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Carbon sequestration and CO_2 absorption by agroforestry systems: An assessment for Central Plateau and Hill region of India

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India ranks fourth in terms of greenhouse gas (GHG) emissions and accounts for 6% of total GHG emissions in the world. Carbon dioxide (CO_2) has major contribution of 76% in total GHG emissions. Agroforestry that integrates trees in the agricultural landscape is regarded as a strategy for both adaptation and mitigation of climate change. Agroforestry plays an important role in reducing the level of GHG emissions vis-à-vis atmospheric CO_2 through carbon sequestration. Carbon sequestration is the process involved in carbon capture and the long period storage of atmospheric CO_2. In the present study, firstly area under agroforestry was estimated in Central Plateau and Hill region (agro-climatic zone-8) using satellite remote sensing data. Secondly, dynamic CO_2FIX model v3.1 was used to assess the baseline total carbon and carbon sequestration potential (CSP) of agroforestry systems for a simulation period of 30 yr. Finally, equivalent CO_2 absorption was assessed with the help of estimated agroforestry area and net CSP in the zone. Estimated area in Central Plateau and Hill region is about 1.96 million ha, which is 5.18% of total geographical area of this zone. Total carbon sequestered at zone level was estimated to be 17.81 Tg (tera gram) C and equivalent CO_2 absorption is at 65.36 Tg. The CSP of agroforestry systems would be about 158.55 Tg C for a simulated period of 30 yr or CSP would be 5.28 Tg C yr^{-1} at country level. On the other hand, equivalent CO_2 absorption was 586.50 Tg for a period of 30 yr or would be 19.55 Tg yr^{-1} at country level. Hence, the present study concludes that agroforestry has significant contribution in reduction of atmospheric CO_2 which would have much more if the area under agroforestry and/or number of trees ha^{-1} on farmlands are increased.

Keywords. Agroforestry; carbon sequestration; climate change; CO_2FIX model; remote sensing.

1. Introduction

Agroforestry is any sustainable land-use system that maintains or increases total yield by combining food crops (annuals) with tree crops (perennials) and/or livestock on the same unit of land, either alternately or at the same time (Sanchez 1995). Agroforestry is key path to prosperity for millions of farm families leading to extra income, employment generation, greater food and nutrient security and meeting other basic human needs in a sustainable manner. Agroforestry provides resilience to agricultural production under current climatic variability as well as long-term climate change through intensification, diversification and buffering of trees in farming systems (Schoeneberger 2009). The role of agroforestry in protecting the environment and providing a number of ecosystem services is promoted as a key benefit of integrating trees into farming systems.

Carbon sequestration is a phenomenon for the storage of atmospheric carbon dioxide or other forms of carbon (C) to mitigate global warming. The prominent role of forestry and agroforestry systems (AFS) in carbon sequestration has increased global interest to stabilise greenhouse gas (GHG) emissions. It has been reported that 630 million ha area would be available for agroforestry, which has the potential to sequester 586 Mt C yr^{-1} by 2040 (Watson *et al.* 2000).

Estimates of annual carbon uptake increment suggest that forests and plantations have been able to remove at least 0.125 Gt of CO_2 from the atmosphere in the year 1995 (Lal and Singh 2000). Swamy and Puri (2005) investigated biomass production, C-sequestration and nitrogen allocation in *Gmelina arborea* planted as sole and an agrisilviculture system on abandoned agricultural land. Kaul *et al.* (2010) used a dynamic CO_2FIX model for estimating the carbon sequestration potential (CSP) of Sal, Eucalyptus, Poplar and Teak forests in India. The results indicated that the largest carbon stock was in the living biomass of long rotation Sal forests (82 Mg C ha^{-1}). Ajit *et al.* (2013) estimated CSP in selected districts of Indo-gangetic plains of India. The CSP of existing AFS for 30 yr simulation has been estimated to be 0.111, 0.126 and 0.551 Mg C ha^{-1} for Sultanpur, North Dinajpur and Ludhiana districts, respectively.

