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Biomass production and carbon sequestration through agroforestry

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Abstract
Productivity of any vegetation system mainly depends on biomass production and carbon storage potential in their different components, which are affected by nature and age of plant, and other climatic, edaphic, topographic and biotic factors. In different vegetation systems, the bole/ stem biomass contributed 28 to 86% of total aboveground biomass. The percentage contributions of bole, branch and leaf were 65-76, 14-19, 3-12 for fast growing tree species. In case of other tree based systems stem contributed about 76 to 80%, branch 11 to 29% and leaves 3 to 14% of aboveground biomass. A tree allocates on an average 81.89% to above ground biomass (stem, branch, leaves and litter) and 18.11% to below ground biomass (roots). The available estimates of carbon stored in tree based systems ranged from 0.29 to 15.21 Mg C ha^{-1}year^{-1} in above ground and 30-300 Mg C ha^{-1} upto 1 m depth in the soil. Soil carbon storage potential in agroforestry systems differed from system to system and highest storage potential was observed in homegardens where it stored 119.3 t SOC per hectare.

Keywords: Agroforestry, Biomass production, Silvipasture, Soil carbon

Introduction
The biomass stock and its storage rate in vegetation systems play an important role in quantifying the system output and determining the carbon sequestration rate for mitigating of climate change problems. The estimation of biomass is also prerequisite for determining the status of agroecosystem, flux of biological material, understanding the basic dynamics and its productivity. The productivity of forests is based on the height, diameter and total above ground biomass, and influenced by association of different vegetation components, area coverage, age, site factors and growth characteristics (Singh, 1994). However, the biomass and productivity estimates of tree species vary from place to place due to variation in climate, soil, temperature and rainfall (Lodhiyal *et al*., 2002). Assessment of biomass is helpful in determining the productivity, carbon stock, carbon sequestration and nutrient cycling performance of tree species. Although biomass has long been of principal importance and interest in forestry, a research study of forest productivity and biomass was given impetus by the work of Ovington (1956) who developed a relationship between phenology of tree and dry matter production which depends on the site conditions. Biomass is also an essential aspect of studies of carbon cycle (Ketterings *et al*., 2001). Earlier foresters were interested in standing crop rather than biomass but with the development of more complete utilization of trees, biomass is becoming their major focus.

Biomass production
Aboveground biomass production : Individual tree biomass values are used to estimate the total biomass of entire system. Above ground biomass is the most important visible and dominant carbon pool in vegetation systems (Ravindranath and Ostwald, 2008). In sodic soil of Gangetic alluvium in north India, *P. juliflora* and *A. nilotica* produced biomass of 56.50 and 50.75 Mg ha^{-1}, respectively at 10 years (Singh *et al.,* 2010). The per cent contribution of the bole biomass to aboveground biomass increased with an increase in diameter and fluctuated between 28 to 86%. The percentage contribution of branch biomass decreased with increasing age and diameter. Pal and Raturi (1989) reported that biomass production in *Acacia nilotica* grown as energy plantation under rain fed conditions was 41.25 t ha^{-1} at the age of 3 years out of which 40.62 t was utilizable biomass. Bole wood alone comprised about 44.1% of total biomass. In four year old agri-silviculture system comprising *Gmelina arborea* and

soybean (*Glycine max*) in sub-humid region of Central India, total biomass varied from 10.89 to 3.65 Mg ha^{-1}depending on tree density. Among the different tree components, stemwood contributed maximum biomass (54.3-79.4%), followed by branches and leaves (Swamy *et al.,* 2003). Toky *et al*. (1989) reported that highest biomass productivity upto 25.8 t ha^{-1}year^{-1} out of which 68 per cent was contributed by the trees in agri-horti-silvicultural system. The lowest productivity of 20.4 t ha^{-1}year^{-1} was observed in agri-silvicultural system which contributed for 27% of the total productivity.

