National Innovations in Climate Resilient Agriculture (NICRA)

A Country Level Assessment of Area under Agroforestry and its Carbon Sequestration Potential

Ram Newaj, R.H. Rizvi, O.P. Chaturvedi, Badre Alam
Rajendra Prasad, Dhiraj Kumar & A.K. Handa

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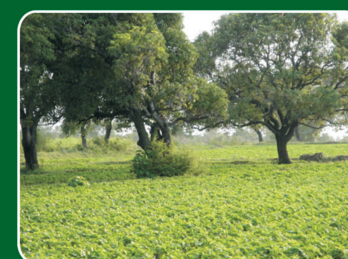

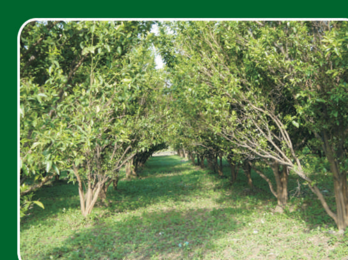

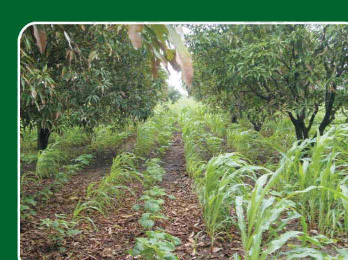

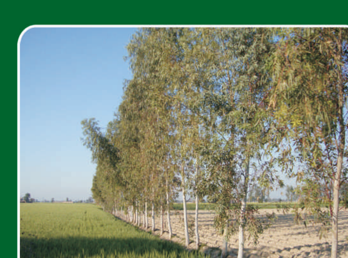

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Progress Through Science

Dr. R.S. Paroda
Founder Chairman

Foreword

Global climate change caused by rising levels of carbon dioxide (CO_2) and other greenhouse gases is recognized as a serious environmental issue of the twenty-first century. The role of land use systems in stablizing the CO_2 levels and increasing the carbon (C) sink potential has attracted considerable scientific attention in the recent past. Climate change has increasingly gained momentum as a major threat against the survival of the biotic community. Removing atmospheric carbon (C) and its storage in the terrestrial biosphere is a vital for compensating the emission of green house gases. Agroforestry, a land-use system has an integral relationship with the farm community to supplement fuel, fodder, fruits, fibers and organic fertilizers on one hand and capture abundant amounts of carbon on the other. Now the researchers and planners are taking interest to increase the carbon storage capacity of terrestrial vegetation through land-use practices such as afforestation, reforestation and agroforestry. Agroforestry system (AFS) has today become an established approach to integrated land management, not only for renewable resource production, but also for climate change mitigation. The carbon storage capacity in agroforestry varies across the specie and geography. Further the amount of carbon in any agroforestry system depends upon the structure and function of different components within system put in to practice. The carbon stock available in agroforestry at country or state level is not well documented.

Now the efforts are being made by the scientists of Central Agroforestry Research Institute, Jhansi to assess carbon sequestration potential (CSP) in agroforestry system and mapping of agroforestry area at country level which has been completed considerably in most of the stats namely Uttar Pradesh, Gujarat, Bihar, West Bengal, Rajasthan, Punjab, Haryana, Himachal Pradesh, Maharashtra, Tamil Nadu, Andhra Pradesh, Karnataka, Madhya Pradesh, Chhattisgarh, Orissa and Telangana. The mapping of agroforestry in 10 agro-climatic zone has already been done. This Bulletin contains assessment of CSP and mapping area under agroforestry and thier achievements.

I congratulate all the authors Drs Ram Newaj, RH Rizvi, OP Chaturvedi, Badre Alam, Rajendra Prasad, Dhiraj Kumar and AK Handa for developing a publication entitled 'A Country Level Assessment of Area under Agroforestry and its Carbon Sequestration Potential' to address the CSP in agroforestry system and area under agroforestry which relevant and timely. The bulletin is highly recommended for use by students and researchers working on carbon sequestration as well as mapping agroforestry area.

(R.S. Paroda)
Chairman, TAAS
Former Director General, ICAR and
Secretary, DARE, Govt. of India

Preface

The biological mitigation of climate change is a very effective for reducing atmospheric concentration of greenhouse gases (GHGs) especially CO_2 emission through conservation of existing carbon pool available in forest and increasing of carbon stock through inclusion of trees with agricultural crop under agroforestry system. The carbon stock available in Indian forests is well documented but the carbon stock available under agroforestry at country or state level is not well documented. The ICAR-Central Agroforestry Research Institute (CAFRI), Jhansi has been working since a decade on assessing carbon sequestration potential and mapping of agroforestry area in the country.

The approach for estimation of agroforestry area in the country and carbon sequestration potential of agroforestry existing on farmer's field in different states are compiled in the form of bulletin. We hope this bulletin will be helpful for students, researchers, NGOs and others who are interested in mapping agroforestry area and carbon sequestration study in agroforestry.

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1. Introduction

National Innovations on Climate Resilient Agriculture (NICRA) is a network project of Indian Council of Agricultural Research, which was launched in February, 2011. The project aims to enhance resilience of Indian agriculture to climate change and climate vulnerability through strategic research and technology demonstration. The research on adaptation and mitigation covers crops, livestock, fisheries and natural resource management. The Central Agroforestry Research Institute, Jhansi is associated with NICRA project from its beginning. The institute is working on three aspects under this project i) assessment of carbon sequestration potential of agroforestry systems existing on farmer's field through simulation model (CO2FIX model), ii) mapping of agroforestry area using GIS and Remote Sensing technique and iii) study on thermo-tolerance of agroforestry species. The approach for estimation of agroforestry area in the country and carbon sequestration potential of agroforestry existing on farmers' field in different states are briefly described in this bulletin.

2. Mapping of agroforestry area in India

Many attempts have been made in this direction to estimate the agroforestry area in the country (Dhyani *et al*., 2013; Rizvi *et al*., 2014). However, these estimates are not the true reflection as they are not based on ground truthing. Some estimates of area and production of wood for the tree cover outside forests are available (FSI, 2015), but these estimates also include trees on canal side, roadside, and in urban areas thus do not represent true agroforestry area. Besides, tree patches of one hectare or more with a tree canopy density of more than 10 per cent have been included in forest cover irrespective of land use and ownership. These tree patches like block plantations may occur on farmers' fields, therefore such agroforestry area is wrongly diverted to forest (Dhyani *et al*., 2013).

A major problem in estimating area under agroforestry is lack of procedures for delineating the area influenced by trees in a mixed stand of trees and crops. In simultaneous systems the entire area occupied by multi-strata systems such as home gardens, shaded perennial systems and intensive tree-intercropping situations can be listed as agroforestry. The problem is more difficult in the case of practices such as windbreaks and boundary planting where although trees are planted at wide distance between rows (windbreak) or around agricultural fields (boundary planting) because the influence of trees extend over a larger than easily perceivable extent of areas (Nair *et al*., 2009).

There are some issues in mapping agroforestry which needs to be addressed before stepping forward in this direction.

2.1 Occurrence of mixed tree species in agroforestry

In any district or region, several forms of agroforestry systems exist such as agri-silviculture, agri-horticulture, block and others plantations on agricultural fields. Mapping of these agroforestry systems requires processing of remote sensing images using some hard or soft classifier in software like ERDAS. For the computerized processing, the signatures of all agroforestry systems have to be clubbed into one signature. Using this signature agroforestry area is mapped and estimated. Since this signature includes spectral reflectance from different tree species (fruit and timber), so the pixels having spectral values close to the spectral values of signature will be grouped into agroforestry class. If this signature has spectral reflectance of Eucalyptus trees, then all the Eucalyptus plantations on roadside or canal side will also be included in agroforestry class. Pixel based classification methods either unsupervised or supervised generally groups the pixels having spectral values close to each other. As an outcome a thematic map of desired number of classes is generated. But such methods may lead to wrong classification in case of agroforestry as discussed.

2.2 Mixing of sugarcane with agroforestry

Another type of error that is usually occurred in agroforestry mapping is the intermingling of sugarcane crop with agroforestry. Reason for this is the similarity between signatures of sugarcane crop and young plantations. Soft classifiers like Fuzzy, though detects more than one features within pixel, cannot separate sugarcane with young plantations. Therefore, agroforestry mapping requires thoughtful and systematic approach as well as skill. Whether we use LISS III or LISS IV data, new plantations on farmlands are unable to be identified by any of these classification methods. So the area estimates so obtained will not include such plantations and lead to wrong estimation. Actually spectral response of each pixel is the result of the contribution of all sub-pixel components, so the attribution of the pixel to a unique category becomes problematic (Gopal and Woodcook, 1994).

2.3 Spatial resolution of remote sensing data

Accuracy of land use land cover (LULC) classification depends upon the spatial resolution of remote sensing data used. If the high resolution image is used say Cartosat-1 (2.5 m resolution) or LISS IV (5.8 m resolution); different vegetation like grass, crop, and trees can be identified and delineated. But the cost and processing of data will be much high if the study area is large say state or agro-climatic region and also administrative approval is required for procuring high resolution data like Cartosat-1 or Cartosat-2. In case of high resolution data, single pixel will have spectral reflectance from single feature, so there are less chances of mixing of features within a pixel. Whereas in case of medium resolution data like Landsat or LISS III (spatial resolution > 20m), single pixel can consist of two or more land features such as crop, soil and trees.

Kumar *et al*. (2011) mapped trees outside forests using merged data products of LISS-IV and Cartosat-1 and found 11.09 per cent area under trees outside forest in Bilaspur block of Yamunanagar (Haryana). Tauqeer *et al.* (2016) mapped *Populus* and *Eucalypts* based agroforestry systems in Ludhiana district using LISS-IV multispectral data. Extensive survey was also performed for ground truthing. Scattered trees on farmlands and boundary plantations are difficult to identify with medium resolution satellite data like LISS III (23.5 m) or Landsat (30 m). For correct estimation of area under scattered trees, high resolution multispectral data either LISS IV (5.8 m) or merged LISS IV and Cartosat-1 datasets must be used. But this would involve enormous data processing and huge cost as far as regional or country level mapping is concerned.

2.4 Selection of suitable method for classification

As far as small area say block or district is concerned, estimation of agroforestry area can be done accurately using merged LISS IV and Cartosat data using object oriented classification technique as demonstrated by Bisen and Patel (2012). But for large geographical area such as state or agro-climatic region, use of high resolution data will result in high cost and more data processing. Thus for agroforestry mapping at larger scale (state or country), one has to rely on medium resolution data like LISS III. But some improved classification technique has to be applied other than maximum likelihood or minimum distance to mean classifiers, where one pixel is assigned to one classonly.

Zomer *et al*. (2007) mapped the extent of adoption of the Poplar agroforestry systems and estimates tree cover within the agricultural landscape of poplar growing areas of Punjab, Haryana and western U.P. The authors adopted multi-phased remote sensing approach; first MODIS data (250 m resolution) was used to map the agricultural areas. Forest Canopy Density (FCD) mapping of Landsat ETM+ data (28.5m resolution) was used to derive the tree cover within agricultural areas. The IKONOS (1 m PAN image) was used to assess the accuracy of the areas of tree cover estimates. Extensive ground truth data used to evaluate and validate the results. There are some limitations in adoption of this methodology, first FCD mapping can only be done with seven bands data of Landsat ETM+ (Baynes, 2007). Second, extensive ground truth is not feasible as far as state or country level agroforestry mapping is concerned.

2.5 Preliminary Estimates of Area under Agroforestry

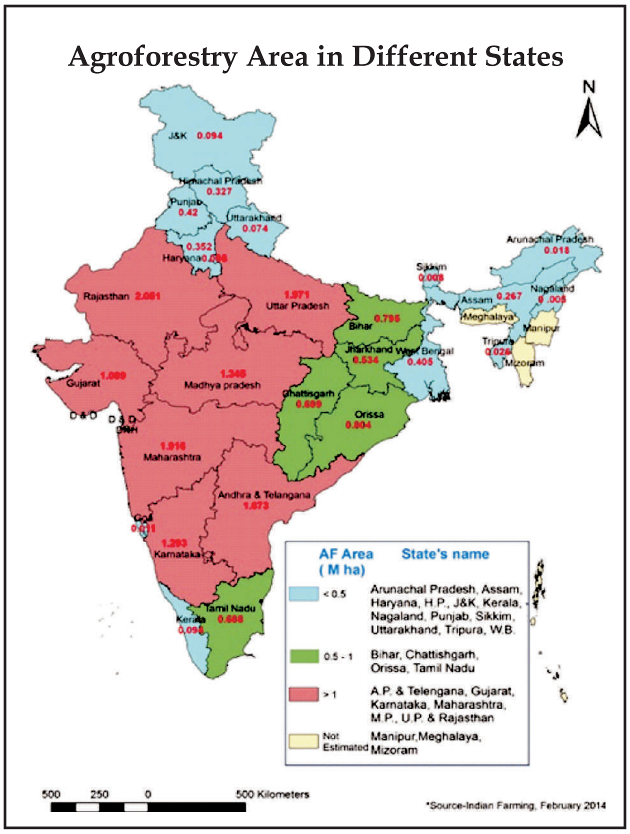
The extent of agroforestry area in India was estimated by using Bhuvan LULC data (http://bhuvan-noeda.nrsc.gov.in/theme/thematic/theme.php) for the year 2011-12. The area under cropland and fallow land were considered for estimation purpose and 10 per cent of these areas were calculated as agroforestry based on the available information. In this way, extent of agroforestry in India was estimated to be 14.46 m ha when fallow land was not included (Table 1). Potential area under agroforestry was estimated to be about 17.45 m ha, when fallow land was included. Similarly the area under agroforestry in different states was also estimated. Among all the states, Uttar Pradesh, Maharashtra and Rajasthan is ranked first, second and third in terms of area under agroforestry (1.86, 1.61 and 1.55 m ha, respectively). These preliminary estimates may be considered for state and country level planning (Rizvi *et al*., 2014)

Table 1. Preliminary estimates of area under agroforestry in India

(Figures in Lakh ha)

State/UT	Cropland	Fallow land	AF area (excluding fallow)	AF area (including fallow)
Andhra Pradesh	117.52	49.83	11.75	16.73
Arunachal Pradesh	1.76	0.06	0.18	0.18
Assam	25.90	0.81	2.59	2.67
Bihar	75.65	3.85	7.56	7.95
Chhattisgarh	60.07	9.90	6.01	6.99
Delhi	0.49	0.08	0.05	0.06
Goa	0.93	0.17	0.09	0.11
Gujarat	81.26	27.71	8.13	10.89
Haryana	33.59	1.58	3.36	3.52
Himachal Pradesh	3.27	--	0.33	--
J & K	8.83	0.53	0.88	0.94
Jharkhand	29.32	24.04	2.93	5.34
Karnataka	92.42	36.94	9.24	12.93
Kerala	8.60	0.83	0.86	0.94
Madhya Pradesh	117.24	17.27	11.72	13.45
Maharashtra	160.67	30.95	16.07	19.16
Meghalaya	2.19	--	0.22	--
Manipur	1.82	--	0.18	--
Mizoram	0.40	--	0.04	--
Nagaland	0.47	0.01	0.05	0.05
Orissa	56.49	23.91	5.65	8.04
Puducherry	0.12	0.05	0.01	0.02
Punjab	41.30	0.73	4.13	4.20
Rajasthan	155.11	50.01	15.51	20.51
Sikkim	0.68	0.11	0.07	0.08
Tripura	2.56	0.03	0.26	0.26
Tamil Nadu	64.99	3.82	6.50	6.88
Uttar Pradesh	186.41	10.71	18.64	19.71
Uttarakhand	7.06	0.39	0.71	0.74
West Bengal	36.00	4.56	3.60	4.05
All India	1445.88	298.95	144.59	174.48

Source: Bhuvan LULC (2011-12), NRSC, Hyderabad,
(http://bhuvan- noeda.nrsc.in/theme/thematic/theme.php)



2.6 Approach for mapping agroforestry area

For mapping and estimating area under agroforestry using medium resolution remote sensing data, phased approach has to be adopted. First, land use/ land cover classification (LULC) on LISS III data is to be done by supervised method. Agricultural land including cropland and fallow land is then extracted from this classified image for masking equivalent area from False Colour Composite (FCC). Applying fuzzy or sub-pixel classifier on extracted agricultural area using the generated signatures, resultant image will consist of pixels of five categories i) pixels covering trees plus cropland, ii) pixels covering fallow land plus trees, iii) pixels covering trees only, iv) pixels covering cropland only and v) pixels covering fallow land only. Pixels of first three categories, which includes scattered trees, boundary plantations as well as block plantations, will represent agroforestry in real sense.