In India, an average CSP in agroforestry has been estimated to be 25 Mg C ha^{-1} over 96 million ha (Sathaye and Ravindranath 1998), but there is a considerable variation in different regions depending upon the biomass production (Dhyani *et al.* 2009) and method of estimation. Based on global estimates of the area suitable for agroforestry, 1.1–1.2 Pg C could be stored in the terrestrial ecosystems over the next 50 yr (Albrecht and Kandji 2003). Average carbon storage by agroforestry practices has been estimated as 9, 20, 50 and 63 Mg C ha^{-1} in semi-arid, sub-humid, humid and temperate regions, respectively. For small holder AFS in tropics, potential carbon sequestration rate ranges from 1.5 to 3.5 Mg C ha^{-1} yr^{-1} (Montagnini and Nair 2004). Zomer *et al.* (2016) reported that in 2010, 43% of all agricultural land globally had at least 10% tree cover. With this tree cover analysis, they estimated 45.3 Pg C on agricultural land globally with trees contributing more than 75%. On an average globally, biomass carbon increased from 20.4 to 21.4 Mg C ha^{-1}.

According to IPCC Annual Report 5 (2014), the agricultural production and ongoing land use change contribute significantly to GHG emissions accounting for 24% globally. GHG emissions in India were of the order of 2008.67 Tg (tera gram) of CO_2 equivalent without emissions from land use, land-use change and forestry (LULUCF). Whereas with LULUCF, the emissions were about 1831.65 Tg of CO_2 equivalent. The energy sector accounted for the highest 69% of the total emission and the agriculture sector contributed to 19% of the emission. The LULUCF sector as a whole was net sink category for CO_2 (Sharma *et al.* 2011). India ranks fourth in the world in GHG emissions and contributes about 6% of the total emissions (Bordon *et al.* 2015). Carbon sequestration has the potential to significantly reduce the level of GHGs that occurs in the atmosphere as CO_2 and to reduce the release of CO_2 to the atmosphere from major stationary human sources, including power plants and refineries (Pacala and Socolow 2004). Finally, more stringent emission reductions are required to achieve the 2°C global warming target, which may require more rapid and tremendous changes in socio-economic conditions (Luderer *et al.* 2011; Rogelj *et al.* 2011, 2013; Riahi *et al.* 2015).

Remote sensing has become an effective tool for mapping and monitoring of agriculture, forestry and other earth features. According to IPCC GPG (Intergovernmental Panel on Climate Change Good Practice Guidance 2004), remote sensing methods are especially suitable for quantification of aboveground vegetation biomass stocks and associated changes. While the importance of biomass carbon and carbon sequestration in forests is widely recognised (Turnet *et al.* 2004; Gibbs *et al.* 2007; Ramchandran *et al.* 2007; Sivrikaya *et al.* 2007; Houghton *et al.* 2009; Pan *et al.* 2011), the biomass carbon pool on agricultural land is seen as arguably negligible as compared to the soil organic carbon pool (Lal 2004). Very few studies (Singh and Chand 2012; Upgupta *et al.* 2015; Rizvi *et al.* 2016a) have been found where geospatial technologies were applied for the estimation of carbon stock and carbon sequestration under agroforestry. In India, preliminary estimates of agroforestry area through remote sensing were reported by Rizvi *et al.* (2014) and methodology for mapping agroforestry using medium resolution remote sensing data was given by Rizvi *et al.* (2016b). Nowadays, carbon dioxide (CO_2) capture and storage is a big issue for all. Nair (2012) highlighted a number of issues like methodologies, sampling, measurements, computation, analysis, interpretation, etc., for less consistent data in agroforestry. Agroforestry has a significant role in reducing the GHG emissions, but neither a systematic study has been conducted nor is methodology available for assessing the contribution of agroforestry in atmospheric CO_2 absorption at regional level.

Keeping this in view, the present study has been carried out with the objectives: (i) estimation of area under agroforestry for Central Plateau and Hill region (ACZ-8) using GIS and remote sensing, (ii) estimation of CSP under AFS using CO_2FIX model at zone level, and (iii) assessment/quantification of equivalent CO_2 absorption by AFS. Besides this, an attempt has also been made to assess the contribution of AFS in carbon sequestration and reduction in GHGs emission at country level.