In another study Lodhiyal and Lodhiyal (2003) estimated the biomass and net primary productivity in 5 to 15 years old *Dalbergia sissoo* forests in Central Himalaya and found that the total biomass of trees ranged from 50.3 ± 2.46 in 5 year old stand to 122.7 ± 3.14 t ha^{-1} in 15 year old stand. Above ground parts contributed 83-84 per cent biomass. The total litter fall of the study ranged from 2.7 in 5 year-old stand to 5.1 t ha^{-1}year^{-1} in 15 year-old stand. Negi *et al.* (1990) studied biomass production in 20 years old plantations of *Tectona grandis* and *Gmelina arborea* in Tripura using mean tree technique and they reported that dry matter contents were 138.37 and 164.4 t ha^{-1}, respectively. The percentage contribution of bole, bark, branch, twig and leaf were 65.30, 9.10, 16.80, 3.40, 5.40 and 73.70, 9.40, 9.50, 5.00, 2.40, respectively for *Tectona grandis* and *Gmelina arborea.* Indeed, the biomass production and allocation of biomass for bole, branch, twig, foliage and roots varies with species, site, density and management practices (Table 1). Osman *et al. (*1992) reported that 4 years old *Acacia auriculiformis* and 8 years *Dipterocarpus turbinatus* plantations at Chittagong, Bangladesh produced 76 and 32 t ha^{-1} dry biomass, respectively. Distribution of biomass in stem, branch and leaf was similar in *Acacia auriculiformis* and *Dipterocarpus turbinatus* and it varied from 72 to 76, 14 to 19 and 9 to 12%, respectively.

Srivastava (1994) reported that green and dry matter production in *Acacia nilotica* (31 to 45 cm gbh*)*, *Dalbergia sissoo (*28 to 41 cm gbh) and *Casuarina equisetifolia* (25 to 36 cm gbh*)* were 66.54, 99.99, 51.74 and 42.02, 62.44, 32.42 kg tree^{-1}, respectively. But total green and dry matter production were predicted to be 93.12, 80.07, 49.02 and 51.18, 51.15, 29.28 t ha^{-1} in *Acacia nilotica, Dalbergia sissoo,* and *Casurina equisetifolia ,* respectively. Singh and Negi (1997) studied biomass production and its distribution amongst different tree components in *Cinnamom camphora* in Doon valley with dbh ranging from 7 to 37 cm. They reported that the percentage contribution of bole to total aboveground biomass decreased from 66.3 (7 to 12 cm, diameter class) to 61.3 (32 to 37 cm diameter class). However, percentage contribution of branch plus twigs and leaves increased with increase in diameter class with respective figures being 23 to 28 and 3.1 to 3.7. Singh *et al.* (2006) reported total biomass between 182.7-207.4 t ha^{-1} in *Dedrocalamus strictus* plantation in dry deciduous forest region of India at three year age.

Below ground biomass production : Knowledge of root biomass is of particular importance for the understanding of root carbon allocation and carbon cycling in different vegetation systems. Roots provide anchorage for the tree and serve the vital functions of absorption and translocation of water and nutrient. Roots provide detrital carbon to soil organisms and are important in immobilizing and processing soil water pollutants and improving soil quality (Groffman *et al*., 1992). Fine and small roots (<5 mm), and coarse roots (> 5 mm) are two major components of belowground biomass, and their vertical distributions define extent to which they modify soil physical, chemical and biological properties. Fine roots represent a dynamic portion of belowground biomass, nutrient capital, and a significant part of net primary production in native and managed ecosystems (Buyanovsky *et al*., 1987). The root shoot ratio varies with species to species, growing stage of species and external climatic conditions. The root and shoot growth also affected by topographic and edapic conditions. From review of literature, it has been found that on an average tree allocates 81.89% to the above ground biomass (stem,branch,leaves and litter) and 18.11 % to below ground biomass (roots). Toky and Bisht (1992) studied the root architecture of six year old trees of nine indigenous and three exotic tree species growing in the arid climate of North West India. Observations made on the excavated root system showed large variations in horizontal and vertical spread. In *Morus alba, Melia azaderach* and *Populus deltoides*, the roots were confined to 80 cm only, while in *Prosopis cineraria, Acacia nilotica* and *Eucalyptus tereticornis,* roots penetrated more deeply up to 233 cm. Further study revealed that roots of *Prosopis cineraria*, *Eucalyptus tereticornis* and *Populus deltoides* exceeded crown spread by 1.2 fold higher than their crown spread. The number of total roots ranged from 103 in *Acacia catechu* to 1932 in *Eucalyptus tereticornis*. Total root biomass varied from 2.2 kg in *Acacia catechu* to 30.6 kg per tree in *Populus deltoides.*

