of the important means to reduce CO_2 emissions as well as enhancing carbon sinks. Agroforestry provides unique opportunity to combine the twin objectives of climate change adaptation and mitigation. In India, area under agroforestry was estimated at 25.3 m ha, which can further be increased up to a considerable level. Recent studies under various agroforestry systems in diverse ecological conditions emphasized that agroforestry systems increase and store carbon stocks in above ground biomass and in soil and also has an important role in increasing livelihood security and reducing vulnerability to climate change. In India carbon sequestration potential of agroforestry systems is estimated between 0.25 – 19.14 and 0.01 to 0.60 Mg C/ha/yr for tree and crop component, respectively. The contribution of agroforestry in soil carbon sequestration varied between 0.003 to 3.98 Mg C/ha/yr. The total C sequestered in each component differs greatly depending on region, types of -species, -system, -site quality, and previous land-use. The review indicates that agroforestry systems in addition to accumulate and sequester carbon, provide an excellent opportunity to increase the tree cover to a level of 33% of the total geographical area of the country as desired by the National Forest Policy.

Key words: Aboveground biomass, Carbon stocks, Cropping system, Global warming, Mitigation

Global warming is the increase in average temperature of the earth‘s surrounding air and ocean, which is believed to be caused mainly by the increase in atmospheric concentrations of the so-called greenhouse gases (GHGs). According to the IPCC (2007), these GHG emissions could rise by 25 – 90% by 2030 relative to 2000 and the earth could warm by 3 °C at the end of this century. Even with a temperature rise of 1– 2.5 °C, the IPCC predict serious disastrous effects, including reduction in crop yields in tropical and subtropical areas leading to increased risk of food shortage, spread of climate responsive diseases such as malaria, and an increased risk of extinction of 20 – 30% of all biodiversity present on earth. Since the pre-industrial era, anthropogenic GHG emissions have driven large increases in concentrations of CO_2, CH_4 and N_2O in the atmosphere. Between 1750 and 2011, cumulative anthropogenic CO_2 emissions to the atmosphere were 2040 ± 310 Gt CO_2 and out of these emissions, about 40% remained in the atmosphere (880 ± 35 Gt CO_2); the rest were stored on land (in plants and soils) and in the ocean. About 50% of CO_2 emission between 1750 and 2011 occurred in the last 40 years (IPCC 2014). Oceans are the major sink for CO_2 removed from the atmosphere, causing acidification of ocean. Increased temperature and CO_2 in the atmosphere is a greater challenge for the human race and it is observed that the world's poor and developing countries will bear the heaviest burden of the climate change, which will lead to designation of new type of refugee – climate change/environmental refugees – that will potentially number in the tens of millions (United Nations 2007). Indian agriculture is highly prone to the risks due to climate change, especially to drought, because $2/3^{rd}$ of the agricultural land in India is rainfed and even the irrigated system is dependent on monsoon (Pathak *et al*. 2015). Further, over the course of this century, millions of people living in the catchment areas of the Himalayas will face increased risk of floods as glaciers retreat followed by drought. In recent times, climate changes have shown significant impact on glacial ecology in high-mountain regions. From 14 to 17 June 2013, the Indian state of Uttarakhand and adjoining areas received about 375% more than the average rainfall during a normal monsoon. This caused the melting of Chorabari glacier, and upsurge of the Mandakini river, which led to heavy floods near Gobindghat, Kedar Dome, Rudraprayag district of Uttarakhand. There were reports of loss of large number of human lives and damage to the property, natural resources and livestock (Dobhal *et al*. 2013). During September 6-7, 2014, the Jhelum river was at highest inundation levels in the archived hydrological history of Jammu and Kashmir (India) with vast areas in Kashmir province inundated, many

[1]Former Director (e mail: shivkdhyani@gmail.com),[2]Scientist (Agronomy) (e mail: ashusirvi84@gmail.com), [3]Principal Scientist (Agronomy) (e mail: drinderdev@gmail.com).

of low lying areas remained under floodwater for about four weeks (Tabish and Nabil 2015). The Centre for Science and Environment (India) analysis showed that the floods in Kashmir during 2014 were a manifestation of an extreme weather events linked to changing climate (www.thehindu.com). Furthermore, the climate change will cause melting of glaciers leading to rise in sea level, inundation of some coastal areas and islands.