2. Materials and methods

2.1 *Study area*

Agro-climatic zone-8, i.e., Central Plateau and Hill region spreads over Bundelkhand, Baghelkhand, Bhander plateau, Malwa plateau and Vindhyachal hills. Total geographical area of the zone is 378439.79 km^2. This zone consists of 60 districts spread over three states (Uttar Pradesh, Madhya Pradesh and Rajasthan) and is centrally located. It is interspersed with plateau and hill areas and lies in arid and semi-arid regions of India. There are vast areas of barren and uncultivatable land. Water run-off is excessive. Nearly 15% of the land is not available for cultivation. Out of 60 districts, seven districts namely Dausa, Guna, Hamirpur, Hoshangabad, Lalitpur, Pali and Panna were selected in various ranges.

2.2 *Agroforestry mapping by remote sensing*

For mapping agroforestry area in selected districts, Resourcesat-2/LISS III multispectral remote sensing data (spatial resolution 23.5 m) were used. Remote sensing data was procured from National Remote Sensing Centre, Hyderabad for the period 2012–2013. These data were visually and digitally interpreted using ERDAS Imagine 11.0 software. Classification accuracy was obtained with the help of ground check points collected on agroforestry from farmers' fields. Thematic maps for land use land cover and agroforestry were prepared using ArcGIS 10.0 software.

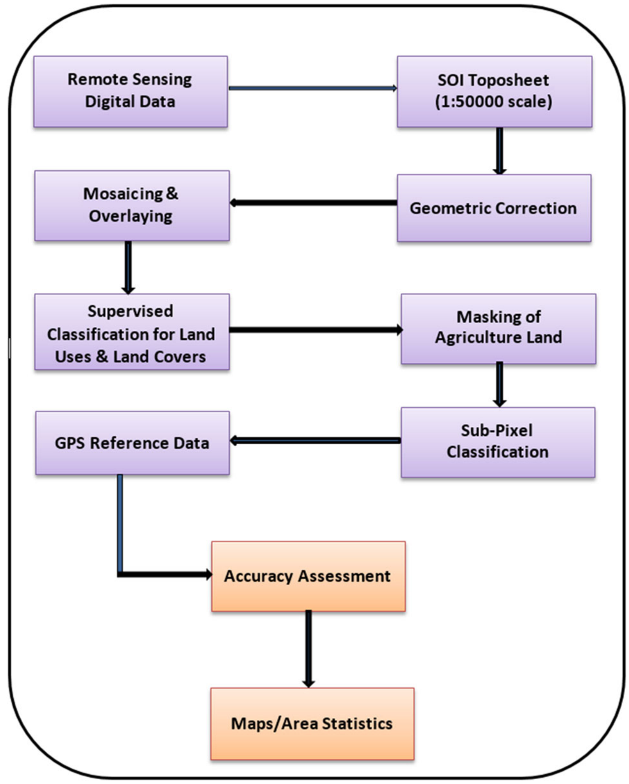

Figure 1. Methodology for mapping agroforestry by remote sensing at district level.

The methodology adopted by Rizvi *et al.* (2016b) was used for mapping agroforestry at district level (figure 1). They applied sub-pixel classifier on medium resolution remote sensing data, which gives an output in the form of per cent tree cover within pixel ranging from 20% to 100%. Advantage of using sub-pixel classifier is that all types of AFS, viz., scattered trees on farmlands, linear, block plantations, etc., can be identified, which is not possible with pixel-based classifiers.

2.3 *Carbon stock estimation by CO_2FIX model*

The dynamic carbon accounting model CO_2FIX v3.1 (Masera *et al.* 2003; Schelhaas *et al.* 2004) was used to assess the baseline carbon and simulating the CSP of AFS in the district. CO_2FIX model has been developed as part of the CASFOR II project. It is a user-friendly tool for dynamically estimating the CSP of forest management, agroforestry and afforestation projects. This model consists of six modules, viz., biomass module, soil module, products module, bioenergy module, financial module and carbon accounting module. For the purpose of simulating carbon stock under AFS in this study, three modules namely biomass, soil and carbon accounting modules were taken into consideration.