Table 1. Biomass production by tree component in forests, agroforestry and plantations in India

Above ground Vegetation	Biomass (t ha^{-1})	% Allocation Bole	Branch	Twig	Foliage	References
Eucalyptus globules	123	66.2	11.1	7.1	7.3	Negi *et al.* (1984)
E. grandis	97.6	83.8	6.8	4.6	4.6	Tandon *et al.* (1988)
E. grandis	275.1	92	3.9	2.0	2	Tandon *et al.* (1988)
E. hybrid	21.9	62.1	15.4	8.8	13.7	Pandey *et al.* (1987)
E. tereticornis	121.0	64.9	15.7	2.3	10.0	Bargali *et al*. (1992)
Mixed plantation	110	71				Vezzanni *et al. (2001*
P. deltoides	105.4	74.4	13		12.6	Singh (1989)
P. deltoides	151.6	71.9	16		12.1	Singh (1989)
P. deltoides	67.6	69.4	14.8	4.3	11.5	Lodhiyal *et al*. (1995)
P. deltoides	134.3	74.7	12.6	4	8.6	Lodhiyal *et al.* (1995)
D. sissoo	82	40.6	34.9		6.5	Sharma *et al.* (1988)
D. sissoo	16.16	65.5	14.2	2.6		Sharma *et al*. (1988)
Acacia catechu	0.352	78.69	0.85		0.28	Chambial (2016)
Melia azedarach	0.684	78.65	1.02		0.29	
Grewia optiva	0.206	77.67	1.94		0.49	
Celtis australis	0.308	78.25	1.30		0.32	
Acer oblongum	0.926	76.57	2.81		0.54	
Bauhinia variegata	0.915	76.94	2.51		0.44	
Morus alba	0.287	76.66	2.44		1.05	
Gmelina arborea	21.37	65.04	10.25		4.12	Swamy and Mishra (2014)
Ceiba pentandra	25.26	55.11	12.35		7.21	
Cajanus cajan	17.64	37.07	25.96		9.81	Laxmi narayanan *et al.* (2005)
Crotolaria tetragona	35.41	52.73	13.72		13.95	
Desmodium rensoni	10.07	44.29	6.16		11.72	
Flemingia macrophyala	11.70	35.30	2.56		17.52	
Indigofera tinctoria	15.93	59.45	2.89		10.86	
Tephrosia candida	12.28	44.38	5.54		22.23	
Acacia auriculiformis	152.00	73.03	11.18		5.26	Kumar *et al.* (1998)
Artocarpus heterophyllus	92.14	59.02	21.54		8.44	
Artocarpus hirsutus	70.08	45.88	21.16		17.05	
Casuarina equisetifolia	36.10	74.79	11.08		4.71	
Emblica officinalis	81.49	56.69	22.37		5.44	
Leucaena leucocephala	25.23	59.45	23.78		3.96	
Pterocarpus marsupium	73.41	71.65	13.73		4.67	

Studies on root biomass in alley cropping in northeast India indicated that 70% of all the root biomass including fine and coarse roots were located in the top 20 cm of soil profile (Dhyani and Tripathi, 2000). Mohsin *et al*. (2000) conducted a study on roots distribution in *Eucalyptus hybrid* plantation at various ages in *Tarai* region at Pantnagar, India. The results revealed that total root biomass of 1.4 and 5.1 kg in 2 and 3 years old trees which increased to 19.50 kg in 6 years and 24.50 kg in 7 years old trees. In case of 2, 3, 6 and 7 year old trees, about 12, 13, 24 and 25.5% of total root biomass was located in 100-150 cm radial distance. It also revealed that majority of root system of 2 and 3 year old trees was made up of medium roots 0.5-1.5 cm which accounted for 48.57 and 49.625 of total root biomass. In case of 6 and 7 year old trees, major part of the root system was made up of thick roots (>1.5 cm), which accounted 78.5 and 79.5% of total root biomass. Total root biomass further decreased continuously with increasing radial distance from the tree base at all the soil depths.