Among all GHGs, CO_2 is a major GHG; between 2000 and 2011; atmospheric concentration of CO_2 has increased from 369 to 391.5 ppm (Conway and Tans 2012). CO_2 emissions from industrial processes and fossil fuel combustion contributed about 78% of the total GHG emission. India's emissions are estimated to be of the order of 1331.6 mt of the CO_2 equivalent GHG emissions in 2007. These emissions indicated an annual growth of 4.2% from the levels observed in 1994. Although India's CO_2 emissions are only about 4% of total global CO_2 emissions, but still India has been conscious of the global challenge of climate change. The Government of India has declared domestic mitigation goal of reducing 20-25% of emissions intensity of Gross Domestic Product (GDP) by 2020 in comparison with 2005 level. There are multiple scenarios with a range of technological and behavioral options having different characteristics and implications for sustainable development, which are consistent with different levels of mitigation. However, sequestering CO_2 from point sources or atmosphere through natural techniques (afforestation, reforestation, natural regeneration of forests and the adaptive agriculture) is more economically and ecologically sound in increasing the C storage capacity of the terrestrial ecosystems. On 30 June, 2008 the Government of India released India's first National Action Plan on Climate Change (NAPCC) to address the climate mitigation and adaptation through existing and future policies and programs. This plan identifies eight core "national missions". There are six national missions, which have direct influence on agriculture selected under the NAPCC due to various objectives in relation to agriculture including agroforestry. Agroforestry has the potential to mitigate the climate change effects through microclimate moderation and conservation of natural resources in the short run and through sequestration of carbon in the long run, which is far greater than the crop and grass systems. The role of agroforestry in stabilizing the CO_2 levels and increasing the C sink potential has attracted considerable attention, especially after the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). Agroforestry has an important role in reducing vulnerability, enhancing resilience of farming systems and buffering households against climate related risks (Dhyani 2014). At present agroforestry meets almost half of the demand of fuelwood, two thirds of the small timber, 70–80% wood for plywood, 60% of raw material for paper pulp and 9–11% of the green fodder requirement of livestock, in addition to its environmental benefits (NRCAF 2013). India has announced the landmark National Agroforestry Policy 2014 that will mainstream the growing of trees on farms to meet a wide range of developmental and environmental goals (Dhyani 2014).

India recently submitted voluntary pledges for climate change action in the form of the Intended Nationally Determined Contributions (INDCs) to the United Nations Framework Convention on Climate Change (UNFCCC). India's INDCs target a 33-35% reduction of emission intensity of its GDP by 2030 from 2005 levels through creation of additional carbon sink of 2.5 to 3 billion tonnes of carbon dioxide equivalent through afforestation and increase in share of non-fossil fuel energy in power generation up to 40% of the total installed power capacity by 2030 (http://unfccc.int/focus/indc_portal/items/8766.php). This review focuses the attention of the policy makers and researchers that agroforestry is likely to play pivotal role in increasing the area under tree cover as well as mitigating effect of changing climate and providing renewable energy through biofuel and bioenergy.

Agroforestry v/s carbon sequestration

The actual aim of farmers and government institutions behind agroforestry was improving rural livelihood and meeting various needs, viz. food, fuel, timber, fodder of the farmers. But in recent era of climate change, agroforestry became economically and ecologically very attractive tool for mitigating harmful effect of GHGs. Since, the Kyoto Protocol allowed industrialized countries with a GHG reduction commitment so as to invest in mitigation projects in the developing and least developed countries under the Clean Development Mechanism (CDM) and there is an attractive opportunity for major practitioners of agroforestry, especially the resource poor farmers (Nair *et al*. 2009). IPCC (2007) also indicated in its special report that the conversion of wasteland and grassland to agroforestry has the best potential to soak up atmospheric CO_2 other than direct benefits. Since CO_2 is the major greenhouse gas, representing 77% of total anthropogenic GHG emissions, its reduction is very essential from the atmosphere. Carbon sequestration is the capturing atmospheric CO_2 and storing for long term through natural (soils/vegetation) and engineering techniques (Schrag 2007). Among all the natural techniques, agroforestry provides a win-win opportunity to achieve the objectives of carbon sequestration and climate change mitigation and adaptation. Although agroforestry systems (AFS) are not primarily designed for carbon sequestration, there are many recent studies to substantiate the evidence that agroforestry systems can play a major role in storing carbon in aboveground biomass (Murthy *et al*. 2013) as well as in belowground biomass (Nair *et al*. 2009).