CO_2FIX model requires both primary and secondary data on tree and crop components for preparing the account of carbon sequestered under AFS on per hectare basis. Primary data include tree species on farmlands along with their numbers, diameter at breast height (DBH in cm), crops grown along with their productivity, area coverage, etc., whereas secondary data include the growth rate of tree biomass components (stem, branch, foliage, root) for tree species on annual basis. For simulating tree biomass components in various tree cohorts, same input parameters as mentioned by Ajit *et al.* (2013) were used in CO_2FIX model.

2.4 *Estimation of equivalent CO_2 absorption*

Biomass carbon and carbon sequestered for selected districts estimated through CO_2FIX model have been multiplied by a factor of 44/12 (or 3.67) to get the estimates of equivalent CO_2 absorption per ha (IPCC 2003). These values were then multiplied by area under agroforestry for estimation of equivalent CO_2 absorption at district level. Equivalent CO_2 absorption and agroforestry area of the selected districts were added to get the total values. These total values and estimated area under agroforestry of the agro-climatic zone-8 were used for extrapolating equivalent CO_2 absorption at zone level.

3. Results and discussion

3.1 *Estimation of area under agroforestry*

Seven districts namely Dausa, Guna, Hamirpur, Hoshangabad, Lalitpur, Pali and Panna were selected from agro-climatic zone-8. Estimated area under agroforestry was the highest in Pali (6.71%) followed by Dausa (6.54%) and Lalitpur (6.53%) with an average of 5.18% in the selected districts (table 1). The tree density was found to be much lower than in Indo-Gangetic plains in Punjab and Haryana and western Uttar Pradesh as reported by Ajit *et al.* (2013) and Rizvi *et al.* (2011), because block plantations and agri-silviculture systems exist there. This estimated area was found to be low because no systematic agroforestry exists in this zone; only scattered trees are found on the farmlands. Considering this average figure, area under agroforestry was extrapolated for whole agro-climatic zone, which is about 1.96 million ha. The spatial distribution of agroforestry area in the selected districts of agro-climatic zone-8 is depicted in figure 2. The estimated area under agroforestry was used for assessment of CSP at district and zone levels.

Table 1. *Estimated agroforestry area in selected districts of agro-climatic zone-8.*

District	Geog. area (ha)	AF area (ha)	AF area (%)
Guna	640150.28	32419.41	5.06
Hoshangabad	669809.04	24598.02	3.67
Panna	707823.28	24098.52	3.40
Dausa	343223.92	22430.59	6.54
Pali	1254939.81	84149.97	6.71
Hamirpur	389469.52	14925.83	3.83
Lalitpur	505002.95	32994.78	6.53
Total	4510418.80	235617.12	5.22

3.2 *Tree species and their density in surveyed districts*

A field survey was conducted in selected districts during 2013–2014 and tree species found on farmlands, their observed DBH and number of trees per ha were recorded (tables 2 and 3). Number of trees ha^{-1} were highest in Lalitpur district (15.9) followed by Pali (14.9) and Dausa (12.9) districts. These values of DBH and tree densities were taken as input for CO_2FIX model to estimate biomass and carbon stock for slow, medium and fast growing trees. Biomass (tree + crop) was then converted into biomass carbon for baseline (2013–2014) and simulated period of 30 yr using carbon accounting module. Soil carbon has also been simulated using soil module of CO_2FIX model by taking soil organic carbon as input. Biomass and soil carbon were then added to get the estimated total carbon in existing AFS.