The root pattern of eight important multipurpose tree species was studied in north-west alluvial plain of Bihar, India (Chaturvedi and Das, 2002). Maximum root depth was observed in *Acacia nilotica* (2.71 m) followed by *Dalbergia sissoo* (2.50 m) and minimum in *Acacia lenticularis* (1.01 m). Variation in horizontal root spread was maximum in *Pithecellobium dulce* (7.70 m) and minimum in *Syzygium cumini* (1.69 m). Further root spread of *A. nilotica, D. sissoo*, *P. dulce, C. fistula* and *S. cumini* exceeded the crown spread by 1.13 to 1.64 folds. The length of main root varied between 23.8 ± 4.3 cm in *Dalbergia sissoo* to 135.2 ± 18.6 cm in *Acacia nilotica*. Lateral roots also showed a wide range of variation in length within and among the species. Total

Table 2. Production potential of silvipasture system in India

Region	Components	Remarks
Alpine region	Only pastures with suitable grasses and legumes	*Agrostis* spp., *Chrysopogon gryllus, Dactylis glomerata, Poa pratensisTrifolium repens, T. pratense, Medicago falcata*
Temperate region	Intensive pasture production, temperate horticultural plant combined with pasture legumes as ground floor, fodder forest legumes	Fodder yield: 5.7 t ha^{-1}; on an average 8 to 10 $tree^{-1}$ dry matter yield
North-eastern region	Silvipastures:*i)Alnus nepalensis+ Stylosanthes guyensis + Panicum maximum* *ii)Ficus hookerii + Thysanolaena maxima*	Fodder yield: 13.5 t ha^{-1} (DM basis) Fodder yield: 12.3 t ha^{-1}
Outer Himalayas region	Silvipasture systems: *Dalbergia sissoo +Chrysopogon fulvus Acacia catechu + Eulaliopsis binataLeucaena l eucocephala* (high density) + Hybrid Napier (NB 5)*Bauhinia purpurea, Albizia lebbek + Eulaliopsis binata*	Suitable system for utilization of degraded lands for fuel, fodder and fibre; 64-71 t ha^{-1} fuelwood 5.2-5.5 t ha^{-1} $year^{-1}$ fodder grass for short rotation of 4 -5 years.Most suitable for gravelly riverbed lands of Doon Valley.
Shiwalik foothills	Silvipastures; Fodder production from wastelands and watershed management	Fodder production increased by 267%
Indo-Gangetic plains	Tree-grass combination Forage production on dry lands (*Leucaena* + sorghum-safflower)	Annual production: 8-10 t ha^{-1} (4.5-5 t ha^{-1} fuelwood and 7-10 t ha^{-1} $year^{-1}$ biomass production)Forage yield of 12.3 t ha^{-1}
Humid and sub-humid	Use of quick growing leguminous fodder plants in crop rotations, plantation crops with pastures,Farm forestry;Deenanath (*Pennisetum pedicellautm*) + Stylosanthes and Deenanath + *Leucaena*i)*Leucaena* (Hawaiian, hybrid-28) + fodder grass *Glyricidia/Sesbania/ii)Ficus hookerii Litsea+ Thysalaena /Andropogon nardus*	Best for pasture development in the eroded marginal and sub-marginal hilly area of Southern Bihar Suitable combination for plain area in West Bengal Suitable for hilly areas
Coastal area (Kerala)	Fodder trees (Subabul/ Agathis/ Desmenthes) + Congo signal + *Stylosanthes or Centrosema*	Total fodder yield of 22-29 t ha^{-1} could be obtained in coconut based fodder production systems
Arid and semi-arid region	Grazing lands, and silvipasture and Hortipasture in arid and integration of agri-silvipasture; Forage-cum-coppicing farming on the marginal and sub-marginal lands with intercropping of dryland cereals and legumes, *Acacia tortilis, Albizia lebbek, Prosopis cineraria* with *Chrysopogon fulvus, Cenchrus ciliaris, C. Setigeres*	Very good potential for silvipastoral enterprise

root biomass was highest in *Pithecellobium dulce* (15.21 kg) followed by *Acacia procera* (12.59 kg).