2.6.1 Methodology developed for mapping agroforestry area

Estimation of area under agroforestry at country level is a gigantic task, and requires huge data processing. Flow chart showing methodology for agroforestry mapping developed by Rizvi *et al.* (2016) is given in (Figure 1). For mapping and estimating area under agroforestry in India, the following approach has been adopted:

1. From each agro-climatic zone, 20 per cent districts representing that zone will be randomly selected.
2. For each district, remote sensing data (LISS III, 23.5 m resolution) will be analyzed for land uses and land covers (LULC) using standard classification methods.
3. From this LULC, agricultural land (cropland + fallow land) will be masked because agroforestry exists on agricultural land only.
4. Then sub-pixel classifier method will be applied on this agricultural area, which gives output in the form of classes as per the tree cover (20-29, 30-39, ..., 90-100 per cent) within a pixel.
5. Advantage of sub-pixel classifier is that all

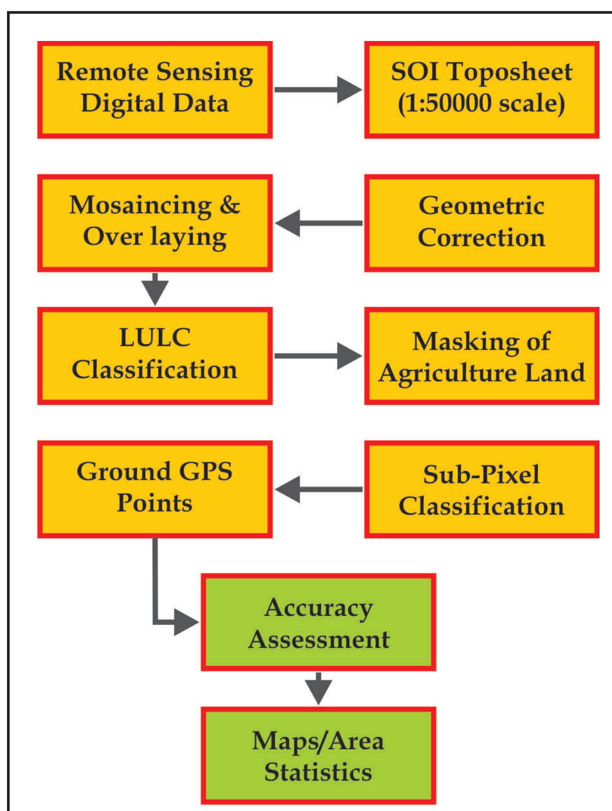


Fig. 1: Flow chart showing methodology for agroforestry

types of agroforestry (scattered trees on farmlands, boundary plantations and agri-silvicuture / agri-horticulture and block plantations), are covered. This is not true in case of pixel based classifiers such as maximum likelihood, minimum distance to mean, etc. [Figures 2(a) & 2(b)].

6. Agroforestry area obtained for such 20 per cent districts in a particular agro-climatic zone will be extrapolated for entire zone.

7. Cumulative sum of area under agroforestry for all agro-climatic zones will give an estimate of area under agroforestry for whole country.

2.6.2 Field survey for GPS data collection

In second phase of the project (2012-2017), field survey were also conducted in selected districts in agro-climatic regions for collection of ground verification points (Table 2). In this way total 44 districts in various states have been surveyed and GPS data on existing agroforestry systems were collected.

Table 2: Surveyed districts for agroforestry mapping

S.No.	State	Surveyed districts
1	Andhra Pradesh	Chittoor
2	Bihar	Darbhanga, Nawada, Purnia
3	Chattishgarh	Bilaspur and Raigarh
4	Gujarat	Anand, Dahod, Junagarh, Patan,
5	Haryana	Hisar, Kurukshetra,
6	Himachal Pradesh	Mandi,
7	Karnataka	Bellary and Tumkur
8	Madhya Pradesh	Guna, Hoshangabad, Khandwa, Panna, Shahdol
9	Maharashtra	Nashik, Thane, Latoor, Wardha
10	Punjab	Bathinda, Faridkot, Ludhiana, Nawashahar, Patiala
11	Rajasthan	Dausa, Pali, Bikaner
12	Uttar Pradesh	Bulandshahar, Firozabad, Gorakhpur, Hamirpur, Lalitpur, Mirzapur, Shahjahanpur, Sultanpur,
13	Uttarakhand	Haridwar
14	Telengana	Nizamabad
15	West Bengal	North Dinajpur and Bardhaman

2.7 Estimation of area under agroforestry for agro-climatic regions

During 2013-14, three agro-climatic regions *viz.* Upper Gangetic plains, Trans Gangetic plains and Gujarat plains& hill regionhave been completed. From these regions, 8, 11 and 6 districts were selected, respectively for mapping agroforestry area. The area under agroforestry in Upper Gangetic plains, Trans Gangetic plains and Gujarat plains & hill region come out to be 2.23, 1.14 and 2.57million ha, respectively (Table 3). Maps showing agroforestry area in selected districts of agro-climatic zones are given in Fig. 3-5.