Agroforestry and its potential for carbon sequestration: Agroforestry is often considered a cost-effective strategy for climate change mitigation. Agroforestry systems store carbon in the soils and woody biomass, and these also reduce greenhouse gas emissions from soils. Majority of the agroforestry systems have the potential to sequester carbon, which may vary according to tree species (Prasad *et al*.

2012) and management practices (Newaj *et al.* 2001). An overall review of the agroforestry for natural resource conservation and management (Dhyani *et al*. 2005, 2009) indicates the following points: (i) Agroforestry is a viable option to prevent and mitigate the climate change. (ii) Agroforestry can increase and stabilize agricultural yieds and reduce soil erosion. (iii) Agroforestry biomass can provide fuelwood, foods, fodder, basic construction materials, shade, medicines, etc. (iv) Agroforestry may allow land to be taken out of fallow rotation in shifting cultivation systems; for example, sustainable managed one hectare of land with agroforestry could replace 5-10 ha of land under shifting rotation/slash and burn (Trexler 1993). (v) Agroforestry in urban areas can provide local biomass and help the public to recognize the usefulness of tree planting. (vi) Indirect effects, such as substitution for fossil fuels, could prevent the release of 17 Mt C/yr worldwide (Evans 1992). (vii) Agroforestry is ideal option to increase productivity of waste and degraded lands, increase tree cover outside the forest, and minimize human pressure on forests under different agro-ecological regions of India. (viii) An IPCC special report (IPCC 2000) indicates that conversion of unproductive croplands and grasslands to agroforestry have the best potential to soak up atmospheric CO_2. (ix) In agroforestry, soil restoration process involves recovery of organic based nutrient cycling through restoration of soil organic matters, trees uptake the nutrients from below the reach of the crop roots.

Strategies for mitigation of climate change: It is now well known that biological mitigation can occur through three strategies, viz. (i) Conservation of existing carbon pool; (ii) Carbon sequestration by increasing the size of existing pool, and (iii) Substitution of sustainably produced biological products, using biomass to replace energy production from fossil fuels or using wood instead of using high energy intensive construction material.

Option first and second result in higher carbon stocks, but can lead to higher carbon emission in the future and option third can continue indefinitely (IPCC 2001). Agroforestry can play important role in this endeavour. Agroforestry practices applicable to different suitable sites for sequestering atmospheric carbon in wood biomass as well as in soils are presented here under:

Expanding carbon sinks: (i) Agri-silviculture or agri-horticulture systems for food and wood/fruit production. (ii) Boundary and contour planting for wind and soil protection. (iii) Silvi-pastoral system for fodder production and soil and water conservation. (iv) Complex agroforestry systems, viz. multistrata tree gardens, home gardens, agri-silvi-horticulture and horti-silvi-pasture systems for food, fruits and fodder especially in hill and mountain regions. (v) Non-timber tree farms for rubber, tannins, medicines, bamboo, rattan, etc. (vi) Bio-fuel plantations. (vii) Taungya system, which is applied in tandem with forest management. (viii) Hedgerow intercropping with fertilizer (nitrogen fixing) trees. (ix) Improved fallows.

Biofuel substitution: (i) The use of sustainably grown biomass for fuels and biofuel and oils from Tree Borne Oilseeds (TBOs) will delay the release of carbon from fossil fuel as long as fossil fuel remains unused. (ii) Wood derived from renewable agroforest, if used as substitute for wood obtained from natural forests will also delay carbon release.