Silvipasture system for biomass production : Silvipasture is a most promising alternate land use system which integrates multi-purpose trees, shrubs, legumes and grasses, mostly on non-arable, degraded lands for optimising land productivity. It mimics a natural forest and helps in conservation of vegetation, soil and nutrients and provides forage, timber and fire wood on a sustainable basis. Trees in silvipasture systems tolerate extreme soil and climatic conditions, whereas grasses provide good ground cover to check soil erosion. The system provides resilience by ensuring continued and sustainable multiple outputs such as forage, fuel, fibre and industrial raw material, besides other positive environmental effects including carbon build up. Although production potentials of silvipastoral systems were found to vary under different agro-climatic regions of India (Table 2; Singh and Chaturvedi, 2011).

Carbon sequestration

Quantifying carbon sequestration : The capturing atmospheric of CO_2 and storing it for long term through natural (soils/vegetations) and engineering techniques is known as carbon sequestration (Schrag 2007). Biomass carbon is a sum of above ground, below ground biomass carbon and dead organic matter. The carbon storage for each tree is computed by multiplying biomass values with carbon concentration generally taken as 0.50 (default value given by IPCC 1996).The above ground biomass carbon contents of individual trees are summed to obtain total above ground biomass carbon. Biomass carbon estimation using remote sensing and GIS has increasingly been gaining momentum in the recent past. It will help us to determine biomass production and carbon storage potential of different agroforestry systems covering a wide area.

Carbon sequestration and its mitigation through plant biomass : Agroforestry practices have wide and promising potentials to store carbon and remove atmospheric carbon dioxide through enhanced growth of trees and shrubs (Singh *et al.,* 2000). Growing trees in agricultural field has a strong implication for sustainable development because of interconnection with food production, rural poverty and environmental degradation. The available estimates of C stored in agroforestry ranged from 0.29 to 15.21 Mg C $ha^{-1}year^{-1}$ above ground, and 30–300 Mg C ha^{-1} upto 1 m depth in the soil (Nair *et al.,* 2010). Average sequestration potential in agroforestry was estimated to be 25 t C ha^{-1} over 96 million ha of land in India, and 6-15 t C ha^{-1} over 75.9 M ha in China (Sathaye and Ravindranath, 1998). The agroforestry for carbon sequestration was found attractive because: (i) it sequesters carbon in vegetation and in soils depending on the pre-conversion

Table 3. Carbon sequestration potential (Mg C ha^{-1} $year^{-1}$) of various trees in different agroforestry systems in India

Agroforestry system	Tree species	State	No. of tree per hectare	Age (year)	CSP	References
Agrisilviculture	*D. hamiltonii*	Uttarakhand	1000	7	15.91	Kaushal *et al.* (2014)
Agrisilviculture	Fruit trees	Himachal Pradesh	69	–	12.15	Goswami *et al.* (2014)
Agrisilviculture	*L. leucocephala*	Andhra Pradesh	4444	4	14.42	Prasad *et al.* (2012)
Agrisilviculture	*L. leucocephala*	Andhra Pradesh	10000	4	15.51	
Agrisilviculture	*P. deltoides*	Uttarakhand	500	8	12.02	Singh and Lodhiyal (2009)
Agrisilviculture	*P. deltoides*	Punjab	740	7	9.4	Chauhan *et al.* (2010a; 2010b)
Agrisilviculture	*P. deltoides*	Punjab	493	6	6.22	Chauhan *et al.* (2011)
Silvipasture	*A. nilotica*	Haryana	1250	7	2.81	Kaur *et al.* (2002)
Silvipasture	*D. sissoo*	Haryana	1250	7	5.37	
Silvipasture	*P. juliflora*	Haryana	1250	7	6.5	
Agrisilviculture	*A. procera*	Uttar Pradesh	312	7	3.7	Ramnewaj and Dhyani (2008)
Agrisilviculture	*A. pendula*	Uttar Pradesh	1666	5.3	0.43	Rai *et al*. (2001)
Agrisilviculture	*G. arborea*	Chhattisgarh	592	5	3.23	Swamy and Puri (2005)
Agrisilviculture	*C. equisetifolia*	Tamilnadu	833	4	1.57	Viswanath *et al.* (2004)
Home garden	Mixed tree spp.	Kerala	667	71	1.60	Saha *et al.* (2009)