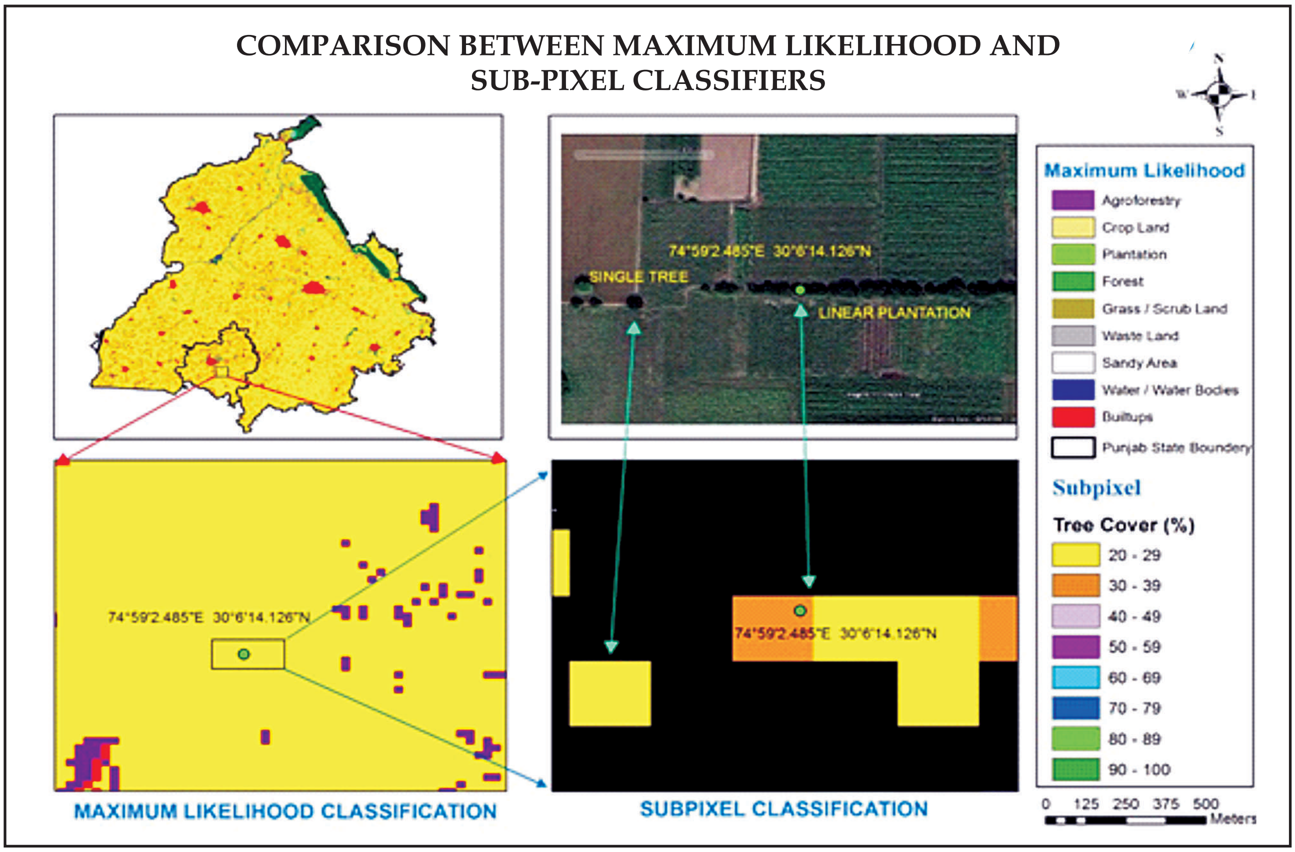


Fig. 2(a): Comparison of pixel and sub-pixel based classifiers

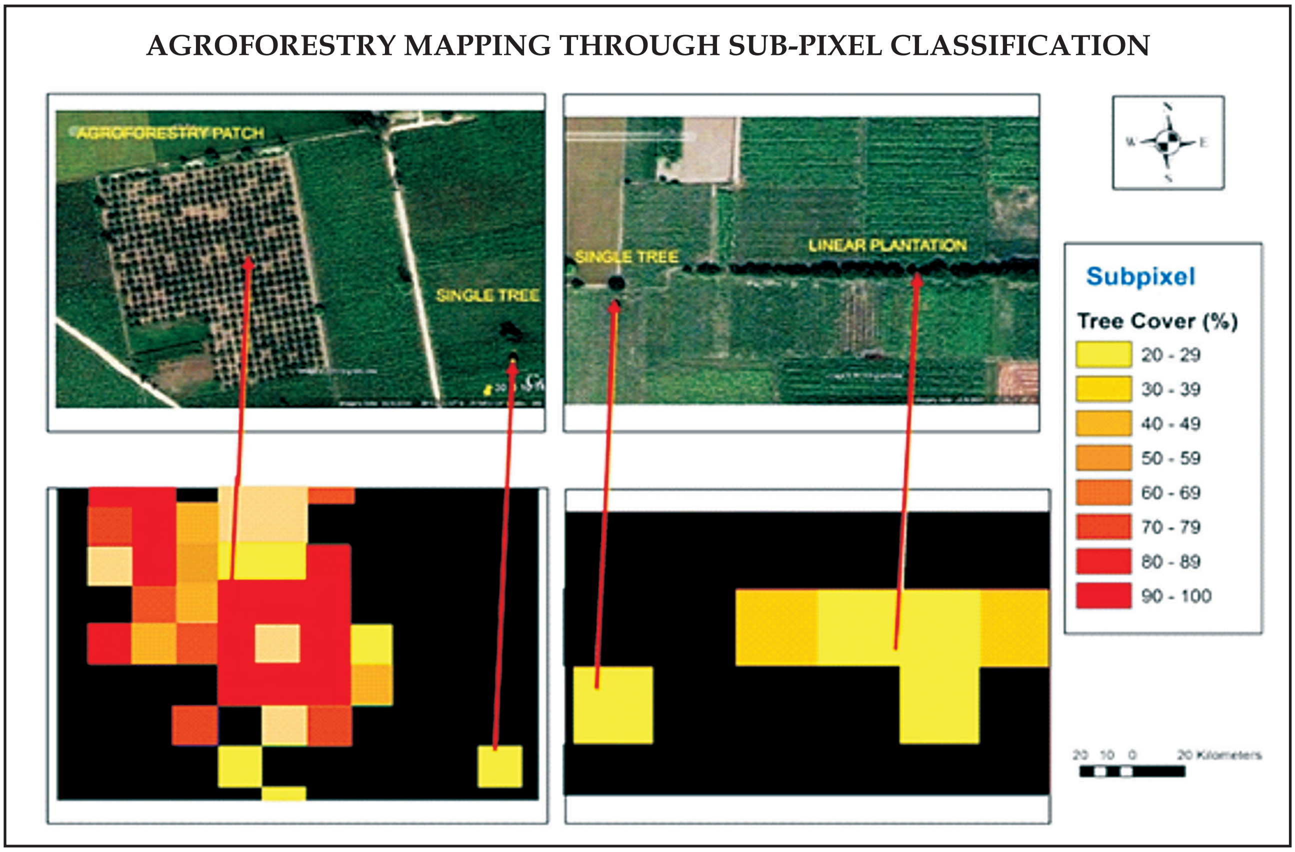


Fig. 2(b): Various agroforestry systems identified through sub-pixel classifier

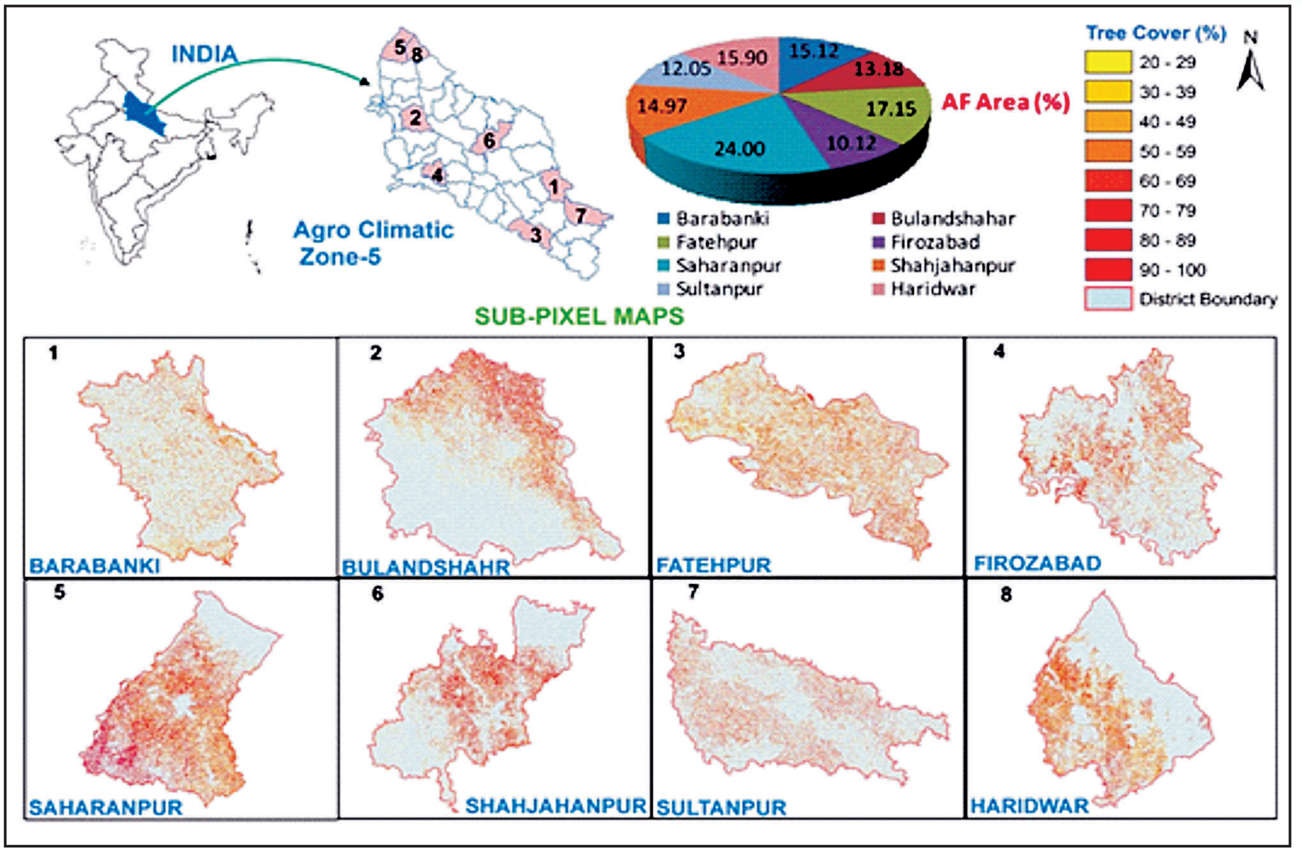


Fig 3: Land uses and land covers in selected districts of agro-climatic region-5

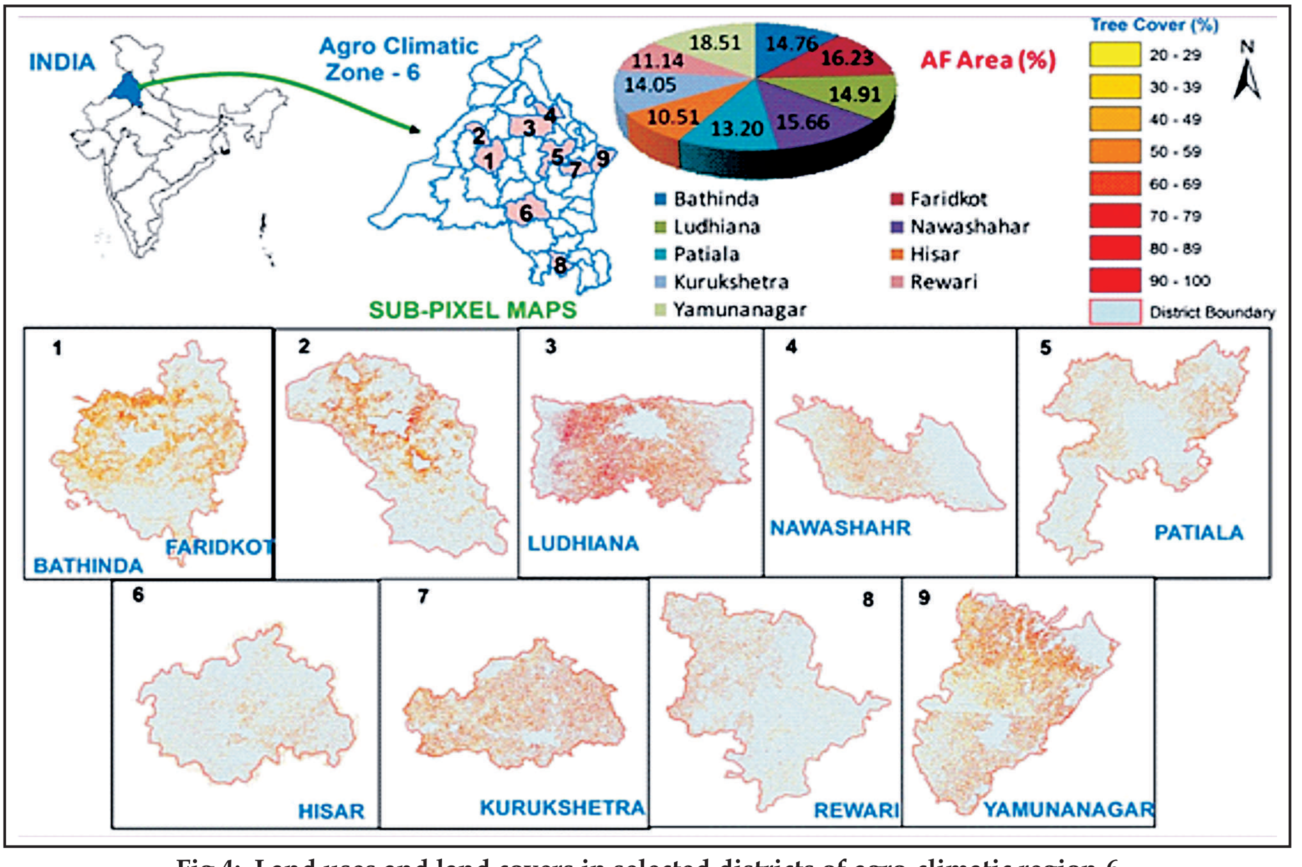


Fig 4: Land uses and land covers in selected districts of agro-climatic region-6

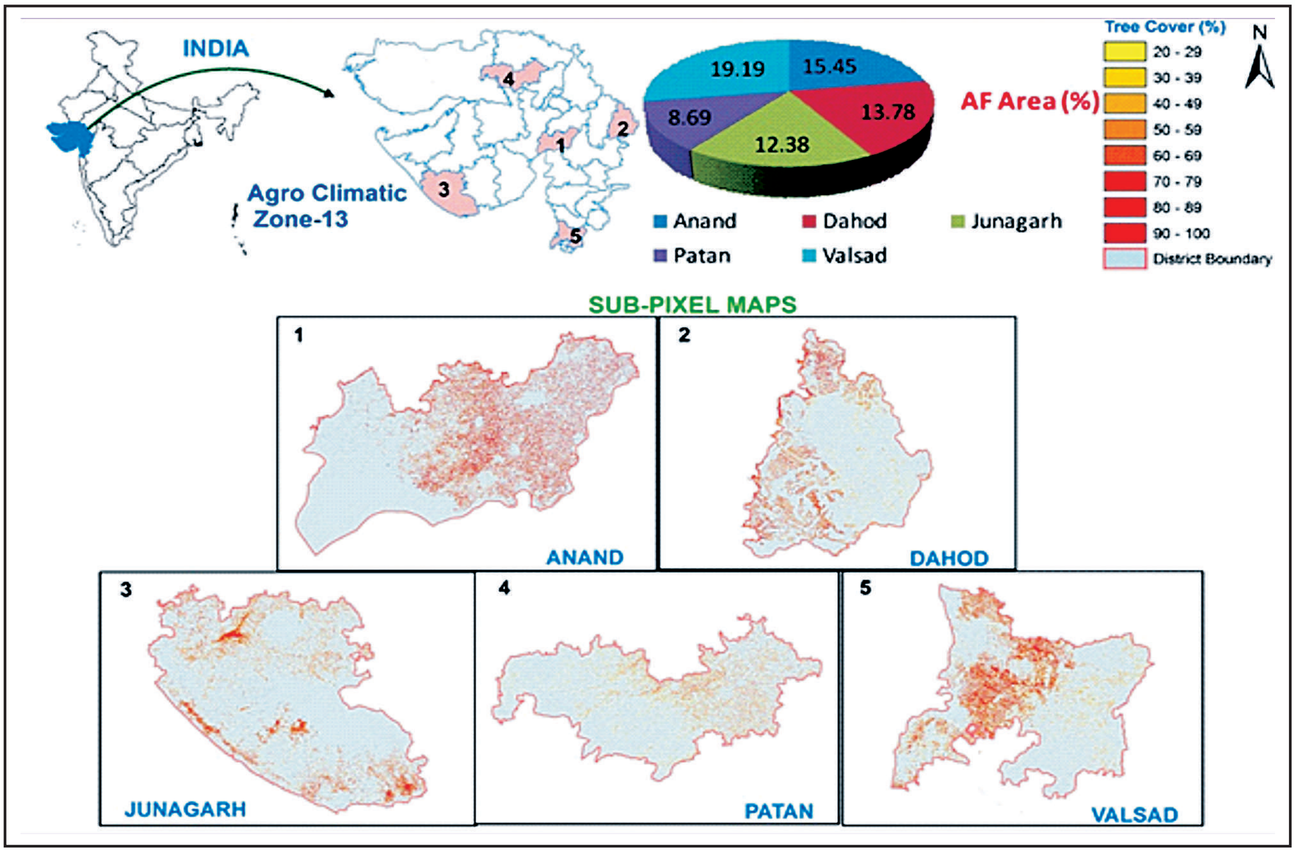


Fig 5: Land uses and land covers in selected districts of agro-climatic region-13

During 2014-15, three agro-climatic regions *viz.* Lower Gangetic plains, Middle Gangetic plains and Central Plateau & Hill region have been completed for agroforestry mapping. Twenty percent of total districts from each region *i.e.* 3, 12 and 12 districts representing that region were selected. Agroforestry area was estimated using RS2/ LISS-3 data and sub-pixel method. Area under agroforestry in the selected districts in Lower Gangetic plains, Middle Gangetic plains and Central Plateau & Hill region was estimated to be 0.802M ha (11.91%), 1.304 M ha (7.87%) and 1.926 M ha (5.09%), respectively. Maps showing agroforestry area in selected districts of agro-climatic zones are given in figures 6-8.

During 2015-16, two agro-climatic regions *viz.* Western Dry region and Western Plateau & hills region were completed for agroforestry mapping. Twenty per cent of total districts from each region i.e. 2 and 8 districts, respectively representing that region were selected. Area under agroforestry in Western Dry region and Western Plateau & hills region was estimated to be 0.43 M ha (2.41%) and 1.55M ha (4.75%), respectively (Table 3). Maps showing agroforestry area in selected districts of agro-climatic zones are given figure 9

During 2016-17, estimation of agroforestry area was done for two agro-climatic regions *viz.* West coast plains & hill region and Southern plateau & hill region. From these regions, 7 and 13 districts have been selected for mapping agroforestry area. Estimated agroforestry area in West coast plains & hill region and Southern plateau & hill region come out to be 1.66 M ha (14.18%) and 2.98 M ha (7.55%), respectively (Table 3).

Total estimated area under agroforestry in 10 agro-climatic zone (ACZ) was about 16.60 million ha, which is 7.98 or around 8.0% of the total geographical area of these regions. Estimated agroforestry area in selected districts of agro-climatic regions of India is presented in Table 4. In total 66 districts have been selected from 10 agro-climatic regions and agroforestry area has been estimated by the methodology described above. Agroforestry area in these districts ranged from 2.72 to 24.0 per cent.