Carbon sequestration potential of agroforestry in india

The CO_2 reduction in atmosphere can only be achieved by shifting from lower biomass land uses (e.g. grasslands, crop fallows etc.) to tree based systems such as agroforestry, forests, and plantation forests (Roshetko *et al*. 2007). There are ample evidences to show that the overall (biomass) productivity, soil fertility improvement, soil conservation, nutrient cycling, microclimate moderation, and carbon sequestration potential of an agroforestry system is generally greater than that of an annual system (Dhyani *et al*. 2009). According to Pandey (2002) carbon sequestration in Indian agroforests varies from 19.56 Mg C/ha/yr in north Indian state of Uttar Pradesh to a carbon pool of 23.46–47.36 Mg C/ha/yr in tree-bearing arid agro-ecosystems of Rajasthan. Carbon sequestration in terrestrial pools include the above ground plant biomass, such as timber, fuelwood and belowground biomass such as roots, soil microorganisms, and all the forms of organic and inorganic C in soils including deep root zone. In agroforestry systems, two major components i.e. trees and crops are mainly responsible for CO_2 sequestration. The total amount sequestered in each component differs greatly and is dependent largely on a number of factors that includes the type of system (and the nature of components and age of plant), site quality, and previous land-use (Albrecht and Kandji 2003, Newaj and Dhyani 2008).

Carbon sequestration by trees: The carbon sequestration potential (CSP) of various trees in AFS in different parts of the country is presented in Table 1. The CSP of trees varies with species, structure, age and spatial distribution. For the most common tree density in the range of 312–800 trees/ha (usually preferred by the farmers in planted AFS), the CSP varied in the range of 0.25 to 19.14 Mg C/ha/yr. Nair *et al*. (2010) have also reported world scenario of carbon stored in AFSs ranged from 0.29 to 15.21 Mg C/ha/yr in above ground, and 30–300 Mg C/ha up to a depth of 1 m in the soil (the age varied from 4 to 35 years). Thus the trees in agroforestry not only improving livelihood of small and marginal farmers, but also helping in mitigating global warming by enhancing carbon sequestration potential of Indian agriculture (Ajit *et al*. 2013). The Central Agroforestry Research Institute (CAFRI), Jhansi has been working on carbon sequestration potential of various agroforestry systems since 2000 through in house and externally aided projects. CAFRI as a partner in ICAR scheme "National Innovations on Climate Resilient Agriculture" (NICRA) is assessing the carbon sequestration potential of selected AFS in the country. The research under the NICRA scheme indicated that in agroforestry, the tree has a capacity for biomass production at least as great as that of natural vegetation. The survey (32 districts of 12 states) for existing

Table 1 Carbon sequestration potential (CSP) of trees in India

Region	Agroforestry system	Tree species	No. of trees/ha	Age (year)	CSP (Mg C/ha/yr)	References
Himalaya	Block plantation	*Eucalyptus tereticornis*	2500	3.5	4.40	Dhyani *et al.* (1996)
			2777	2.5	5.90	
		Tectona grandis	570	10	3.74	Negi *et al.* (1995)
			500	20	2.25	
			494	30	2.87	
		Cedrus deodara	100	19	2.47	Wani *et al.* (2014)
		Acacia/Dalbergia/Prosopis		6	1.13-3.08	Kaur *et al.* (2002)
		Acacia/Dalbergia/Prosopis		6	0.25-2.05	
	Agrihortipasture	*Malus domestica*, *Prunus persica* etc.			1.15	AICRPAF (2006)
	Hortipasture	*Prunus persica* etc.			1.08	
	Agrisilviculture	*Dendrocalamus hamiltonii*	1000	7	15.91	Kaushal *et al.* (2014)
		Populus deltoides	500	8	12.02	Singh and Lodhiyal (2009)
	Grove	*Bambusa* spp.	11033 (culm)	4	19.14	Nath and Das (2012)
	Silvipasture	*Grewia optiva, Morus alba* etc.			2.17	AICRPAF (2006)
	Farm forestry	*Acacia catechu*		30	1.5	Hooda *et al*. (2007)
		Pinus spp.		30	7.1	
		Mixed plantation		30	5.9	
		Mangifera indica		30	1.7	
		Kinnow		30	0.2	
Indo-Gangetic	Agrisilviculture	*Leucaena leucocephala*	10666	6	10.48	Mittal and Singh (1989)
		Populus deltoides	400	7	1.98	Rizvi *et al*. (2011)
			400	7	2.48	
			740	7	9.40	Chauhan *et al.* (2010)
	Block plantation	*Acacia nilotica*	1250	7	2.81	Kaur *et al.* (2002)
		Dalbergia sissoo	1250	7	5.37	
		Prosopis juliflora	1250	7	6.50	
Humid and sub-humid	Agrisilviculture	*Gmelina arborea*	592	5	3.23	Swamy and Puri (2005)
	Forest plantation	*Eucalyptus* spp.		6	2.18	Bala *et al*. (2012)
	Block plantation	*Gmelina arborea*		6	4.01-5.01	Swamy *et al*. (2003)
	Silviculture	*Tectona grandis*	444	20	3.32	Negi *et al.* (1990)
		Gmelina arborea	452	20	3.95	
Arid and semi-arid	Block plantation	*Albizia procera*	312	10	1.79	Rai *et al.* (2000)
		Albizia amara	312	10	1.00	
		Acacia pendula	312	10	0.95	
		Dalbergia sissoo	312	10	2.55	
		Dichrostachys cinerea	312	10	1.05	
		Emblica officinalis	312	10	1.55	
		Hardwickia binata	312	10	0.58	
		Melia azaderach	312	10	0.49	
		Leucaena leucocephala	2500	9	10.32	Rao *et al.* (2000)
		Eucalyptus camaldulensis	2500	9	8.01	
		Dalbergia sissoo	2500	9	11.47	
		Albizia lebbeck	625	9	0.62	
		Acacia albida	1111	9	0.82	
		Acacia tortilis	1111	9	0.39	
		Acacia auriculiformis	2500	9	8.64	
		Eucalyptus tereticornis	320	2	13.86	Pragason and Karthik (2013)