3.3 *Estimation of biomass carbon and carbon sequestration*

Total biomass (tree + crop) under AFS in Guna, Hoshangabad, Panna, Dausa, Pali, Lalitpur and Hamirpur districts was estimated by CO_2FIX model. It was about 9.55, 11.16, 7.83, 12.88, 17.19, 35.57 and 26.5 Mg DM ha^{-1}, respectively, for baseline (table 4). Biomass carbon was estimated to be 4.31, 5.06, 3.54, 6.09, 7.95, 16.80 and 12.32 Mg C ha^{-1} for baseline for these districts,

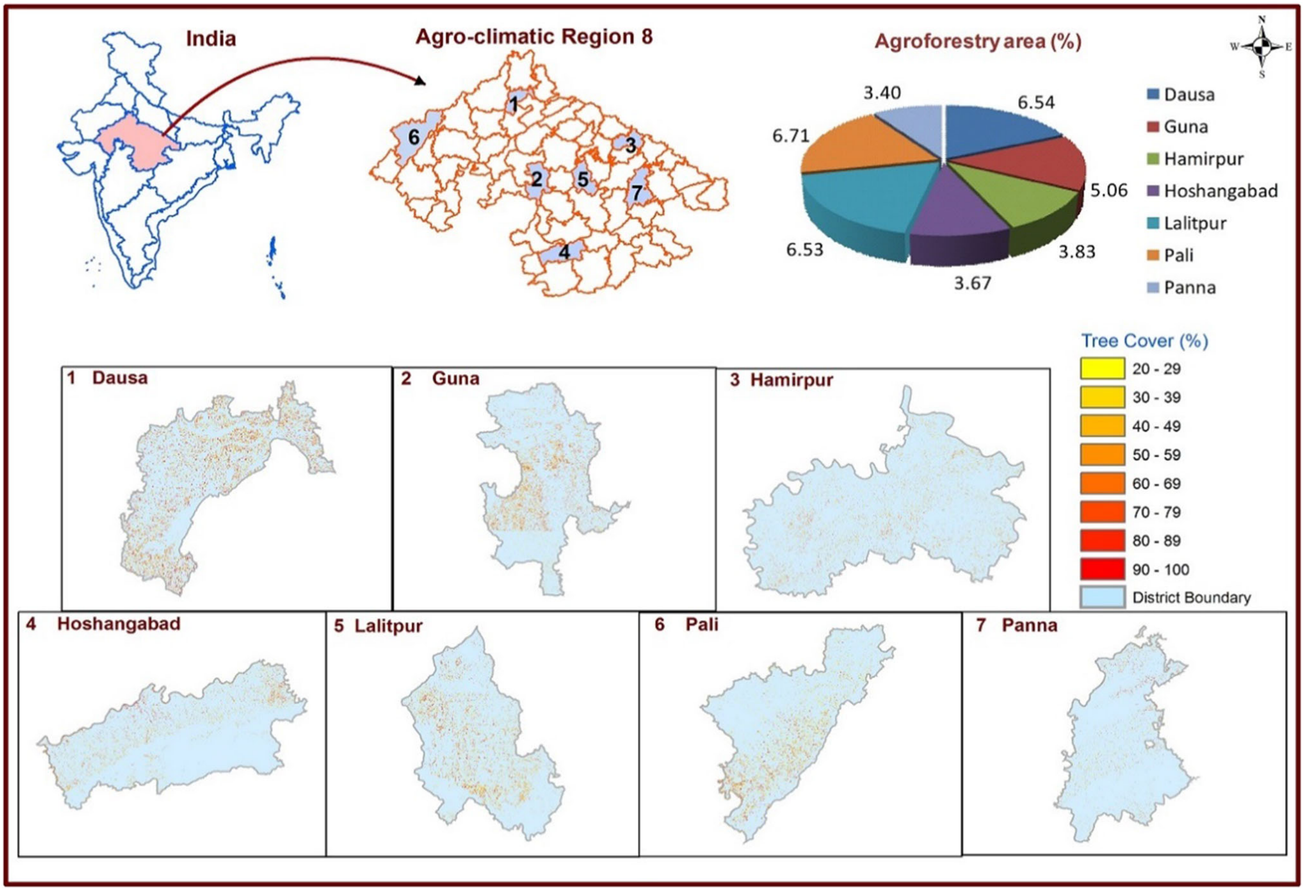

Figure 2. Agroforestry area statistics and maps of selected districts in ACZ-8.