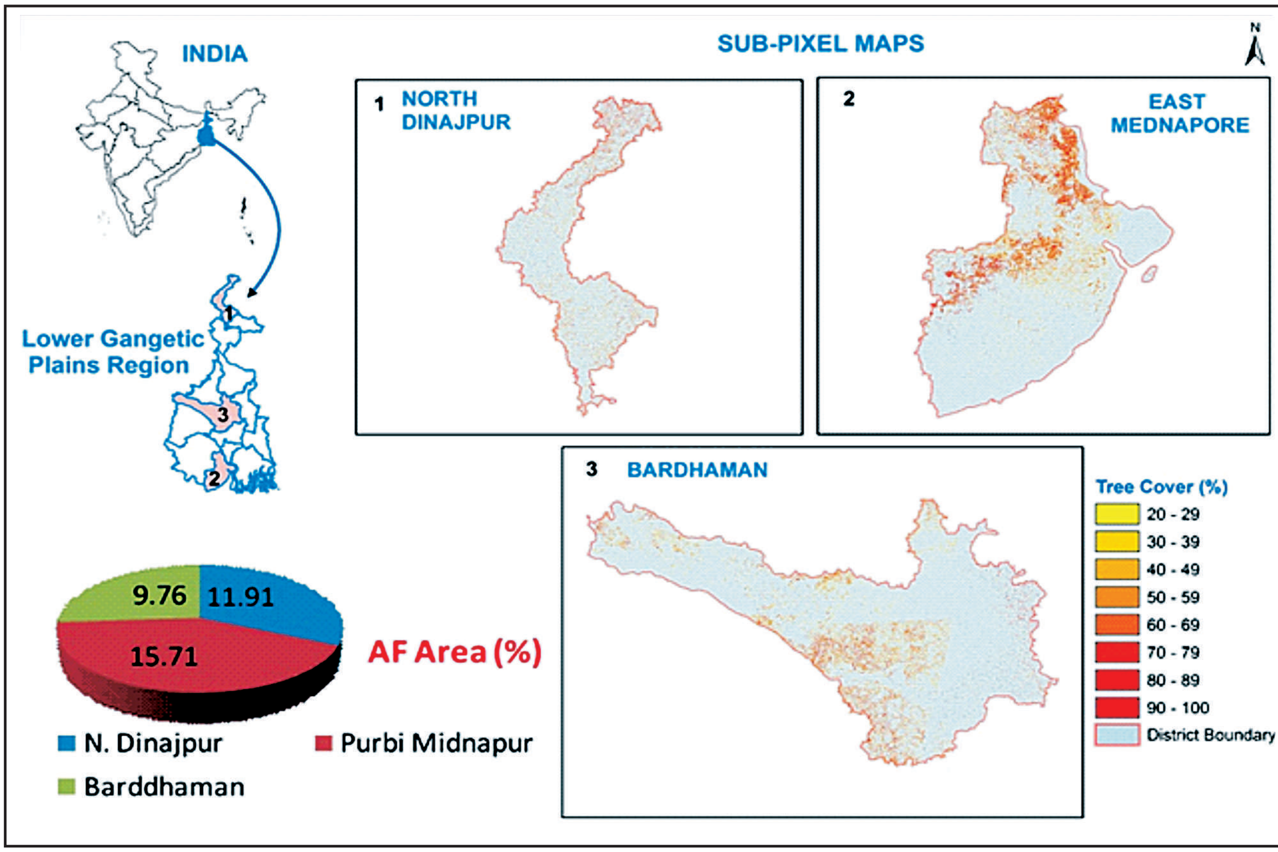


Fig 6. Land uses and land covers in selected districts of agro-climatic region-3

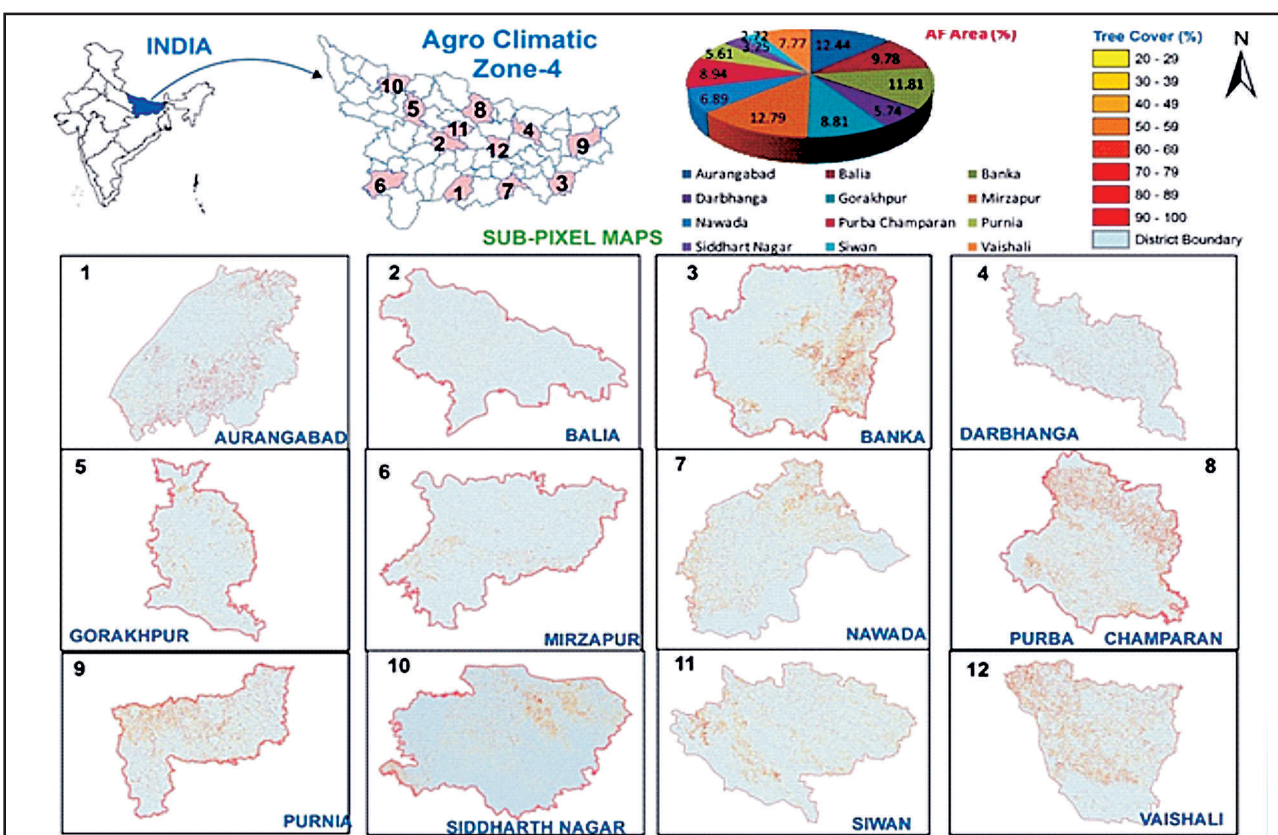


Fig 7. Land uses and land covers in selected districts of agro-climatic region-4

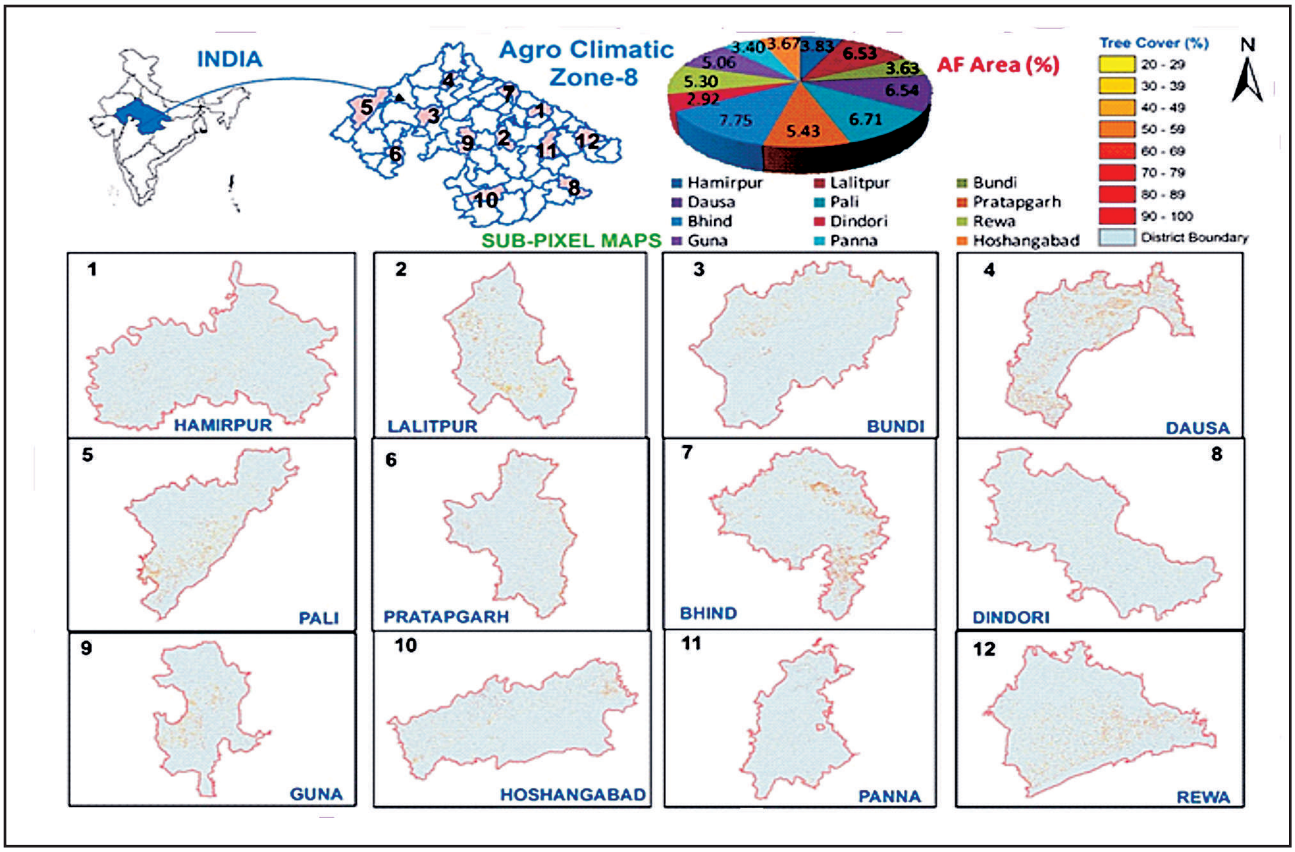


Fig 8. Land uses and land covers in selected districts of agro-climatic region-8

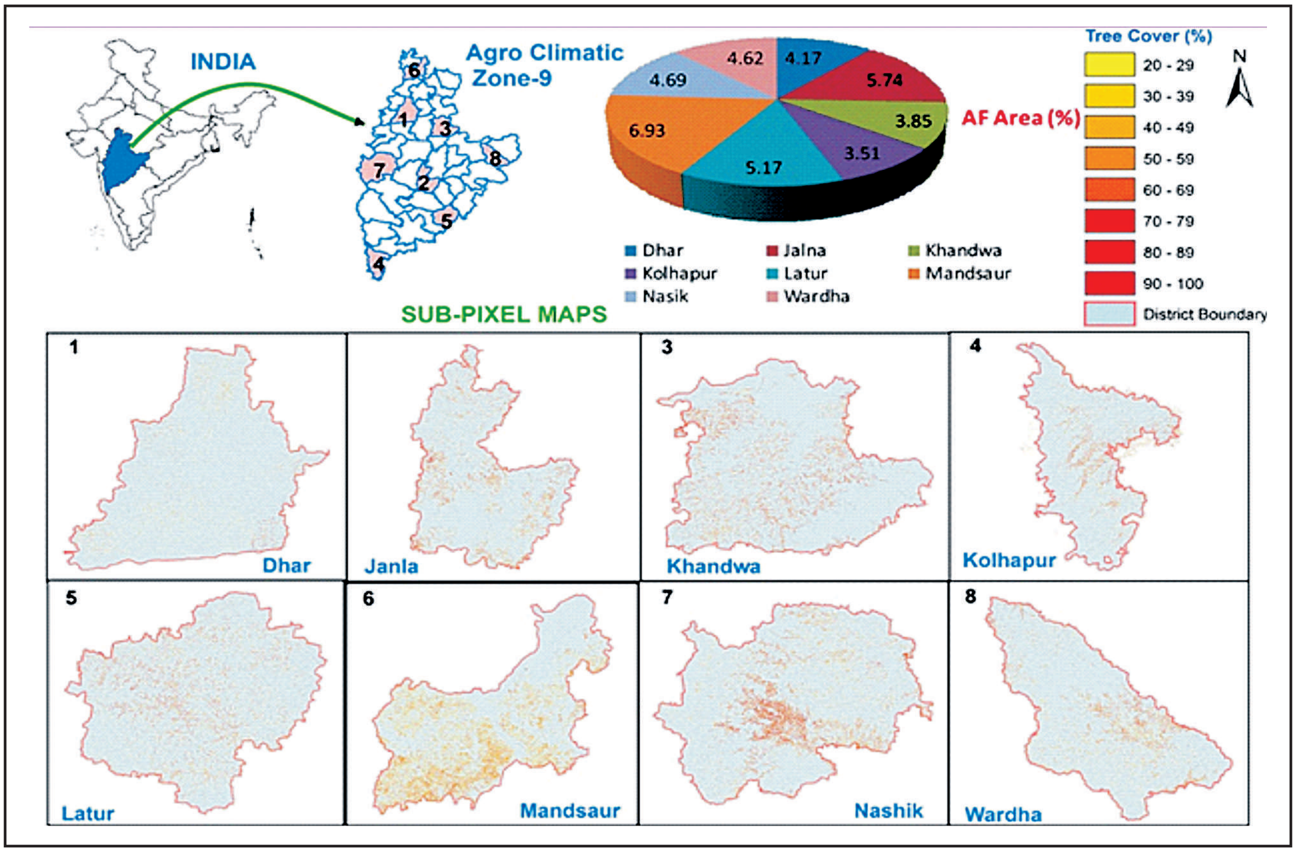


Fig.9: Land uses and land covers in selected districts of agro-climatic region-9

Table 3: Agro-climatic zone-wise estimated agroforestry area

ACR No.	Agro-climatic zones	Geographical Area (M ha)	Agroforestry Area (M ha)	Agroforestry Area (%)
3	Lower Gangetic Plains Region	6.733	0.802	11.91
4	Middle Gangetic Plains Region	16.570	1.304	7.87
5	Upper Gangetic Plains Region	14.441	2.234	15.47
6	Trans Gangetic Plains Region	11.603	1.143	9.85
8	Central Plateau & Hill Region	37.843	1.926	5.09
9	Western Plateau & Hill Region	32.740	1.556	4.75
10	Southern Plateau & Hill Region	39.412	2.976	7.55
12	West Coast Plains & Hill Region	11.682	1.657	14.18
13	Gujarat Plains & Hill Region	18.977	2.570	13.56
14	Western Dry Region	17.871	0.431	2.41
	Total	207.872	16.599	7.98

Table 4: Estimated area under agroforestry in selected districts of agro-climatic zones

Sl. No.	ACZ No. & Name	Total (Selected) Districts	State's Name	Selected Districts Name	Agroforestry Area by Subpixel (ha)
1	3- Lower Gangetic Plains Region	14 (3)	West Bengal	Bardhaman	313961.05 (09.76)
				East Medinipur	401047.38 (15.71)
				North Dinajpur	709195.27 (11.91)
2	4- Middle Gangetic Plains Region	61 (12)	Bihar	Vaishali	202971.75 (12.44)
				Banka	305532.52 (09.78)
				Purnia	324468.90 (11.81)
				Darbhanga	252365.20 (05.74)
				Siwan	222290.61 (08.81)
				PurbaChamparan	398238.09 (12.79)
				Aurangabad	331375.47 (06.89)
				Nawada	250414.07 (08.94)
			Uttar Pradesh	Gorakhpur	333238.28 (05.61)
				Mirzapur	441654.86 (03.25)
				Balia	299761.75 (02.72)
				Siddhart Nagar	289743.82 (07.77)
3	5- Upper Gangetic Plains Region	42 (8)	Uttar Pradesh	Saharanpur	372721.00 (24.00)
				Bulandshahar	352699.56 (13.18)
				Firozabad	242208.00 (10.12)
				Shahjahanpur	431469.78 (14.97)
				Sultanpur	442816.99 (12.05)
				Barabanki	384337.71 (15.12)
				Fatehpur	416686.54 (17.15)
			Uttarakhand	Haridwar	229359.23 (15.90)

4	6- Trans Gangetic Plains Region	54 (10)	Haryana	Kurukshetra	23679.59 (14.05)
				Hisar	43061.47 (10.51)
				Yamunanagar	31991.21 (18.51)
				Revari	17463.69 (11.14)
			Punjab	Nawashahar	19889.22 (15.66)
				Ludhiana	55336.15 (14.91)
				Patiala	43526.13 (13.20)
				Bathinda	49477.31 (14.76)
				Faridkot	24162.39 (16.23)
			Rajasthan	Sri Ganganagar	NA
5	8- Central Plateau & Hill Region	60 (12)	Madhya Pradesh	Bhind	34647.84 (07.75)
				Dindori	16771.74 (02.92)
				Rewa	33357.77 (05.30)
				Guna	32419.41 (05.06)
6				Panna	24098.52 (03.40)
				Hoshangabad	24598.02 (03.67)
			Rajasthan	Dausa	22430.59 (06.54)
				Bundi	20988.17 (03.63)
				Pali	84149.97 (06.71)
				Pratapgarh	24241.88 (05.43)
			Uttar Pradesh	Hamirpur	14925.83 (03.83)
				Lalitpur	32994.78 (06.53)
7	9- Western Plateu & Hill Region	40 (8)	Madhya Pradesh	Dhar	34325.74 (04.17)
				Khandwa	28924.47 (03.85)
				Mandsaur	38793.89 (06.93)
			Maharashtra	Nasik	73638.09 (04.69)
				Satara	27296.47 (03.51)
				Latur	37388.85 (05.17)
				Jalna	44332.01 (05.74)
				Wardha	29187.19 (04.62)
8	12- West Coast Plains & Hill Region	30 (6)	Maharashtra	Sindhudurg	516826.50 (03.96)
				Thane	968903.10 (02.84)
			Goa	North Goa	176149.98 (04.14)
			Karnataka	Shimoga	847301.53 (10.76)
			Kerala	Thrissur	NA
				Kottayam	NA
				Kannaur	NA

9	13- Gujarat Plains & Hill Region	29 (6)	Daman & Diu	Daman	6309.79 (03.93)
			Gujarat	Anand	325790.17 (15.45)
				Dahod	365692.15 (13.78)
				Junagarh	882442.84 (12.38)
				Patan	590606.90 (08.69)
				Valsad	294959.46 (19.19)
10	14- Western Dry Region	9 (2)	Rajasthan	Sikar	777215.06 (04.99)
				Bikaner	NA

Figures in parenthesis are the percentages

3. Assessment of carbon sequestration potential of agroforestry system existing on farmer's field

There is a worldwide debate on reducing atmospheric concentration of greenhouse gases(GHGs) especially CO_2 emission and increase carbon sink. Since forest is large carbon sink but there is no scope to increase the forest area in the country. But there is lot of scope to increase carbon storage through afforestation, reforestation and agroforestry. The carbon storage capacity in agroforestry varies across the species geography. Further the amount of carbon in any agroforestry system (AFS) depends upon the structure and function of different components within system put in to practice (Ram Newaj *et al.*, 2014). The carbon stock available in Indian forests is well documented but the carbon stock available under agroforestry at country or state level is neither documented nor available. The Central Agroforestry Research Institute, Jhansi has been working since a decade on carbon sequestration and carbon sequestration potential (CSP) has been assessed for 16 states. Similarly the work on mapping of agroforestry area is also completed in 10 agro-climatic regions. The approach for estimation of agroforestry area in the country and carbon sequestration potential of agroforestry existing on farmer's field in different states are described in detail by Ram Newaj *et al.*, 2014.