Contd.

Table 1 (*Concluded*)

Region	Agroforestry system	Tree species	No. of trees/ha	Age (year)	CSP (Mg C/ha/yr)	References
		Acacia farnesiana	170	2	2.42	
		Cassia montana	154	2	1.84	
		Prosopis juliflora	138	2	1.16	
		Acacia nilotica	106	2	5.70	
	Agrisilviculture	*Albizia procera*	312	7	3.70	Newaj and Dhyani (2008)
		Acacia pendula	1666	5.3	0.43	Rai *et al.* (2002)
		Leucaena leucocephala	11111	4	2.77	Rao *et al.* (1991)
			6666	4	1.90	
			4444	4	14.42	Prasad *et al.* (2012)
			10000	4	15.51	
		Casuarina equisetifolia	833	4	1.57	Viswanath *et al.* (2004)
		Delbergia sissoo		11	1.47	NRCAF (2007)
		Emblica officinalis		8	1.58-1.62	Swamy *et al.* (2003)
		Hardwickia binnata		8	1.07-1.10	
		Colophospermum mopane	8	0.59-0.66		
	Silvipasture	*Acacia nilotica* + Natural pasture	312	5	1.9-5.4	Rai *et al.* (2001)
		Acacia nilotica + Established pasture	312	5	5.9	
		Dalbergia sissoo+ Natural pasture	312	5	2.5	
		Dalbergia sissoo+ Established pasture	312	5	3.44	
		Hardwickia binnata+ Natural pasture	312	5	3.24	
		Hardwickia binnata+ Established pasture	312	5	3.40	
Tropical	Home garden	Mixed tree species	667	71	1.60	Saha *et al.* (2009)
	Block plantation	*Eucalyptus* spp.		7-10	3.71	Ajit *et al.* (2014)
		Acacia mangium	5000	6.5	12.59	Kunhamu *et al.* (2011)
			2500	6.5	9.94	
			1250	6.5	9.51	
			625	6.5	6.37	

Source: Modified from Newaj *et al.* (2014).

agroforestry systems in the farmer's field revealed that agroforestry is practiced in all parts of India and is recognized as having high potential for carbon sequestration. The observed number of trees on farmers' fields in these districts varied from 2 to 204/ha. The baseline standing biomass in the tree component varied from 0.58 to 113.12 Mg DM/ha, whereas, the total biomass (tree and crop) ranged from 4.96 to 123.58 Mg DM/ha. The soil organic carbon in the baseline ranged from 4.28 to 24.13 Mg C/ha. The CSP of existing AFS at district level has been estimated to range from 0.05 to 2.78 Mg C/ha/yr. Based on this study, estimated value of trees/ha was 19.44 and average CSP of existing AFS at country level was 0.34 Mg C/ha/yr or equivalently AFS in India has the potential to mitigate 1.245 Mg CO_2 ha/yr. Thus, the trees in existing agroforestry systems on farmers' fields are estimated to mitigate more than 33% of the total GHG emissions from agriculture sector annually at the country level (Ajit *et al.* in press).