respectively. Total biomass as well as biomass carbon were highest for Lalitpur district because tree density was also highest (15.9 trees ha^{-1}) in this district. Total carbon (biomass + soil) in Guna, Hoshangabad, Panna, Dausa, Pali, Lalitpur and Hamirpur districts was estimated to be 27.61, 22.81, 21.49, 22.58, 24.45, 26.50 and 20.67 Mg C ha^{-1}, respectively, for baseline. This total carbon would increase to 32.39, 27.22, 24.73, 31.56, 35.39, 41.93 and 32.10 Mg C ha^{-1} in these districts, respectively, for a simulated period of 30 yr. In this way, net carbon sequestered by AFS in simulated period of 30 yr will be 4.78, 4.41, 3.24, 8.98, 10.94, 15.43 and 11.43 Mg C ha^{-1} in these districts, respectively.

3.4 *Carbon sequestration and equivalent CO_2 absorption*

Carbon sequestered at district level was computed by multiplying net carbon sequestered with agroforestry area in the district. In this way, highest carbon sequestered was obtained in Pali district, i.e., 0.921 million t C (Mt C) followed by Lalitpur district, i.e., 0.509 Mt C (figure 3). Carbon sequestered in all seven districts was about 2.141 Mt C. This district level sequestered has been extrapolated for agro-climatic zone-8 by considering 1.96 million ha area under agroforestry of this zone. Therefore, carbon sequestered at zone level was estimated to be 17.81 Mt C.

Equivalent CO_2 absorption by AFS has been assessed for the selected districts as well as for the agro-climatic zone-8. Pali district has maximum contribution in equivalent CO_2 absorption of 3.378 Mt (43%) followed by Lalitpur 1.868 Mt (24%) and Dausa 0.732 Mt (9%) districts (figure 4). Equivalent CO_2 absorption by AFS was maximum in Pali district because it has highest area under agroforestry and also C-sequestered at district level among the selected districts. Equivalent CO_2 absorption was estimated to be 7.86 Mt in seven districts and extrapolated to 65.87 Mt for whole agro-climatic zone.

Rizvi *et al.* (2016a) assessed the carbon storage potential of AFS in Gujarat plains of India using

Table 2. *Site characteristics, dominant trees/crops and climate of the study districts.*

Attributes	Guna	Hosangabad	Panna	Dausa	Pali	Lalitpur	Hamirpur
Location	24.65°N; 77.32°E	22.75°N; 77.72°E	24.72°N; 80.17°E	26.88°N; 76.33°E	30° 43′ N; 76° 03′E	24.69°N; 78.41°E	25.95°N; 80.15°E
Rainfall (mm),	1042 mm	1214 mm	1069 mm	561 mm	330 mm	904 mm	900 mm
Climate	Tropical	Normal	Warm and temperate	Hot and dry	Hot and dry	Hot and dry	Hot summer, pleasant cold season
Soil type	Red and yellow	Red and yellow	Mix and red	Deep brown loam and sandy	Medium light yellowish brown Sandy and loamy	Black and red	Dark black to light brown
Dominant agroforestry trees	*Acacia nilotica* (21.16), *A. indica* (12.65), *Leucaena leucocephala* (9.57), *Madhuca indica* (8.12), *Simaruba glauca* (8.11)	*Leucaena leucocephala* (17.3), *Acacia nilotica* (15.27), *Tectona grandis* (14.84), *Mangifera indica* (9.79), *Eucalyptus tereticornis* (7.08)	*Leucaena leucocephala* (20), *Acacia nilotica* (12.2), *Mangifera indica* (7.75), *A. indica* (7.15), Zizyphus mautitiana (4.52)	*A. indica* (30.9), *Acacia nilotica* (19.44), *Prosopis cineraria* (8.05), *Dalbergia sissoo* (6.51), *Prosopis juliflora* (2.5)	*Prosopis cineraria* (59.52), *Prosopis juliflora* (16.31), *Zizyphus mautitiana* (8.55), *A. indica* (7.84), *Dalbergia sissoo* (3.92)	*Mangifera indica* (21%), *A. indica* (20%), *Acacia nilotica* (15%), *Zizyphus mautitiana* (12%)	*Azadirachta indica* (22%), *Mangifera indica* (18%), *Psidium gujava* (17%), *Acacia nilotica* (14%), *Zizyphus mautitiana* (10%)

CO_2FIX model and satellite remote sensing data. They estimated 2.907 and 3.251 Mt C as total carbon storage for baseline and simulated period of 30 yr in four districts of Gujarat.