3.1 Approach to assess carbon stock

3.1.1 Field survey of study area

A field survey of selected districts was done to know the agroforestry practices adopted by the farmers, tree density, tree species existing on the farmers field, tree growth etc. First of all, blocks in each district were identified and after selection of blocks, number of villages were identified to conduct the survey. Since, each block is having large number of villages and it was not possible to cover each and every village, a sample of six villages representing the whole block was selected. The survey was conducted on the basis of transect walk in the selected village. The village head, local farmers and village youth were associated in the transect walk to have a clear picture of the village. The sampling involves enumeration of trees on farmlands, farm bunds, culturable wastelands etc. All trees more than 1.5 m tall or more than 5 cm diameter at breast height (dbh) were enumerated. The data was obtained for the number of trees for each tree species and the dbh for each tree. In this way, the data was generated for different tree species and their intensity for a particular village. These tree species were classified as slow, medium and fast growing depending upon their growth habit and mean annual increment (MAI). The number of trees per hectare was calculated for slow, medium and fast growing trees per village. This was multiplied with the total number of villages per block and thus calculated for all the blocks of a particular district.

3.1.2 Simulation models for quantification of carbon sequestration in agroforestry

Agroforestry will be required to contribute substantially to meet the demands of rising population for food, fruits, fuelwood, timber, fodder, bio-fuel and bio-energy as well as for its perceived ecological services. In such situation biomass estimates, through sequential harvesting, are useful for quantifying net primary productivity and C-cycle. However, periodic harvesting is time consuming, labour intensive and un-economical. Model development is therefore an essential tool for assessing the biomass stored and carbon sequestered.

Many of the process based models developed for agriculture and forestry are still first choice for use in agroforestry as well. Ravindranath and Ostwald (2008) have compiled and compared different models used in estimating changes in carbon stock for forestry and plantation projects. The model contrasted includes PROCOMAP (developed by Lawrence Berkeley National Laboratory), CO2FIX (developed as an inter-institutional collaborative project involving AL-TERRA, Netherland; The Instilutode Ecologia of University of Mexico, Mexico; The Centro

Agronomica Tropical de Investigaciony Ensenanza (CATIE) Costa Rica and Europian Forest Institute, Finland), CENTURY (developed by Natural Resource Ecology Laboratory, Colorado State University) and ROTH (developed by Rothmsted Agriculture Research Station, UK) on the basis of their comparative feature, input/output and applications. The CENTURY model computes the form of carbon, nitrogen, phosphorus and sulphur. Both CENTURY (Century 1992) and ROTH concentrate on dynamics of soil carbon stocks for agriculture and forestry projects. PROCOMAP (Sathye and Mayers, 1995) is generally used for project level carbon stocks (biomass and soil) for forestry projects. CO2FIX has been extensively used for estimating biomass and changes in soil carbon stocks for forestry, agriculture and agroforestry projects. CO2FIX was preferred over other models (*viz*. PROCOMAP, CENTURY and ROTH) and CO2FIX can simulate the carbon dynamics of single/multiple tree species simultaneously, and can handle trees with varied ages and agroforestry systems (AFS).

3.1.2.1 Brief Description of the CO2FIX Model

CO2FIX v.3.1 is a carbon accounting model developed as part of the CASFOR II project and has been described in detail by (Masera *et al.*, 2003; Schlaas *et al.*, 2004 and Numbrus *et al.*, 2002). In CO2FIX model, the biomass and carbon credits are simulated on hectare scale with time steps of one year. The biomass module converts volumetric net annual increment data to the annual carbon stock of the biomass compartment. Turnover and harvest parameter drive the fluxes from biomass to soil. The model has a soil module known as YASOO which takes into account the initial litter quality and the effect of climate on decomposition. Litter enters the soil module based on the size of the litter and is then dissociated into contents of different classes of organic compounds. The validity of its soil carbon estimates, mass loss estimates and ability to appropriately describe the effects of climate on decomposition rates has been tested within a wide range of environments. The CO2FIX model can be applied to coniferous or deciduous forests, as well as to monocultures or mixed tree stands. A number of case studies have been made both in temperate and tropical climates, to estimate biomass and soil carbon. The CO2FIX model has been used to estimate the dynamics of C-stocks and flows for a variety of ecosystem around the world. It is an invaluable tool that has contributed to IPCC climate assessments and estimation of C implication in the context of Kyoto –Protocol. The CO2FIX model has been tested and validated for the forest ecosystem in the Philippines, mixed pine-oak forest of central Mexico, multi-strata AFS and tropical rainforest in Costa-Rica and woodlots in Zambia.

3.1.2.2 Input Parameters for the CO2FIX model

The main input parameters relevant to CO2FIX model are the cohort wise values for the stem CAI (current annual increment in $m^3ha^{-1}yr^{-1}$) over years; relative growth of the foliage, branches, leaf and root with respect to the stem growth over years; turnover rates for foliage, branches and roots; and climate data of the site (annual precipitation in mm and monthly values of minimum and maximum temperatures in ^{O}C). Other inputs to the model include initial surface soil organic carbon (Mg C ha^{-1}), rotation period of a tree species, per cent carbon contents, wood density and initial values of baseline carbon (Mg C ha^{-1}) in different tree parts, when the simulation are being carried out for the existing tree plantations as in the present case.

3.1.2.3 Basic data required for running the CO2FIX model

For the purpose of simulating carbon stocks under agroforestry systems (AFS) in different districts, the modules taken into considerations are biomass, soil and carbon accounting modules. CO2FIX model requires primary as well as secondary data on tree and crop components (called 'cohorts' in CO2FIX terminology) for preparing the account of carbon sequestered under AFS on per hectare basis. The primary data includes existing tree species on farmlands along with their number, diameter at breast height (DBH), crops grown on farmlands along with their productivity, area coverage etc. Whereas the secondary data includes the growth rates of tree biomass components (stem, branch, foliage, root) for various species on annual basis as well as the productivity of different crops grown in that region. The site characteristics (altitude, longitude, total rainfall, monthly temperature, soil type, vegetation etc.) of the study area are required to know the actual condition of study area.

Accordingly, to account for the carbon sequestered under AFS in various states of the country, district wise survey were conducted to record the primary and secondary data, as described above, on tree, crop and soil component. Twelve villages were selected using two stage random sampling from each district for comprehensive primary survey. The tree species being grown on farmland were classified into three categories/cohort's *viz.* slow, medium and fast growing trees as per the growth rate and nature of the species. The basic parameters (*viz.* rotation length, wood density, carbon contents) set for the tree cohorts have been detailed in Table 5. DBH of the surveyed trees was used to approximately find out the age of the standing trees. To derive the incremental data of tree stem growth, the volume equations published in State Forest Report 2009 (www.fsi.nic.in/sfr_2009.htm) were used as the secondary data.

3.1.2.4 Parametrization of the tree cohorts

Stem volume equations, available in Forest Survey of India Report (2009) for the species found in survey, were used to generate the DBH (m) and stem volume (m^3/tree) data. The individual species wise generated data sets were then clubbed into single files for the slow, medium and fast growing species separately. These three data sets pertaining to slow, medium and fast growing species were independently used to fit non-linear functions for stem volume-DBH relationships (Fig.10). These tree wise absolute stem volume-DBH relationships were then converted into hectare wise stem volume-DBH relationships, by multiplying tree wise stem volume from the average number of trees found in the village survey in a specified category (slow/medium/fast). This DBH was transformed back into age to obtain hectare wise stem volume–age relationships. Ultimately, these absolute stem volume values were converted into CAI (current annual increment) values of stem volume by taking the difference of current year value from preceding year value (Table 6). Thus, we obtained the CAI equations for stem-volume-age for the three categories/cohorts of slow, medium and fast growing trees in a given district.

The harvested data available for different tree species (classified as under the slow, medium and fast growing categories/cohorts) at National Research Centre for Agroforestry (NRCAF), Jhansi was used to find out the relative growth of foliage, branch and root with respect to stem. These relative proportions were parameterized in CO2FIX model for branch, foliage and root growth (Table 7).

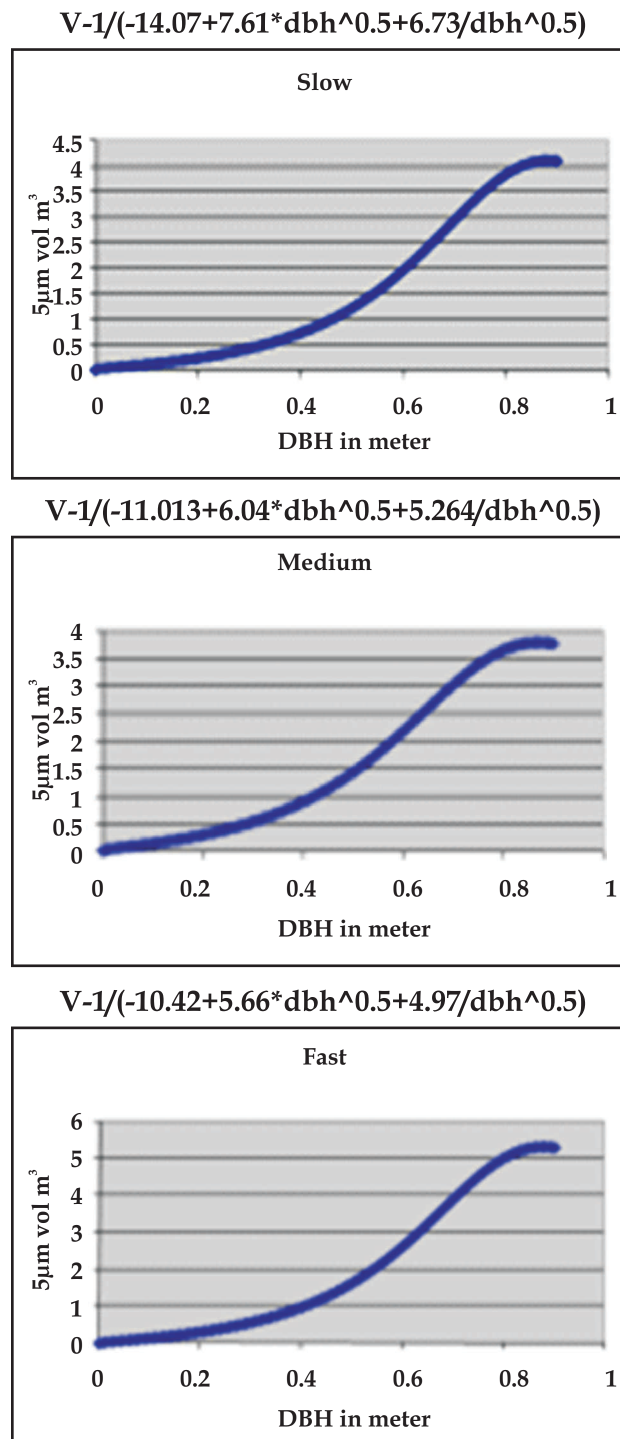


Fig. 10: Stem volume - DBH relationship

Table 5. Input parameter used in CO2FIX model for simulating tree biomass components in various tree cohorts (uniform for all the districts)

Cohorts	Slow growing trees	Medium growing trees	Fast growing trees
Rotation (year)	90	50	10
Wood density (Mg DM m^{-3})	0.67	0.65	0.61
Carbon content (% dry weight)	48	48	48
Turnover rate foliage	0.5	0.5	0.6
Turnover rate branch	0.02	0.04	0.02
Turnover rate root	0.02	0.1	0.2
Product allocation for Thinning harvesting Stem log wood	0.8	0.8	0.8
Stem slash	0.2	0.2	0.2
Branch log wood	0.8	0.8	0.2
Branch slash	0.2	0.2	0.8
Foliage slash	1	1	1
Foliage slash soil	0.7	0.7	0.7

Table 6. Current Annual Increment as a function of stand age for slow growing, medium growing and fast growing trees

Slow Growing				Medium Growing		Fast Growing	
Age	CAI (m^3/ha/Yr)	Age	CAI (m^3/ha/Yr)	Age	CAI (m^3/ha/Yr)	Age	CAI (m^3/ha/Yr)
0	0.010012	60	0.047447	0	0.025965	1.0	0.000034
5	0.010351	65	0.054997	5	0.028022	2.0	0.000327
10	0.010838	70	0.060794	10	0.037653	3.0	0.01686
15	0.012261	75	0.068128	15	0.053272	4.0	0.045807
20	0.014233	80	0.072757	20	0.076952	5.0	0.089064
25	0.016043	85	0.085282	25	0.106986	6.0	0.107065
30	0.018928	90	0.091707	30	0.155177	7.0	0.117595
35	0.022415	95	0.092945	35	0.217803	8.0	0.117019
40	0.025476	100	0.087666	40	0.279257	9.0	0.110056
45	0.030217			45	0.292525	10	0.103423
50	0.034304			50	0.119924		
55	0.040483						

Table 7. Relative growth of various tree components with respect to stem growth for tree cohorts over years

Components	Slow growing		Medium growing		Fast growing	
	Age	**Rates**	**Age**	**Rates**	**Age**	**Rates**
Foliage	0	1	1	0.26	0	0.30
	10	0.50	5	0.63	2	0.44
	20	0.73	15	0.50	3	0.40
	30	0.64	20	0.38	4	0.38
	40	1.02	25	0.32	5	0.37
	50	1.12	30	0.50	6	0.32
	60	0.98			7	0.56
	70	0.91			8	0.58
	Age	**Rates**	**Age**	**Rates**	**Age**	**Rates**
Branch	0	0.20	1	0.44	0	0.25
	10	0.18	5	0.44	2	0.22
	20	0.15	15	0.33	3	0.18
	30	0.16	20	0.38	4	0.18
	40	0.16	25	0.32	5	0.21
	50	0.15	30	0.32	6	0.28
	60	0.14			7	0.43
	70	0.14			8	0.58
	Age	**Rates**	**Age**	**Rates**	**Age**	**Rates**
Root	0	0.40	0	0.44	0	0.30
	10	0.40	5	0.48	2	0.43
	20	0.39	15	0.63	3	0.58
	30	0.30	20	0.60	4	0.49
	40	0.31	25	0.77	5	0.36
	50	0.31	30	0.82	6	0.31
	60	0.29			7	0.47
	70	0.27			8	0.37

3.1.2.5 Parametrization of the crop cohort

In order to simulate the crop component, the crop was considered as a 'tree' with a very small stem volume, no branches and a lot of foliage and roots. The stem part is needed, since allocation to foliage and roots are driven by stem increment. In order to keep the influence of the stem compartment as small as possible, a very small increment was specified, in our case 0.01 $m^3 ha^1 yr^{-1}$. The foliage (grain and straw) and root compartment receive a very high relative increment, say for example set as 8657 and 865 respectively for any district. When the wood density has been set to '0.09', the aboveground production is 8657*0.09*0.01 = 7.79 Mg DM ha^{-1} (dry matter per hectare). Similarly, belowground production is 0.77 Mg DM ha^{-1} for the district. Additionally, it was presumed for CO2FIX model that 5 per cent of the above ground crop biomass (grain and straw) incorporates into the soil, while 95 per cent is exported out from the system. Likewise, 30 per cent of the below ground crop biomass is incorporated into the soil. Characteristic for cropland systems are the high turnover rates in foliage and roots, in this case set at 0.9 for both.