Carbon sequestration by crops: In agroforestry systems, although trees sequester more carbon, but crops also fix and store carbon in considerable amounts. Crop improves the organic matter in soil, which is a significant component of the terrestrial C pool (Ciampitti *et al*. 2011). An increment in carbon pool in soil can be achieved through adoption of appropriate crop rotations (Wright and Hons 2005), integrated soil fertility management (Lal 2010, Srinivasarao *et al*. 2012), precise use of fertilizers and organic amendments (Schuman *et al*. 2002, Mandal *et al*. 2007, Majumder *et al*. 2008), and adoption of conservation agriculture (Lal 2009). Multiplicity of cropping systems is one of the main features of Indian agriculture. The number of soil and climatic parameters, which determine overall agro-ecological conditions for a crop or set of crops for cultivation decided the type of cropping system. There are many studies available in published literature on CSP of crops and cropping systems. However, the choice of crop species, cropping system, timing of fallowing and quality and quantity of residue returned to the soil have considerable impact on soil organic carbon stocks (Halvorson *et al*. 2002, Mandal *et al*. 2007). It is estimated that throughout the country more than 250 double cropping systems are followed. However, in each district in the country based on rational spread of crops 30 important cropping systems were identified. Kushwah *et al*. (2014) conducted an experiment at ICAR-Indian Institute of Soil Science, Bhopal to assess the carbon sequestration potential of different crops and concluded that maize, sorghum and pearl millet had higher potential to carbon sequestration as compared to rice, finger millet and soybean. Pathak *et al*. (2011) compiled the information on carbon sequestration potential of different cropping systems of Indian agriculture studied through different long term experiments (LTE's) in different agroclimatic zones of India and reported that C sequestration rate varied from 0.02 Mg C/ha/yr (in NPK treatment for soybean-wheat cropping systems over the 28 years duration at Jabalpur in Madhya Pradesh) to 1.2 Mg C/ ha/yr (in NPK+FYM treatment for cassava based systems over 13 years duration at Thiruvananthapuram, Kerala). The CSP of 30 year duration pure crop based LTE's ranged from 0.02 to 0.10 Mg C/ha/yr with an average value of 0.062 Mg C/ha/yr (Table 2). However, majority of published reports assents that carbon sequestration in pure cropping systems is only feasible, when some organic matter (FYM, green manure, straw, stover or some other tree material used for growing crops) is used. Looking into the CSP of cropping systems in without organic matter added scenario (NPK), it can be inferred that balanced application of NPK to crop could also promote carbon sequestration in crops, however, integrated nutrient management (INM) remained always at higher side as compared to NPK in terms of CSP of cropping system. Several reports have published showing the positive effect of no-tillage practices on soil carbon pool in rice-wheat cropping systems. Based on eight years study in rice-wheat cropping system, Pandey *et al*. (2014) reported 0.59 Mg C/ha/yr carbon sequestration potential of rice-wheat cropping system in no-tillage conditions.

Carbon sequestration in soil: Carbon sequestration in soil is the process of transferring CO_2 from the atmosphere into the soil through crop residues, tree roots and other organic solids, and in a form that is not immediately re-emitted. The sequestered carbon in soil helps in reducing CO_2 present in the atmosphere, while enhances soil quality and a sustained productivity. Soil carbon sequestration can be accomplished by management practices that add high amounts of biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, and enhance soil faunal activity.

The studies on carbon sequestration in soils of India and rest of the world revealed a general trend of increasing soil carbon sequestration (SCS) in agroforestry as compared to other land-use practices (with the exception of forests). Overall in terms of SOC content, the land-use systems were ranked in the order: forests>agroforests>tree plantations>arable crops (Nair *et al*. 2010). Furthermore, it is noted that the estimated values of SCS in AFS varied greatly and were a reflection of many factors including biological, physical and socio-economic characteristics of the system parameters as well as the lack of uniformity in study procedures.