CSP: Carbon sequestration potential; Source: Modified and adopted from Ajit *et al.* (2016)

soil C, (ii) the more intensive use of the land for agricultural production which reduces the need for slash-and-burn or shifting cultivation, (iii) the wood products produced under agroforestry serve as substitute for similar products unsustainably harvested from the natural forest, (iv) it increases the income of farmers, which reduces the incentive for further extraction from the natural forest for income augmentation, and finally, (v) agroforestry practices may have dual mitigation benefits as fodder species with high nutritive value can help to intensify diets of methane-producing ruminants, while they can also sequester carbon (Singh and Pandey, 2011). In India number of studies were conducted to estimate the total carbon storage potential of different agroforestry systems (Table 3). The carbon stock varied with the region and the kind of agroforestry system within the region. Ajit *et al.* (2016) estimated the carbon sequestration potential (CSP) of existing agroforestry systems (AFS) for simulation period of 30 years in twenty six districts from ten selected states of India. The biomass in the tree component varied from 0.58 to 48.50 Mg DM ha^{-1}, whereas the total biomass (tree and crop) ranged from 4.96 to 58.96 Mg DM ha^{-1}. The soil organic carbon ranged from 4.28 to 24.13 Mg C ha^{-1}. The average estimated carbon sequestration potential of AFS, representing varying edapho-climatic conditions, on farmers field at country ranged from 0.05 to 1.03 Mg C $ha^{-1}year^{-1}$ with average value of 0.21 Mg C $ha^{-1}year^{-1}$. Watson *et al*. (2000) estimated carbon gain of 0.72 Mg C $ha^{-1}year^{-1}$on 400 million ha land under agroforestry with potential for sequestering 26 Tg C $year^{-1}$ by 2010 and 45 Tg C $year^{-1}$ by 2040. It was also reported that 630 million hectares area would be available for agroforestry, which has the potential to sequester 586 Mt C per year by 2040, Carbon stocks were estimated in farm forestry and agroforestry situations (Eucalyptus and Leucaena) in Khammam district of Andhra Pradesh, India. Study revealed that carbon stock in Leucaena was significantly higher in farm forestry system (62 t ha^{-1}) than agroforestry system. Among the various tree components, carbon stock was highest in bole (44 t ha^{-1}), whereas contribution of below-ground biomass was about 12 t ha^{-1}. In the case of Eucalyptus, carbon stock ranged from 31 to 34 t ha^{-1} and was higher in farm forestry system, but the differences were not significant (Prasad *et al.,* 2012).

Carbon stock was sudied over 10 years by averaging the annual biomass production of *Theobroma cacao*, *Cordia alliadora* and *Erythrina poeppigiana* in Costa Rica (Beer *et al.,* 1990). The results revealed that 11 Mg C ha^{-1} $year^{-1}$ was stored over 10 years in the system including 6 Mg C ha^{-1} $year^{-1}$ in the shade trees. Wang and Feng (1995) carried out a study on carbon sequestration in *Populus canadensis* and *Paulownia* based agroforestry systems in the North China Plain and observed that CO_2 emission into the atmosphere was reduced by 0.23 t C ha^{-1} $year^{-1}$ by Poplar shelterbelt and 0.50 t C ha^{-1} $year^{-1}$ for *Paulownia* intercropping systems, respectively. In a carbon sequestration trial in Mexico, live fence trees were reported to store 24-36 Mg C ha^{-1} during a cycle of 25-30 years (De Jung *et al.,* 1995). Carbon input from litter fall of 6 year old hybrid Poplar was found to 1.2 Mg C ha^{-1} $year^{-1}$ which increased to 1.6 Mg C ha^{-1} $year^{-1}$ in the following year (Thevathasan and Gordon, 1997). In another study carbon input from litter fall was 0.63 Mg C ha^{-1} $year^{-1}$ in a 10 year old hybrid poplaralley cropping system in the southern Canada (Zhang, 1999). Chesney and Nygren (2002) conducted a study on 10 year old *Erythrina poeppigiana* alley cropping system at a stand density of 833 trees ha^{-1} and found that sequestered carbon in trunk was 0.3 Mg C ha^{-1} $year^{-1}$, while the values in branches and leaves were 1.4 Mg C ha^{-1} $year^{-1}$. Further they reported that 0.04 Mg C ha^{-1} $year^{-1}$ was sequestered in fine roots and 0.4 Mg C ha^{-1} $year^{-1}$ in coarse roots up to 60 cm depth. Oelbermann *et al.* (2004) reported above ground biomass has potential of sequestering 2.1×10^9 Mg C $year^{-1}$ in the tropical and 1.9×10^9 Mg C $year^{-1}$ in the temperate regions. Albrecht and Kandji (2003) estimated the carbon storage potential of agroforestry systems lie between 12 and 228 Mg ha^{-1} with a median value of 95 Mg ha^{-1}. In another study, Montagnini and Nair (2004) estimated that average carbon storage potential of agroforestry practices to 9, 21, 50 and 63 Mg C ha^{-1} in semiarid, sub-humid, humid and temperate regions, whereby for smallholder agroforestry systems in the tropics, potential rates ranged from 1.5 to 3.5 Mg C ha^{-1} $year^{-1}$.