3.1.2.6 Parametrization of the soil module

The district wise climatic data on monthly temperature and precipitation was obtained from IMD (Indian Meteorological Department) and was fed as the general parameters for the soil compartment of the model. The dynamic soil carbon model YASSO describes decomposition and dynamics of soil carbon in well-drained soils. The soil module consists of three litter compartments (non-woody, coarse-woody and fine-woody) and five decomposition compartments (extractives, cellulose, lignin like compound, humus-1 and humus-2). Litter is produced in the biomass module through biomass turnover. For the soil carbon module, the litter is grouped as non-woody litter (foliage and fine roots), fine woody litter (branches and coarse roots) and coarse woody litter (stems and stumps). Since the biomass module makes no distinction between fine and coarse roots, root litter is separated into fine and coarse roots according to the proportion between branch litter and foliage litter.

3.2 Basic information of study area

The occurrence of tree species in any district of a particular state depends upon soil type, rainfall, temperature, availability of water etc. For example in Karnataka, *Areca catechu, Acacia nilotica, Azadirachta indica, Cocos nucifera, Mangifera indica* are the most common trees occurring on farmer's field and tree population in these district varied from 2.38 to 69.0 trees ha^{-1}. In different districts of Maharashtra, *Tectona grandis, Citrus sinesis, Azadirachta indica, Mangifera indica* and *Ziziphus mauritiana* are commonly found trees on farmer's field and tree population varied from 2.11 to 11.98 trees ha^{-1} in surveyed districts (Table 8). Similarly in other states also tree population varied from district to district and tree species also differs from one district to other district, if the districts of the state having different type of weather.

3.3 Tree density in existing agroforestry on farmer's field

In different states (U.P., Gujarat, Bihar, West Bengal, Rajasthan, Punjab, Haryana, Himachal Pradesh, Maharashtra, Madhya Pradesh, Tamil Nadu, Andhra Pradesh, Karnataka, Orissa, Chattisgarh and Telangana) of the country, the minimum tree population is 1.39 tree ha^{-1} and maximum is 204.87 tree ha^{-1} with the average number of 18.42 trees ha^{-1} (Table 9).

Table 8. Location, major crops, crop productivity and dominant trees in surveyed districts of different states

State	District	Location and soil type	Dominant crop (Productivity in Mg DM ha^{-1})	Dominant trees (Contribution in per cent)
Punjab	Faridkot	30.40°N 74.45°E Coarse loamy & fine loamy associations & Fine loamy	*Oryza sativa* (4.35), *Triticum aestivum* (4.66), *Gossypium* spp. (0.70), *Vigna radiata* (0.47)	*Eucalyptus tereticornis* (58.00), *Melia azedarach* (10.38), *Ziziphus mauritiana* (6.18)
	Ludhiana	30.91°N 75.85°E Coarse loamy & Fine loamy soils	*Oryza sativa* (4.47), *Triticum aestivum* (4.39), Zea mays (3.57), *Saccharum officinarum* (81.0), *Gossypium* spp. (0.74)	*Populus deltoides* (53.25), *Eucalyptus tereticornis* (35.19), *Melia azedarach* (3.33), *Dalbergia sissoo* (0.44)
	Nawan-shahar	31.12°N 76.11°E Coarse loamy and fine loamy association, Fine loamy	*Oryza sativa* (4.10), *Triticum aestivum* (3.91), *Zea mays* (3.96), *Saccharum officinarum* (68.0)	*Populus deltoides* (38.66), *Bambusa* spp. (28.64), *Eucalyptus tereticornis* (9.90)
Haryana	Kuru-kshetra	29.96°N 76.83°E Clayey loam & Sandy loam	*Oryza sativa* (3.19), *Triticum aestivum* (4.47), *Brassica nigra* (1.86), *Saccharum officinarum* (69.8), *Vigna radiata* (0.55)	*Populus deltoides* (48.14), *Eucalyptus tereticornis* (27.84), *Melia azedarach* (8.94), *Mangifera indica* (2.88)
	Hisar	29.15°N 75.70°E Sandy to sandy loam, loamy and clay loam	*Oryza sativa* (2.50), *Pennisetum glaucum* (2.23), *Triticum aestivum* (4.62), *Hordeum vulgare* (3.69), *Vigna radiata* (0.0.46) *Cicer arietinum* (0.90)	*Eucalyptus tereticornis* (32.61), *Populus deltoides* (28.13), *Dalbergia sissoo* (16.45), *Azadirachta indica* (6.74)
Uttar Pradesh	Gorakhpur	26.75°N 83.36°E Sandy, Sandy loam or Clay loam & Khadar soil	*Oryza sativa* (1.69), *Triticum aestivum* (2.52), *Saccharum officinarum* (54.7), Oil seeds (0.79)	*Mangifera indica* (37.55), *Tectona grandis* (28.01), *Eucalyptus tereticornis* (6.31), *Azadirachta indica* (4.07), *Madhuca latifolia* (2.32)
	Buland-sahar	28.40°N 77.85°E Loamy sand, sandy loam and sandy silt loam	*Oryza sativa* (2.22), *Triticum aestivum* (3.77), Pulses (0.77) *Saccharum officinarum* (59.4)	*Mangifera indica* (32.64), *Populus deltoides* (28.57), *Psidium guajava* (8.19), *Azadirachta indica* (4.17)
	Mirzapur	25.15°N 82.60°E Red lateritic & Sandy Loam, Black soils	*Oryza sativa* (1.93), *Triticum aestivum* (2.03), Oil seeds (0.71), Pulses (0.96), *Saccharum officinarum* (43.3)	*Mangifera indica* (70.00), *Dalbergia sissoo* (15.00), *Eucalyptus tereticornis* (10.00)

	Faizabad	26.78°N 82.13°E Silty loam (Bhat), Alluvial Silt loam	*Oryza sativa* (1.72), *Triticum aestivum* (2.03), *Saccharum officinarum* (41.6), Oil seeds (1.26), Pulses (0.74)	*Eucalyptus tereticornis* (18.16), *Acacia nilotica* (18.16), *Mangifera indica* (12.99)
	Sultanpur	26.45°N 82.11°E Silty Loam & Gray	*Oryza sativa* (1.78), *Cajanus cajan* (0.89), *Triticum aestivum* (2.72), *Saccharum officinarum* (54.2)	*Eucalyptus tereticornis* (35.19), *Azadirachta indica* (5.05), *Madhuca latifolia* (4.87), *Dalbergia sissoo* (3.93), *Butea monosperma* (3.86), *Tectona grandis* (3.33)
Bihar	Darbhanga	26.17°N 85.90°E Very deep, Calcareous fine loamy, Loamy	*Oryza sativa* (0.96), *Triticum aestivum* (2.33), *Zea mays* (3.06), *Lens culinaris* (0.76)	*Mangifera indica* (70.00), *Tectona grandis* (4.00), *Ziziphus mauritiana* (3.00), *Leucaena* leucocephala (2.00)
	Purnia	25.13°N 86.59°E Sandy loam, Clay loam & Loam	*Oryza sativa* (1.26), *Triticum aestivum* (1.96), *Zea mays* (3.07) *Lens culinaris* (0.63)	*Mangifera indica* (30.00), *Tectona grandis* (20.00), *Azadirachta indica* (12.00), *Albizia procera* (2.50)
	Nawada	24.88°N 85.53°E Sandy loam, Clay loam, Loam, Clay	*Oryza sativa* (1.03), *Triticum aestivum* (2.02), *Lens culinaris* (1.05), *Cicer arietinum* (1.06), *Zea mays* (2.35)	*Tectona grandis* (44.00), *Mangifera indica* (43.00), *Dalbergia sissoo* (10.00)
	Pusa	25°86'N 85°78'E Sandy loam soil	*Oryza Sativa* (3.6), *Triticum aestivum* (3.2), *Sesamum indicum* (0.85), *Zea mays* (0.4)	*Litchi chinensis* (19.34), *Dalbergia sissoo* (18.97), *Mangifera indica* (16.75), *Wendlandia exserta* (5.64)
West Bengal	Uttar Dinajpur	25.62°N 88.12°E Clay loam, Sandy loam & Sandy	*Oryza sativa* (2.78), *Corchorus* spp. (2.25), *Triticum aestivum* (2.44), *Brassica juncea* (0.55), *Solanum tuberosum* (13.6)	*Albizia procera* (18.86), *Terminalia arjuna* (10.69), *Mangifera indica* (10.50), *Eucalyptus tereticornis* (10.38), *Neolamarckia cadamba* (7.08), *Dalbergia sissoo* (5.00)
	Bardhman	23.23°N 87.86°E Gravelly loamy, Loam & Clay	*Oryza sativa* (3.01), *Triticum aestivum* (2.31), *Zea mays* (3.30), Pulses (0.85), Oil seed (0.85), *Corchorus* spp.(3.01), *Solanum tuberosum* (21.7)	*Acacia auriculiformis* (36.00), *Albizia procera* (20.00), *Eucalyptus tereticornis* (15.00)
Gujarat	Anand	22.55°N 72.95°E Clay loam & Sandy loam	*Oryza sativa* (2.11), *Pennisetum glaucum* (2.65) *Triticum aestivum* (1.28)	*Azadirachta indica* (70.00), *Mangifera indica* (9.80), *Eucalyptus tereticornis* (10.18)

	Dahod	22.86°N 74.25°E Hilly light soils, Sandy loam shallow & Deep black	*Zea mays* (1.70), *Oryza sativa* (0.89), *Glycine max* (0.80), *Triticum aestivum* (1.98) *Cicer arietinum* (0.81)	*Eucalyptus* spp.(65.00), *Leucaena leucocephala* (15.00), *Tectona grandis* (10.00), *Mangifera indica* (4.00)
	Junagarh	21.52°N 70.47°E Medium to shallow black, Mix red & Coastal alluvial	*Arachis hypogaea* (2.16), *Triticum aestivum* (4.31)	*Mangifera indica* (70.00), *Tectona grandis* (10.00), *Dendrocalamus strictus* (5.00), *Manilkara zapota* (4.00)
	Patan	23.83°N 72.12°E Alluvial sandy to Sandy loam & Sandy clay loam	*Pennisetum glaucum* (0.65), *Sorghum bicolor* (1.70), *Triticum aestivum* (3.23), *Ricinus communis* (1.85), *Sesamum indicum* (0.41)	*Ailanthus excelsa* (49.00), *Azadirachta indica* (33.00), *Leucaena leucocephala* (1.20)
	Banas-kantha	24.17°N 72.43°E Alluvial sandy to sandy loam & Sandy clay loam	*Pennisetum glaucum* (1.66), *Sesamum indicum* (0.46), *Ricinus communis* (2.37), *Solanum tuberosum* (30.0), *Cuminum cyminum* (0.45), *Arachis hypogaea* (1.39)	*Azadirachta indica* (58.36), *Delonix elata* (13.97), *Mangifera indica* (2.36), *Tamarindus indica* (1.85)
Rajasthan	Jhunh-junu	28.13°N 75.40°E Sandy loam & Shallow depth red soil	*Pennisetum glaucum* (1.01), *Hordeum vulgare* (2.72), *Triticum aestivum* (3.26), *Cyamopsis tetragonoloba* (0.26), Pulses (0.31) and *Arachis hypogaea* (1.49)	*Prosopis cineraria* (64.78), *Tecomella undulata* (10.20), *Acacia tortilis* (3.88), *Ailanthus excels* (2.92)
	Sikar	27.62°N 75.15°E Sandy loam, shallow depth red soil	*Pennisetum americanum* (1.03), *Triticum aestivum* (2.98), *Hordeum vulgare* (2.53), Pulses (0.34), *Cyamopsis tetragonoloba* (0.44), *Arachis hypogaea* (1.49)	*Prosopis cineraria* (46.19), *Capparis decidua* (16.06), *Tecomella undulata* (7.27), *Acacia tortilis* (7.02)
	Bikaner	28.1°N 73.18° E Sandy loam, shallow depth	*Pennisetum americanum* (1.23), *Triticum aestivum* (2.28), *Hordeum vulgare* (2.13), Pulses (0.36), *Cyamopsis tetragonoloba* (0.34) and *Arachis hypogaea* (1.38)	*Prosopis cineraria* (45.17), *Acacia tortilis* (28.65), *Prosopis juliflora* (15.53) *Ziziphus mauritiana* (4.57) *Azadirachta indica* (1.40), *Dalbergia sissoo* (2.95)
	Dausa	26.53° N 76.20°E Sandy loam, shallow depth red soil	*Pennisetum americanum* (1.33), *Triticum aestivum* (2.18), *Hordeum vulgare* (2.43), Pulses (0.34), *Cyamopsis tetragonoloba* (0.48), *Arachis hypogaea* (1.60)	*Ailanthus excels* (27.47), *Acacia tortilis* (19.48), *Prosopis cineraria* (8.06), *Azadirachta indica* (30.98),

	Pali	25.46°N 73.19°E Sandy loam, shallow depth red soil	*Pennisetum americanum* (1.23), *Triticum aestivum* (2.08), *Hordeum vulgare* (2.53), Pulses (0.304), *Cyamopsis tetragonoloba* (0.34) and *Arachis hypogaea* (1.59)	*Prosopis cineraria* (59.22), *Tecomella undulate* (10.20), *Prosopis juliflora* (16.31), *Azadirachta indica* (7.84), *Acacia tortilis* (2.96)
Tamil Nadu	Coim-batore	11.01°N 76.97°E Deep Black	*Oryza sativa* (3.96), *Saccharum officinarum* (118.0), *Gossypium* spp. (2.56), *Arachis hypogaea* (2.08), *Zea mays* (5.06)	*Cocos nucifera* (81.40), *Morus alba* (8.47), *Azadirachta indica* (4.20)
	Kanchi-puram	12.82°N 79.71°E Deep black, Deep red & Very deep black	*Oryza sativa* (3.77), *Arachis hypogaea* (2.99), *Saccharum officinarum* (99.0), *Cicer arietinum* (0.74), *Vigna radiata* (0.58)	*Prosopis juliflora* (23.81), *Gliricidia sepium* (19.63), *Azadirachta indica* (19.37), *Leucaena leucocephala* (18.53), *Moringa oleifera* (14.15)
Karnataka	Bellary	15°16'N 76°26'E Sandy loam soil	*Oryza Sativa* (4.1), *Zea mays* (2.4), *Triticum aestivum* (0.98), *Pennisetum americanum* (0.82), *Arachis hypogaea* (0.4)	*Acacia nilotica* (42.13), *Azadirachta indica* (12.43), *Bambusa dendrocalamus* (8.39), *Tectona grandis* (7.14), *Cocos nucifera* (6.70)
	Tumkur	13°20' N, 77°8'E Red loam soil	*Oryza Sativa* (4.0), *Zea mays* (2.3), *Eleusine coracana* (1.6)	*Areca catechu* (39.92), *Cocos nucifera* (29.26), *Azadirachta indica* (7.95), *Mangifera indica* (7.54), *Tectona grandis* (6.07)
	Kolar	13°09'N78°11' E Red sandy and loam	*Oryza Sativa* (5.5), *Zea mays* (1.04), *Eleusine coracana* (1.02)	*Eucalyptus tereticornis* (89.78), *Mangifera indica* (4.00), *Melia dubia* (2.18)
Andhra Pradesh	Chittoor	13°13' N, 79°8' E Red loamy soil	*Oryza Sativa* (2.7), *Arachis hypogaea* (1.6)	*Mangifera indica* (41.91), *Tectona grandis* (13.23), *Azadirachta indica* (12.28), *Cocos nucifera* (8.09), *Acacia nilotica* (7.75)
Telangana	Nizama-bad	18°05' N 77°04' E' Red soils, Black soils	*Saccharum officinarum* (80.98), *Zea mays* (4.16), *Oryza Sativa* (3.20), *Glycin max* (1.46), *Phaseolus mungo* (0.42), *Vigna radiata* (0.38)	*Tectona grandis* (57.12), *Pongamia pinnata* (27.78), *Mangifera indica* (4.17), *Azadirachta indica* (1.26)
Maha-rashtra	Latur	18°24'N, 76°36'E Shallow soils, Deep soils	*Arachis hypogaea* (1.35), *Sorghum bicolor* (1.29), *Triticum aestivum* (1.29), *Cajanus cajan* (0.89), *Glycine max* (0.78)	*Tectona grandis* (81.05) *Pongamia pinnata* (6.03), *Acacia nilotica* (2.96), *Delonix regia* (2.57)