Agroforestry systems with better management have greater amounts of C sequestration potential in and out of the soil. Below ground biomass of trees in the form of roots comprise about 1/5th to 1/4th of the total living biomass and

Table 2 Carbon sequestration potential of various cropping systems in India

Cropping system	Carbon sequestration (Mg/ha/yr)		References
	NPK	INM	
Rice-Wheat	0.22	0.34	Ghosh *et al.* (2009)
Rice-Wheat	0.15	0.05	Mandal *et al.* (2007)
Rice-Wheat	0.07	0.11	Yadav *et al.* (2000)
Rice-Wheat	0.34	0.11	Yadav *et al.* (2000)
Rice-Wheat	0.13	0.18	Prasad and Sinha, (2000)
Rice-Wheat	0.17	0.05	Yadav *et al.* (2000)
Rice-Wheat	0.10	0.03	Yadav *et al.* (2000)
Rice-Wheat	0.05	0.45	Yadav *et al.* (2000)
Rice-Wheat	0.04	0.06	Yaduvanshi and Swarup (2005)
Rice-Rice	0.26	0.04	Nayak *et al.* (2009)
Rice-Lentil	0.12	0.15	Srinivasarao *et al.* (2012)
Rice-Mustard-Sesame	0.56	0.06	Mandal *et al.* (2007)
Rice-Berseem	0.04	0.09	Majumdar *et al.* (2008)
Rice-Wheat-Jute	0.07	0.05	Manna *et al.* (2005)
Soybean-Wheat	0.10	0.29	Kundu *et al.* (2007)
Soybean-Wheat	0.06	0.01	Manna *et al.* (2005)
Soybean-Wheat	0.14	0.14	Behra *et al.* (2007)
Soybean-Wheat-Maize	0.02	0.12	Hati *et al.* (2007)
Maize-Wheat	0.04	0.40	Sharma *et al.* (1998)
Maize-Wheat-Cowpea	0.06	0.31	Rudrappa *et al.* (2006)
Maize-Chickpea	0.02	0.02	Vineela *et al.* (2008)
Sorghum-Wheat	0.26	0.31	Manna *et al.* (2005)
Sorghum-Castor	0.11	0.28	Sharma *et al*. (2005)
Cotton-Sorghum	0.31	0.23	Venugopalan and Pundrikakshud (1998)
Finger millet-Maize-Cowpea	0.10	0.10	Murugappan *et al.* (1998)
Cassava	0.60	0.58	John *et al.* (1998)
Pearlmillet	0.06	0.05	Srinivasarao *et al.* (2009)

Source: Modified from Pathak *et al*. (2011).

there is constant addition of organic matter to the soil through decaying dead roots (Dhyani and Tripathi 2000), which leads to improvements in the C status of the soil. Better soil aggregation under natural forest, multi-storeyed AFS and Agri-horti-silvi-pastoral systems maintaining intensive vegetative cover round the year could be ascribed to the effect of the higher percentage of organic carbon.

Based on the CO2FIX models for carbon sequestration in soil, it is expected that agroforestry systems [with 37.95 trees (Poplar/*Eucalyptus/Melia*)/ha] in Ludhiana (Punjab) can sequester 0.513 Mg C/ha/yr in soil (Ajit *et al.* in press, Table 3). Similar results outside India reported by Post and Kwon (2000) revealed that the average rate of SCS under tree based systems ranged between 0-3 Mg C/ha/yr. Although the rate of SCS appears to be affected by tree density to some extent, however there are a large number of other factors influencing it under agroforestry systems, viz. precipitation, temperature, evapotranspiration, decomposition rates, litter fall, decay rates of tertiary tree roots, crop residue, species of tree/crop, chemical properties of the litter etc.

The multipurpose tree species (MPTs) in agroforestry form an integral component of crop sustainability. The MPTs, besides providing multiple outputs such as fuel, food, fodder, timber and other miscellaneous products and also help in the improvement of soil health and other ecological conditions. MPTS like *Alnus nepalensis*, *Parkia roxburghii*, *Michelia oblonga, Pinus kesiya*, and *Gmelina arboria* with greater surface cover, constant leaf litter fall and extensive root systems increased the soil organic carbon by 96.2%, improved aggregate stability by 24.0%, available soil moisture by 33.2%, and in turn reduced soil erosion by 39.5% (Subba Rao and Saha 2014).

Carbon sequestration through agroforestry: Lessons learnt

This review clearly indicates that, (i) Long rotation agroforestry systems such as windbreak, shelterbelts, woodlots, boundary plantation, agrihorticulture, silvipasture, home gardens, and multi-storeyed systems have large potential in carbon storage in biomass. (ii) Short rotation systems (agrisilviculture) have high potential for soil carbon sequestration. (iii) Fast growing hardwoods (*Eucalyptus*, Poplar, *Melia, Casuarina, Leucaena* etc.) and tropical bamboos have large potential for biomass than slow growing species. (iv) Both types (Long and short rotation AFS) have similar soil carbon sequestration potential.