In one study in Uttar Pradesh, approximately 20 million t of C was estimated to be sequestered by the farm forestry plantations (Singh *et al.,* 2000). Gera *et al.* (2006) reported 115, 64 and 56 t C ha^{-1} sequestration potential under poplar block, poplar boundary, and eucalyptus boundary plantations respectively under an irrigated agroecosystem on a farmer's fields. Contribution of poplar plantations to carbon storage was found to be 27–32 t ha^{-1} in boundary system, whereas it was 66–83 t ha^{-1} in agri-silviculture system at a rotation period of 7 years in Saharanpur (UP) and Yamunanagar (Haryana) districts of northwestern India (Rizvi *et al.,* 2011). Maikhuri *et al.* (2000) found the aboveground biomass accumulation in central Himalayan agroforestry systems is 3.9 t ha^{-1} $year^{-1}$

compared to 1.1 t ha^{-1} $year^{-1}$ at the degraded forestland. Carbon allocation studies in different components of some important tree species of India was also made by Negi *et al.* (2003). They reported that carbon content of *Dalbergia sissoo* in leaf was 38.93%, while in wood the value was 44.45%. In *Populus deltoides*, leaf carbon content was 32.265 and in wood the value was 45.29%. Mendoza *et al.* (2005) reported that carbon accumulation in the above ground biomass of *Bambusa oldhamii* plantation was 103.97 Mg C ha^{-1} of which 83.75% was found in stem, 12.3% in foliage and 4% in branches.

Carbon sequestration and its mitigation through soil : Soil carbon is an important determinant of site fertility due to its role in maintaining soil physical and chemical properties (Sarvade *et al.,* 2016). Soil stores 2 or 3 times more carbon than that which exists in the atmosphere (Davidson *et al.,* 2000), although measurements of carbon stocks in soils are not very accurate due to sampling and measurement problems (Koskela *et al*., 2000). For the past 20 years, scientists are attempting to calculate the global carbon stocks of tropical forests, as well as the changes in these stocks as changes in land use occur. Globally carbon stocks in the soil exceed carbon stocks in vegetation by a factor of about five. Tropical savannas store about one third of carbon in vegetation as do tropical forests, but savannas also have large carbon stocks in soils, similar to those of temperate grasslands. Croplands, worldwide have the smallest carbon stock in vegetation, with intermediate values for soils. In agroforestry, carbon stock depends on the number of trees included in the systems, soil management and conservation practices. According to the IPCC (2000) tropical forests are by far the largest carbon stock in vegetation, while boreal forests represent the largest carbon stock in soils. The world's soils hold about twice (1400-1500 Gt C) as much carbon as the atmosphere (Schlesinger, 1977). Carbon stored in agricultural soil was estimated to 170 Gt, while the entire vegetation constituted 550 Gt C (Rastogi *et al.,* 2002).