3.5 *Contribution of agroforestry in GHG reduction*

CSP of AFS estimated in previous section was to the tune of 17.811 Tg C at zone level (1 Tg = 1 million t). Considering an area of 17.45 M ha under agroforestry in India as given by Rizvi *et al.* (2014), the CSP would be about 158.55 Tg C for a simulated period of 30 yr and the rate of CSP would be 5.28 Tg C yr^{-1} at country level. The equivalent CO_2 absorption was estimated to be 65.87 Tg at zone level and 581.97 Tg at country level for a period of 30 yr (table 5). In other words, annual CO_2 absorption by AFS would be 19.40 Tg yr^{-1} at country level. This would be more if the area under agroforestry in the country increases. In 2007, total emission from agriculture sector was to the tune of 372.65 Tg of CO_2 equivalent emissions, which was 19% of total GHG emissions from the country (Sharma *et al.* 2011). Therefore, as per our estimate of equivalent CO_2 absorption, AFS can offset about 5.24% of emissions from agriculture sector. Watson *et al.* (2000) reported that agroforestry has potential to sequester 586 Tg C yr^{-1} over an area of 630 million ha, which will be 2150.60 Tg yr^{-1} equivalent CO_2 absorption. Thus, country level estimate of equivalent CO_2 absorption by AFS covering an area of 17.45 million ha seems quite reasonable. This country-level assessment is based on estimates of agroforestry area and CSP for agro-climatic zone-8, i.e., Central Plateau and Hill region only. Therefore, actual figures would be much higher when all the 15 agro-climatic zones of the country are taken into consideration.

In India, total emissions from the energy sector in 2007 were 1388.31 Tg of CO_2 equivalent. Of this, 1285.81 Tg was emitted as CO_2, 4.06 Tg as CH_4 and 0.06 Tg as N_2O (Sharma *et al.* 2011). If CO_2 emission by energy sector in 2007 is taken as base, the contribution of agroforestry in atmospheric CO_2 absorption will be 1.52% of the total CO_2 emission. This contribution would be much higher if tree density on agricultural lands is increased from just 10–15 to 50–100 trees ha^{-1}. Moreover, if area under agroforestry also increases from present 17.45 to 28.0 M ha as envisaged in Planning Commission Report on

Table 3. *Number of trees and their observed DBH in surveyed districts of ACZ-8.*

Selected districts	Estimated age of existing trees (yrs)			Observed DBH of existing trees (cm)			No. of trees
of ACZ-8	Slow	Medium	Fast	Slow	Medium	Fast	(ha^{-1})
Guna	40.3	17.2	9.6	29.41	27.20	22.87	6.4
Hosangabad	47.0	20.0	9.0	34.31	31.60	21.33	4.4
Panna	65.1	19.8	7.3	47.50	31.31	17.37	6.8
Dausa	67.9	19.4	8.4	49.58	30.60	19.93	12.9
Pali	59.5	16.7	8.1	43.40	26.24	19.26	14.9
Lalitpur	40.0	17.0	7.0	29.20	26.86	16.59	15.9
Hamirpur	42.0	16.0	6.0	30.66	25.28	14.22	8.5

Table 4. *Estimated biomass, carbon and carbon sequestered under agroforestry systems.*