AFS provide the climate change mitigation mechanism through: (i) CO_2 assimilation, providing biological and economic gains. (ii) Improvement in production environment, further enhances CO_2 assimilation. (iii) C sequestration can be rewarded if mechanism is developed as recommended by the National Agroforestry Policy 2014.

Therefore, the evidences are clear to suggest that agroforesry is desirable, both for its beneficial effects on climate change adaptation and mitigation, and for sustaining farm income. The combination of trees with crop gives not only timber, fuel, fodder and food but also reduces CO_2 from the atmosphere at acceptable level. The carbon sequestration potential of agroforestry system is higher than any other land use system except forest, however CSP of agroforestry system varies according to tree species, age of system, crop/variety, type of agroclimate, etc. Agroclimatic zones in India represents different agroforestry systems and their aboveground and belowground (soil) CSP varies between 0.25 to 19.14 Mg C/ha/yr and 0.003 to 3.98 Mg C/ha/yr, respectively. Besides the potential of agroforestry systems to accumulate and sequester C, these systems provide the unique opportunity to increase the tree cover to a level of 33% in India.

Way forward

Agriculture including agroforestry sector is an important component in overall goals set up by the Government of India in meeting the adaptation and mitigation targets. The government has taken a number of measures to address the threat of climate change and promote sustainable development at national and sub-national level through a number of schemes and policy initiatives, which include

Table 3 Soil carbon sequestration through agroforestry systems

Region	Agroforestry system	Tree species	No. of trees/ha	Age (year)	CSP (Mg C/ha/yr)	References
Himalaya	Block plantation	Eucalyptus, Oak etc.		21	0.6-3.98	Devi *et al.* (2013)
Indo-	Agrisilviculture	*Populus deltoides*	38		0.513	Ajit *et al.* (in press)
Gangetic			357	6	1.95	Gupta *et al.* (2009)
			357	6	2.63	
			740	7	1.62	Chauhan *et al.* (2010)
Humid and	Block plantation	*Gmelina arborea*			1.6-2.8	Swamy *et al.* (2003)
Sub-humid		*Ceiba pentandra*			1.3-3.4	
Tropical		*Acacia mangium*	5000	6.5	1.09	Kunhamu *et al.* (2011)
			2500	6.5	1.53	
			1250	6.5	0.36	
			625	6.5	0.82	
All India (All agroclimates)	Various AFS	Miscellaneous trees	2-51	30	0.003-0.513	Ajit *et al.* (in press)

Soil Health Card Scheme, *Pradhan Mantri Krishi Sinchai Yojana, Paramparagat Krishi Vikas Yojana*, National Agroforestry and Bamboo Mission, Mission for Integrated Development of Horticulture, National Mission on Sustainable Agriculture (NMSA), National Mission on Agriculture Extension and Technologies, National Innovations in Climate Resilient Agriculture (NICRA), and National Policy for Crop Residues. Two recent policy initiatives viz. National Agroforestry Policy 2014 (http://www.indiaenvironmentportal.org.in/ content/389156/national-agroforestry-policy-2014/) and National REDD+ Policy (http://unfccc.int/focus/indc_portal/items/8766.php) will be helpful in integration of trees into adaptation and mitigation straggles particularly for resource-poor farmers of the country. The National Agroforestry Policy emphasized on developing strategies to provide incentives through value chain development to farmers for adopting agroforestry, while the National REDD+ Policy lays down the broad principles for developing and implementing REDD+ programmes in India to enable the country to gain from international REDD+ mechanism for its pro conservation policies and efforts and at the same time create financial incentives to local communities which are in the forefront of conservation of forests. To get the benefits from the policy initiatives it is urgently required to develop appropriate mechanism for channeling the benefits to the farmers, particularly benefits arising from the ecosystem services provided by the tree farming. In addition, a conducive investment regime for farmers by asking banks to provide loans for plantations on private lands, creating a buy-back arrangement with farmers and fix suitable Minimum Support Price for the wood is urgently needed.

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