The soil organic carbon and net carbon sequestered is generaly greater in the silvipastoral systems (Table 4). Kang *et al.* (1999) conducted a study on *Leucaena leucocephala* hedgerow intercropping in Nigeria and reported that surface soil organic carbon was 2.38 Mg C ha^{-1} which was 15% higher than the controlled plot. Eswaran *et al.* (2000) estimated that the global forest soil organic carbon stock was about 580 Pg, while Lal (2000) estimated that soil carbon pool was about 2500 Pg, comprising of 1550 Pg of soil organic carbon (SOC) and 950 Pg of soil inorganic carbon. Ajit *et al.* (2016) estimated that rate of soil carbon sequestration under the existing agroforestry at district level in India ranged from 0.003 to 0.51 Mg C ha^{-1} $year^{-1}$. Soil carbon storage potential of different agroforestry systems of India also varied based in sites/regions (Table 5). Velayutham *et al.* (2000) studied the total stock of soil organic carbon of Indian soils by taking 22 sources of data and classified them in 0-30 cm and 0-150 cm soil depths under eight important soil orders found in India and reported that organic carbon stocks were 20.99 and 63.19 Pg in respective soil depths. Oelbermann (2002) reported that *Erythrina poeppigiana* alley cropping system was able to increase soil organic carbon by 1.1 Mg C ha^{-1} $year^{-1}$and 9.6×10^{5} Mg C ha^{-1} could be sequestered by adopting agroforestry practices in Costa Rica. Smith and Heath (2002) reported that soil carbon stocks at 0-20 cm surface

Table 4. Soil organic carbon (SOC) stock in silvipasture systems

Region	Agroforestry system and components	Total storage (t C ha^{-1})
Semi-arid	Silvipastoral system	(age 5 years)
	A. nilotica + natural pasture	9.5-17.0
	A. nilotica+ established pasture	19.7
	D. sissoo + natural pasture	12.4
	D. sissoo + established pasture	17.2
	H. binata + natural pasture	16.2
	H. binata+ established pasture	17
North-western India	Silvipastoral system (age 6 years)	
	Acacial Dalbergial Prosopis + *Desmostacya*	6.8-18.55
	Acacial Dalbergial Prosopis + *Sporobolus*	1.5-12.32
North- western Himalaya	Silvipastoral system	2.17

Source : Rai *et al.* (2001)

Table 5. Soil carbon storage potential of different agroforestry systems of India

Regions	**Agroforestry systems**	**Soil carbon storage potential (t ha^{-1})**	**Source**
Northern India	Agri-silviculture	27.50-92.65	Goswami *et al.* (2014); Sarvade *et al.* (2016); Singh *et al.* (2015); Saha and Jha (2012); Rizvi *et al.* (2016)
	Agri-horticulture	35.93-90.07	
	Agri-horti-silviculture	29.05-84.14	
	Agri-silvi-horticulture	35.73-95.46	
	Silvi-pasture	34.27-115.45	
Central India	Agri-silviculture	23.38	
	Alley cropping	2.38	
South India	Agri-silviculture	24 - 35	
	Homegardens	119.3	
North east India	Agri-silviculture	65.27- 106.00	

soil in Amazonia ranged from 9.1 to 11.6 kg m^{-2}, while the bulk density ranged from 0.77 to 0.84 g cm^{-3}. Swamy and Puri (2005) reported that the rate of soil carbon sequestration was 0.42 Mg C ha^{-1} $year^{-1}$ in *Gmelina arborea* (576 trees ha^{-1}) based AFS in Raipur (Chhattisgarh) at 5 years of age.

Future thrust areas

Productive lands are subjected to various degrees of degradation and are fast turning into wastelands. Increasing population pressure, biotic pressure, unplanned urbanization, and break down of traditional institutions for managing Common Property Resources (CPRs) and lack of appropriate management practices are some of the key reasons for the land degradation. The land degradation has both on-site and off-site impacts which need to be managed properly. Degraded lands can be suitably reclaimed for agriculture or some alternate uses following afforestation, agroforestry and bioengineering measures which are simple and cost effective. The carbon sequestration potential of agroforestry system is higher than any other land use system, but the potential varies with tree species, age of system, crop/variety, type of agroclimate etc. Agroforestry systems offer a win-win opportunity by acting as sinks for atmospheric carbon, while helping to attain food security, increase farm income, improve soil health and discourage deforestation.There is a need to reorient our research priorities and integrated systems such as silvipasture and hortipasture system with focus on wasteland development should be given priority to assure enhancement system productivity and conserving the resources on sustainable basis. Genetic improvement of identified potential multipurpose trees (MPTs) is required for their productivity improvement. Attention must be paid to soil and water conservation techniques in relation to agroforestry based interventions for better resource utilization, besides exploring unexploited and under-exploited trees and grasses of high economic values such as tree borne oil seeds and utilizing them in silvipasture systems. Research on quality assessment of the products obtained from degraded lands such as saline habitats must be given priority for enhancing the area under silvipsature systems.

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