Baseline and simulated biomass carbon		Agro-climatic zone-8						
		Guna	Hosangabad	Panna	Dausa	Pali	Lalitpur	Hamirpur
Total biomass (tree+ crop) Mg DM ha^{-1}	Baseline	9.55	11.16	7.83	12.88	17.19	35.57	26.5
	Simulated	16.45	16.88	12.13	30.51	39.11	58.12	37.37
Soil carbon (Mg C ha^{-1})	Baseline	23.38	17.75	17.95	16.49	16.50	9.70	8.35
	Simulated	24.80	19.42	19.12	17.01	16.92	14.30	14.56
Biomass carbon (Mg C ha^{-1})	Baseline	4.31	5.06	3.54	6.09	7.95	16.80	12.32
	Simulated	7.59	7.80	5.61	14.55	18.47	27.63	17.54
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline	27.61	22.81	21.49	22.58	24.45	26.50	20.67
	Simulated	32.39	27.22	24.73	31.56	35.39	41.93	32.1
Net carbon sequestered by agroforestry in simulated period of 30 years (Mg C ha^{-1})		4.78	4.41	3.24	8.98	10.94	15.43	11.43
Annual carbon sequestered by agroforestry (Mg C $ha^{-1}yr^{-1}$)		0.15	0.15	0.11	0.29	0.36	0.51	0.38

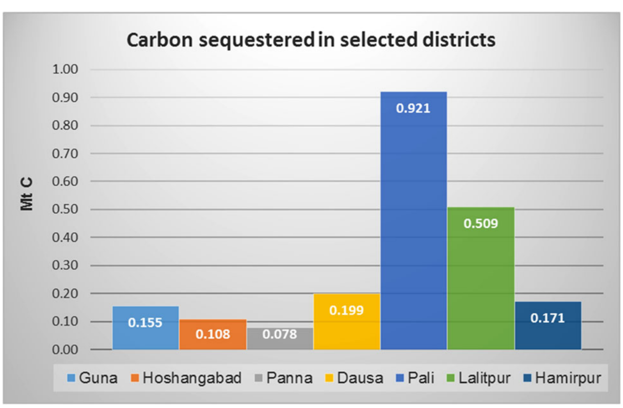

Figure 3. Total carbon sequestered in selected districts of ACZ-8.

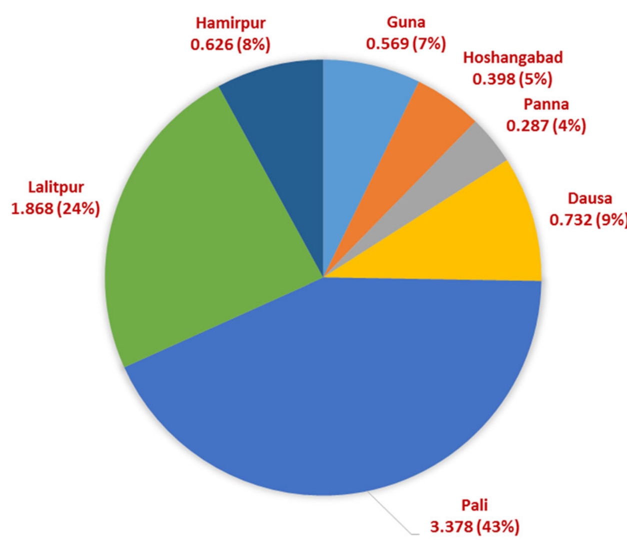

Figure 4. Equivalent CO_2 absorption (Mt) in selected districts of ACZ-8.

Table 5. *Estimated equivalent CO_2 absorption at zone and country level.*

Estimates	ACZ-8	India
Agroforestry area (M ha)	1.975	17.45
Total carbon sequestration (Tg C)	17.947	158.55
Equivalent CO_2 assimilation (Tg)	65.870	581.97

1 Tera gram (Tg) = 1 million ton (Mt).

Greening India (2001), the contribution of agroforestry to offset atmospheric CO_2 would be significantly higher than the estimates of present study.

4. Conclusion

The study revealed that agroforestry has great potential of reducing atmospheric CO_2 through carbon sequestration as plant and soil C. AFS can also offset GHG emissions from agriculture sector. In order to know the potential of carbon sequestration by AFS at regional or country level, an accurate estimate of area is essential for which geospatial technologies can play an important role. The methodology proposed in this study may be used for assessment of CO_2 absorption by AFS at regional level. Thus by development of suitable AFS in different agro-climatic regions of the country, not only can the green tree cover be increased but also level of GHG in atmosphere can be reduced to a great extent. Hence, agroforestry will prove to be a viable strategy for climate change mitigation if it is promoted for wider adoption by the farmers in the country.

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