	Wardha	20°18'N, 78°4'E Deep black soil, Shallow black soils	*Cajanus cajan* (1.08) *Glycine max* (1.05), *Sorghum bicolor* (0.89), *Gossypium* spp. (0.21)	*Tectona grandis* (69.38), *Citrus sinensis* (11.73), *Pongamia pinnata* (8.07), *Acacia nilotica* (4.54), *Mangifera indica* (2.37)
	Thane	19°12'N 73°02'E Brownish-black soil	*Oryza Sativa* (2.50), *Vigna radiata* (2.14), *Eleusine coracana* (0.72), *Cajanus cajan* (0.63), *Arachis hypogaea* (0.44)	*Tectona grandis* (25.79), *Azadirachta indica* (19.28), *Ziziphus mauritiana* (14.58), *Mangifera indica* (13.90), *Syzygium cumini* (12.23), *Acacia nilotica* (9.49)
	Nasik	20°02'N 73°50'E Laterite soil	*Zea mays* (5.17), *Triticum aestivum* (1.52), *Oryza Sativa* (1.21), *Pennisetum americanum* (0.76)	*Acacia nilotica* (20.12), *Azadirachta indica* (20.08), *Syzygium cumini* (19.52), *Leucaena leucocephala* (11.25), *Mangifera indica* (10.43)
	Ahmed Nagar	19°05'N 74°48'E Red to reddish brown lateritic	*Pennisetum americanum* (1.80), *Triticum aestivum* (1.39), *Glycine max* (1.17), *Oryza Sativa* (0.84)	*Moringa oleifera* (14.33), *Azadirachta indica* (13.63), *Emblica officinalis* (13.18), *Melia azedarach* (8.16)
	Ratnagiri	17°00'N 73°50'E Laterite & Alluvial	*Oryza sativa* (2.86), *Eleusine coracana* (1.21), Pulses (0.46) & Oilseeds (0.39)	*Mangifera indica* (62.00), *Cocos nucifera* (20.00), *Terminalia elliptica* (13.23), *Artocarpus heterophyllus* (3.00)
Odisha	Kurdha	20°11'N85°40'E Red and black soils	*Oryza Sativa* (2.32), *Zea mays* (2.11), *Arachis hypogaea* (1.05)	*Bambusa vulgaris* (53.87), *Musa sapientum* (17.02), *Cocos nucifera* (12.23), *Acacia auriculiformis* (7.42)
Himanchal Pradesh	Solan	30°54'N77°5'E Light textured soil	*Zea mays* (2.5), *Triticum aestivum* (1.78), *Oryza Sativa* (1.75)	*Grewia optiva* (25.00), *Leucaena leucocephala* (23.44), *Ficus palmata* (7.58), *Toona ciliata* (7.24)
	Mandii	31°70'N 76°93'E Mountainous & skeletal, Calcareous, Deep & Loam soil	*Triticum aestivum* (1.82), *Zea mays* (2.82), *Oryza sativa* (1.25), *Malus domestica* (3.03)	*Cedrus deodara* (17.50), *Pinus roxburghii* (15.69), *Mangifera indica* (9.00), *Eucalyptus* spp. (8.98), *Grewia optiva* (7.74), *Populus deltoides* (7.25), *Cassia fistula* (6.40)
Madhaya Pradesh	Guna	24°63'N 77°29' E Mixed Red & Black Soil	*Triticum aestivum* (1.90), *Cicer arietinum* (1.16), *Glycine max* (1.26), *Sorghum bicolor* (1.12) *Oryza sativa* (1.33), *Zea mays* (1.39), *Lens culinaris* (1.73)	*Acacia nilotica* (21.16), *Azadirachta indica* (12.65), *Leucaena leucocephala* (9.57), *Madhuca latifolia* (8.12), *Simarouba glauca* (8.11)

	Hosanga-bad	22°64'N 78°01' E Deep soil, medium Black soil, shallow soils	*Triticum aestivum* (1.99), *Cajanus cajan* (1.26), *Glycine max* (1.14), *Cicer arietinum* (1.27), *Sorghum bicolor* (1.05) *Oryza sativa* (1.44), *Zea mays* (1.27), *Lens culinarisl* (0.93) *Saccharum officinarum* (3.14)	*Leucaena leucocephala* (17.3), *Acacia nilotica* (15.27), *Tectona grandis* (14.84), *Mangifera indica* (9.79), *Eucalyptus tereticornis* (7.08), *Ziziyphus mauritiana* (4.58)
	Panna	24°48' N 80°18' E Yellow clay and sandy soil mixed red & black soil	*Triticum aestivum* (1.67), *Cicer arietinum* (0.87), *Glycine max* (1.31), *Sorghum bicolor* (0.97), *Oryza sativa* (0.85), *Zea mays* (0.77), *Lens culinaris* (1.66)	*Leucaena leucocephala* (20.00), *Acacia nilotica* (12.2), *Mangifera indica* (7.75), *Azadirachta indica* (7.15), *Ziziphus mauritiana* (4.52)
	Jabalpur	23°10' N 79°59' E Deep soil, medium black soil, black cotton soil	*Triticum aestivum* (1.99), *Cajanus cajan* (1.26), *Glycine max* (1.14), *Cicer arietinum* (1.27), *Sorghum bicolor* (1.05) *Oryza sativa* (1.44), *Zea mays* (1.27), *Lens culinaris* (0.93), *Saccharum officinarum* (3.14)	*Eucalyptus tereticornis* (88.43), *Leucaena leucocephala* (4.61) *Butea monosperma* (1.78), *Acacia nilotica* (1.66)
	Khandwa	24°10' N 80°56' E Deep soils, Moderately deep soils, Shallow soils	*Triticum aestivumt* (1.99), *Cajanus cajan* (1.28), *Glycine max* (1.26), *Sorghum bicolor* (1.26)	*Azadirachta indica* (22.84), *Tectona grandis* (19.81), *Acacia nilotica* (18.21), *Mangifera indica* (16.48), *Ziziphus mauritiana* (8.43)
	Shahdol	81°21' E.23°18' N Deep soils, Moderately deep soils	*Triticum aestivum* (1.89), *Cajanus cajan* (1.36), *Glycine max* (1.94), *Cicer arietinum* (1.67), *Oryza sativa* (1.24), *Lens culinaris* (1.93), *Zea mays* (1.87)	*Tectona grandis* (29.81) *Azadirachta indica* (18.81) *Butea monosperma* (2.78), *Acacia nilotica* (8.66)
Chhatis-garh	Bilaspur	82°8' E 22°4' N Deep soil, Medium Black Soil, Black Cotton Soil	*Triticum aestivum* (1.89), *Cicer arietinum* (1.67), *Oryza sativa* (1.24), *Lens culinaris* (1.93), *Zea mays* (1.87), *Gossypium* spp. (0.25)	*Tectona grandis* (39.81) *Acacia nilotica* (8.36) *Mangifera indica* (7.70) *Eucalyptus tereticornis* (5.08), *Butea monosperma* (2.78)
	Raigarh	83°4' E 21°9' N Deep soil, Medium Black Soil, Black Cotton Soil	*Triticum aestivum* (1.98), *Cicer arietinum* (1.88), *Oryza sativa* (1.64), *Lens culinaris* (1.93), *Zea mays* (2.17), *Gossypium* spp. (0.25)	*Tectona grandis* (32.84) *Acacia nilotica* (5.36) *Mangifera indica* (12.70) *Eucalyptus tereticornis* (8.08), *Butea monosperma* (3.78)

Table 9. Tree population in three categories existing on farmer's field

State	District	Observed number of trees (tree ha^{-1})			
		Slow	Medium	Fast	Total
Himachal Pradesh	Mandi	21.84	18.91	10.16	50.91
	Solan	2.299	14.41	5.757	22.47
Punjab	Faridkot	0.15	0.33	1.46	1.94
	Nawasahar	0.31	2.03	11.51	13.85
	Ludhiana	0.17	1.00	36.78	37.95
Haryana	Hisar	0.04	0.85	1.27	2.16
	Kurukshetra	0.23	0.57	5.78	6.58
Uttar Pradesh	Bulandshar	1.31	3.09	2.39	6.79
	Gorakhpur	0.77	13.22	1.77	15.76
	Mirzapur	0.46	8.40	1.29	10.15
	Sultanpur	0.90	2.88	2.36	6.14
	Faizabad	3.69	10.21	6.03	19.93
Bihar	Darbhanga	0.18	1.98	0.29	2.45
	Purnia	0.48	2.86	0.63	3.97
	Nawada	0.92	27.5	0.79	29.21
	Pusa	0.98	1.97	0.71	3.66
West Bengal	Uttar Dinajpur	0.24	4.04	1.93	6.21
	Bardhman	0.39	2.91	1.39	4.69
Gujarat	Anand	0.58	2.86	1.41	4.85
	Dahod	0.34	1.57	5.19	7.10
	Junagrah	0.32	1.66	0.08	2.06
	Patan	0.86	0.90	0.03	1.79
	Banaskhanta	0.21	3.90	0.19	4.30
Rajasthan	Jhunjhnu	6.03	0.76	0.16	6.95
	Sikar	9.21	2.58	0.62	12.41
	Bikaner	0.09	1.26	0.04	1.39
	Dausa	0.08	12.52	0.26	12.86
	Pali	0.75	14.0	0.14	14.89
Maharashtra	Ratnagiri	10.18	116.66	78.03	204.87
	Latur	0.20	1.87	0.04	2.11
	Wardha	1.35	12.06	0.11	13.523
	Thane	1.28	9.68	0.63	11.59
	Nasik	1.99	8.74	1.24	11.97
	Ahmed Nagar	1.77	2.25	2.71	6.73

Tamil Nadu	Kanchipuram	0.65	5.08	3.53	9.26
	Coimbatore	4.54	33.72	3.96	42.22
Andhra Pradesh	Chittoor	0.45	20.54	2.10	23.09
Odisha	Kurdha	10.05	9.64	36.24	55 .93
Karnataka	Bellary	0.07	1.94	0.35	2.36
	Tumkur	0.51	31.72	0.83	33.06
	Kolar	6.32	12.05	50.62	69.99
	Dharwad	1.67	2.93	1.21	5.81
Madhya Pradesh	Guna	1.39	3.80	1.20	6.39
	Hosangabad	0.73	4.04	2.00	6.77
	Panna	0.34	2.89	1.13	4.36
	Jabalpur	3.69	3.81	21.98	29.48
	Khandawa	0.75	6.40	0.41	7.568
	Shahdol	2.89	0.39	0.51	3.79
Telangana	Nizamabad	2.14	5.63	0.15	7.92
Chhattisgarh	Raigarh	1.91	1.52	0.11	3.54
	Bilaspur	1.60	1.29	0.10	2.99
Mean					**18.42**

3.4 Carbon sequestration potential of selected districts of different states

Assessment of carbon sequestration potential (CSP) of agroforestry system existing on farmer's field was done through simulation model CO2FIX in 51districts covering 16 states (U.P., Gujarat, Bihar, West Bengal, Rajasthan, Punjab, Haryana, Himachal Pradesh, Maharashtra, Madhya Pradesh, Tamil Nadu, Andhra Pradesh, Karnataka, Orissa, Chhattisgarh and Telangana). Tree biomass, total biomass (tree + crop), biomass carbon, soil carbon, net carbon sequestered over simulated period of 30-years and carbon sequestration potential (CSP) of surveyed districts of each state has been given in Table 10 (A-I). It was observed that above mentioned parameter depends upon the tree density as well as growth habit of the tree. If fast growing trees are more in total tree population, the rate of biomass accumulation as well as carbon will be more, but due to their short rotation cycle (7-10 year), the carbon sequestration potential will be less, when it is predicted for next 30 years. In case of slow and medium growing trees, the rotation cycle is more, carbon stored in biomass remain locked for 30 to 60 years period, which yields higher carbon sequestration potential than fast growing trees. For example in Haryana, district Kurukshetra is having 5.78 tree ha^{-1} under fast growing out of total tree population 6.59 tree ha^{-1} but CSP of the district 0.06 Mg C ha^{-1} yr^{-1}. In case Hisar, fast growing trees is 1.27 tree ha^{-1} out of total 2.17 tree ha^{-1} but CSP is more than Kurukshetra because medium growing trees is more in Hisar [Table 10 (A-I)].

Table 10. Biomass, soil carbon and carbon sequestered in agroforestry system existing on farmer's field (A to I)

(A)			**(No. of tree ha^{-1})**			
Parameters			**Haryana**		**West Bengal**	
			Hisar (2.17)	Kurukshetra (6.59)	Bardhman (5.00)	Dinajpur (6.20)
Tree Biomass (above and below around) Mg DM ha^{-1}	Baseline Simulated	Biomass	0.78 2.40	0.97 3.00	2.76 6.43	2.45 8.22
Total Biomass (tree+ crop) Mg DM ha^{-1}	Baseline Simulated		17.54 19.63	7.96 10.18	7.70 11.58	12.10 17.59
Soil carbon (Mg C ha^{-1}) Carbon	Baseline Simulated		10.31 12.89	9.1 9.75	11.76 13.47	8.16 9.28
Biomass carbon (Mg C ha^{-1})	Baseline Simulated	Carbon	7.58 8.57	3.48 4.53	3.45 5.30	5.33 8.00
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline Simulated		17.89 21.46	12.49 14.28	15.21 18.77	13.49 17.28
Net carbon sequestered in agroforestry systems over the simulated period of thirty years (Mg C ha^{-1})		Carbon sequestered	3.57	1.80	3.56	3.79
Estimated annual carbon sequestration potential of agroforestry system in different districts of Haryana and West Bengal (Mg C $ha^{-1}yr^{-1}$)			0.12	0.06	0.11	0.13

(B)								
Parameters			**Madhya Pradesh (No. of tree ha^{-1})**					
			Khandwa (7.58)	Guna (6.40)	Hosangabad (6.78)	Panna (4.37	Jabalpur (29.49)	Shadol (3.80)
Tree Biomass (above and below ground) Mg DM ha^{-1}	Baseline Simulated	Biomass	7.4 14.88	3.99 10.67	5.37 10.93	3.57 7.75	7.39 11.99	2.02 4.08
Total Biomass (tree+ crop) Mg DM ha^{-1}	Baseline Simulated		17.43 26.13	9.55 16.45	11.16 16.88	7.83 12.13	12.66 17.41	19.76 22.32
Soil carbon (Mg C ha^{-1})	Baseline Simulated	Carbon	14.8 16.19	23.38 24.80	17.75 19.42	17.95 19.12	12.04 12.74	7.92 11.23
Biomass carbon (Mg C ha^{-1})	Baseline Simulated		3.39 11.98	4.31 7.59	5.06 7.80	3.54 5.61	5.56 8.09	8.6 9.79
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline Simulated		18.19 28.17	27.61 32.39	22.81 27.22	21.49 24.73	16.10 20.83	16.52 21.02

Net carbon sequestered in agroforestry systems over the simulated period of thirty years (Mg C ha^{-1})	Carbon sequestered	9.98	4.78	4.41	3.33	4.73	4.50
Estimated annual carbon sequestration potential of agroforestry system (Mg C $ha^{-1}yr^{-1}$)		0.33	0.159	0.147	0.111	0.15	0.15

(C)									
Parameter			**Odisha (No. of tree ha^{-1})**	**Karnataka (No. of tree ha^{-1})**			**Chhattisgarh (No. of tree ha^{-1})**		
			Kurdha (56)	Dharwad (5.83)	Bellari (2.38)	Tumkur (33.08)	Kolar (69.0)	Raigrah (3.55)	Bilaspur (3.0)
Tree biomass (above and below ground) in Mg DM ha^{-1}	Baseline Simulated	Biomass	21.07 48.1	1.85 4.95	2.86 5.06	45.13 80.59	27.87 51.07	2.06 5.59	1.76 4.87
Total biomass (tree+ crop) in Mg DM ha^{-1}	Baseline Simulated		39.94 66.47	11.75 15.13	23.4 26.17	57.86 93.68	40.95 64.51	9.98 13.73	13.39 16.82
Soil carbon (Mg C ha^{-1})	Baseline Simulated	Carbon	14.78 16.47	9.89 10.88	19.24 20.11	17.03 19.63	6.17 12.14	10.61 15.54	12.32 13.11
Biomass carbon (Mg C ha^{-1})	Baseline Simulated		17.8 30.99	5.08 6.76	9.9 11.51	27.14 44.31	19.0 30.29	4.4 6.19	5.85 7.48
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline Simulated		32.58 47.46	14.97 17.64	29.14 31.62	44.17 63.94	25.17 42.43	15.01 18.73	18.17 20.59
Net carbon sequestered in agroforestry systems over the simulated period of thirty years (Mg C ha^{-1})		Carbon sequestered	14.88	2.67	2.48	19.77	17.26	3.72	2.42
Estimated annual carbon sequestration potential of agroforestry system (Mg C $ha^{-1}yr^{-1}$)			0.49	0.10	0.08	0.65	0.57	0.12	0.08

(D)

Parameter			Andhra Pradesh (No. of tree ha^{-1})	Maharashtra (No. of tree ha^{-1})					
			Chittor (23.10)	Ratnagiri (204)	Latur (2.11)	Wardha (13.53)	Thane (11.60)	Ahmed Nagar (6.73)	Nashik (11.98)
Tree Biomass (above and below ground) in Mg DM ha^{-1}	Baseline Simulated	Biomass	21.1 49.26	113.12 274.49	1.36 3.85	9.01 29.06	11.11 22.74	3.1 7.34	10.37 25.27
Total biomass (tree+ crop) in Mg DM ha^{-1}	Baseline Simulated		41.21 69.93	123.58 285.24	14.69 17.69	23.92 45.18	26.91 39.89	9.02 13.42	28.22 44.44
Soil carbon (Mg C ha^{-1})	Baseline Simulated	Carbon	16.36 18.15	20.6 25.9	18.65 19.2	16.87 20.80	17.6 19.23	12.04 14.51	14.82 17.63
Biomass carbon (Mg C ha^{-1})	Baseline Simulated		18.77 32.53	58.8 136.37	0.66 7.8	4.32 20.88	5.34 18.28	4.03 6.14	4.99 20.37
Total carbon (biomass+soil) (Mg C ha^{-1})	Baseline Simulated		35.13 50.68	78.86 162.27	19.31 27.00	21.19 41.68	22.94 37.51	16.07 20.65	19.8 38.0
Net carbon sequestered in agroforestry systems over the simulated period of thirty years (Mg C ha^{-1})		Carbon sequestered	15.55	83.81	7.69	20.49	14.57	4.58	18.2
Estimated annual carbon sequestration potential of agroforestry system (Mg C ha^{-1}yr^{-1})			0.51	2.78	0.25	0.68	0.48	0.15	0.60

(E)

Parameter			Himachal Pradesh (No. of tree ha^{-1})		Punjab (No. of tree ha^{-1})		
			Mandi (50.91)	Solan (22.47)	Faridkot (1.94)	Ludhiana (37.95)	Nawansahar (13.85)
Tree Biomass (above and below ground) in Mg DM ha^{-1}	Baseline Simulated	Biomass	10.69 24.86	11.8 31.38	0.58 0.96	2.88 4.67	6.70 6.71
Total biomass (tree+ crop) in Mg DM ha^{-1}	Baseline Simulated		26.77 41.39	24.95 44.9	12.18 12.91	25.97 28.41	23.91 24.94
Soil carbon (Mg C ha^{-1})	Baseline Simulated	Carbon	22.28 24.98	14.0 15.26	9.02 10.32	9.12 24.51	6.95 11.31
Biomass carbon (Mg C ha^{-1})	Baseline Simulated		12.05 19.04	11.33 20.86	5.27 5.61	11.21 12.45	10.30 10.90

Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline Simulated		34.33 44.02	25.33 36.12	14.29 15.93	20.43 36.96	17.25 22.21
Net carbon sequestered in agroforestry systems over the simulated period of thirty years (Mg C ha^{-1})		Carbon sequestered	9.69	10.97	1.64	16.53	4.96
Estimated annual carbon sequestration potential of agroforestry system (Mg C $ha^{-1}yr^{-1}$)			0.32	0.35	0.05	0.55	0.16

(F)							
Parameter			**Uttar Pradesh (No. of tree ha^{-1})**				
			Sultanpur (6.14)	Bulandsahar (7.01)	Gorakhpur (15.78)	Mirzapur (10.00)	Faizabad (19.94)
Tree Biomass (above and below ground) in Mg DM ha^{-1}	Baseline Simulated	Biomass	2.56 8.24	2.71 8.65	18.20 31.66	8.68 20.45	15.50 31.45
Total biomass (tree+ crop) in Mg DM ha^{-1}	Baseline Simulated		11.14 17.05	6.95 13.20	19.66 34.5	12.38 24.28	44.44 61.20
Soil carbon (Mg C ha^{-1})	Baseline Simulated	Carbon	8.13 8.63	10.65 11.26	9.89 11.01	13.76 14.45	4.60 11.17
Biomass carbon (Mg C ha^{-1})	Baseline Simulated		4.92 7.75	3.11 6.11	9.30 16.41	4.17 9.82	19.90 27.87
Total carbon (biomass+soil) (Mg C ha^{-1})	Baseline Simulated		13.05 16.38	13.76 17.37	19.19 27.42	5.25 11.47	24.50 39.04
Net carbon sequestered in agroforestry systems over the simulated period of thirty years (Mg C ha^{-1})		Carbon sequestered	3.33	3.61	8.23	8.23	14.54
Estimated annual carbon sequestration potential of agroforestry system (Mg C $ha^{-1}yr^{-1}$)			0.11	0.12	0.32	0.32	0.48

(G)							
Parameter			**Gujarat (No. of tree ha^{-1})**				
			Dahod (7.11)	Junagrah (2.07)	Patan (1.81)	Banaskantha (4.32)	Anand (4.85)
Tree Biomass (above and below ground) in Mg DM ha^{-1}	Baseline Simulated	Biomass	3.43 4.92	1.30 4.36	1.58 2.16	3.74 9.30	3.02 8.00
Total biomass (tree+ crop) in Mg DM ha^{-1}	Baseline Simulated		5.63 7.18	8.50 11.77	6.84 7.57	19.24 25.24	6.85 11.94
Soil carbon (Mg C ha^{-1})	Baseline Simulated	Carbon	24.13 29.66	23.38 23.49	10.02 11.17	11.11 12.64	11.75 12.03
Biomass carbon (Mg C ha^{-1})	Baseline Simulated		2.60 3.33	3.73 5.28	3.02 3.37	8.47 11.31	3.10 5.52
Total carbon (biomass+ soil) (Mg C ha^{-1})	Baseline Simulated		26.73 32.99	27.11 28.77	13.04 14.54	19.58 23.95	14.85 17.55

Net carbon sequestered in agroforestry systems over the simulated period of thirty years (Mg C ha^{-1})		Carbon sequestered	6.26	1.61	1.50	4.37	2.70
Estimated annual carbon sequestration potential of agroforestry system (Mg C ha^{-1} yr^{-1})			0.21	0.06	0.05	0.14	0.09

(H)

Parameter			**Rajasthan (No. of tree ha^{-1})**				
			Jhunjhunu (6.95)	Sikar (12.42)	Pali (14.90)	Dausa (12.87)	Bikaner (1.40)
Tree Biomass (above and below ground) in Mg DM ha^{-1}	Baseline Simulated	Biomass	4.33 10.04	7.62 18.74	11.25 33	11.01 28.59	0.86 2.87
Total biomass (tree+ crop) in Mg DM ha^{-1}	Baseline Simulated		17.13 23.2	19.19 30.64	17.19 39.11	12.88 30.51	2.22 4.27
Soil carbon (Mg C ha^{-1})	Baseline Simulated	Carbon	4.51 8.48	4.28 7.34	16.5 16.92	16.49 17.01	8.00 11.34
Biomass carbon (Mg C ha^{-1})	Baseline Simulated		7.58 10.48	8.64 14.11	7.95 18.47	6.09 14.55	1.0 1.98
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline Simulated		12.09 18.96	12.92 21.45	24.45 35.39	22.58 31.56	9.0 13.32
Net carbon sequestered in agroforestry systems over the simulated period of thirty years (Mg C ha^{-1})		Carbon sequestered	6.87	8.53	10.94	8.98	4.32
Estimated annual carbon sequestration potential of agroforestry system (Mg C ha^{-1} yr^{-1})			0.22	0.28	0.36	0.29	0.14

(I)

Parameter			**Bihar (No. of tree ha^{-1})**				**Telangana (No. of tree ha^{-1})**
			Pusa (3.67)	Nawada (30.00)	Darbhanga (2.50)	Purnia (4.00)	Nizamabad (7.93)
Tree Biomass (above and below ground) in Mg DM ha^{-1}	Baseline Simulated	Biomass	3.35 7.07	6.97 21.77	1.95 4.85	3.40 6.72	8.31 13.75
Total biomass (tree+ crop) in Mg DM ha^{-1}	Baseline Simulated		19.39 23.56	11.02 25.93	4.96 7.95	8.75 12.22	30.28 37.11
Soil carbon (Mg C ha^{-1})	Baseline Simulated	Carbon	4.31 6.58	16.67 17.11	14.73 15.22	17.38 18.65	17.76 19.04
Biomass carbon (Mg C ha^{-1})	Baseline Simulated		8.99 10.79	5.09 12.24	2.24 3.67	3.94 5.58	4.00 16.65

Total carbon (biomass + soil) ($Mg\,C\,ha^{-1}$)	Baseline Simulated		13.3	21.53 29.35	16.97 18.89	21.32 24.23	21.76 35.69
Net carbon sequestered in agroforestry systems over the simulated period of thirty years ($Mg\,C\,ha^{-1}$)		Carbon sequestered	4.07	7.82	1.92	2.91	13.93
Estimated annual carbon sequestration potential of agroforestry system ($Mg\,C\,ha^{-1}yr^{-1}$)			0.13	0.26	0.06	0.09	0.46

The carbon sequestration potential in different state is given in Table 10, which clearly showed that Maharashtra had higher CSP followed by Himachal Pradesh and Tamil Nadu. Total carbon in baseline of the project was maximum in Andhra Pradesh (35.13Mg C ha^{-1}) followed by Himachal Pradesh and Odisha. The net carbon sequestered in agroforestry system existing on farmer's field under different states is about 11.35Mg C ha^{-1} from baseline over simulated period of 30-year (Table 11). On an average, carbon sequestration potential (CSP) of agroforestry system in these states is 0.35Mg C ha^{-1} yr^{-1}.

The total carbon sequestration potential for these states was computed on the basis of agroforestry area and CSP of the state. The total CSP varied from 0.032 to 1.849 million tones carbon and total CSP of all 16 states come out to be 7.23 million tones carbon (Table 12). Thematic maps of annual and total CSP of different states are also depicted in figures 11& 12. The carbon sequestered in the agroforestry system under different states is converted into CO_2 equivalent carbon sequestered by multiplying 3.67 and the values are depicted on India's map (Figure 13).

Table 11. Total carbon stock, net carbon sequestered and carbon sequestration potential of different states

State (No. of District)	Tree density (tree ha^{-1})	Total C stock in baseline ($Mg\,C\,ha^{-1}$)	Net C-sequestered over simulated period of 30-year ($Mg\,C\,ha^{-1}$)	CSP ($Mg\,C\,ha^{-1}yr^{-1}$)
Uttar Pradesh	11.75	15.15	7.19	0.25
Gujarat	4.02	20.26	3.29	0.11
Bihar	9.82	15.28	7.51	0.22
West Bengal	5.45	14.35	3.68	0.12
Rajasthan	9.70	22.29	7.05	0.49
Punjab	17.91	17.32	7.71	0.25
Haryana	4.37	15.19	2.69	0.09
Himachal Pradesh	36.69	33.48	28.36	0.65

Maharashtra	41.80	27.70	28.95	0.82
Madhya Pradesh	9.73	21.24	5.54	0.18
Karnataka	27.567	28.36	10.55	0.35
Tamil Nadu	25.74	24.50	17.95	0.60
Andhra Pradesh	23.09	35.13	15.55	0.51
Telangana	7.92	21.76	13.93	0.46
Odisha	55.93	32.58	18.61	0.49
Chhattisgarh	3.27	16.59	3.07	0.19
Mean	18.42	22.97	11.35	0.35

Table 12. Agroforestry area, tree density and carbon sequestration potential (CSP) in different states

State	Agroforestry area (M ha)	Annual CSP Mg C $ha^{-1}yr^{-1}$	Total CSP (million tones C)
Uttar Pradesh	1.971	0.25	0.472
Gujarat	1.089	0.11	0.119
Bihar	0.795	0.22	0.199
West Bengal	0.405	0.12	0.050
Rajasthan	2.051	0.49	0.482
Punjab	0.420	0.25	0.108
Haryana	0.352	0.09	0.032
Himachal Pradesh	0.327	0.65	0.309
Maharashtra	1.916	0.82	1.849
Madhya Pradesh	1.346	0.18	0.248
Karnataka	1.293	0.35	0.455
Tamil Nadu	0.688	0.60	0.412
Andhra Pradesh &Telanagana	1.673	0.55	0.853
Orissa	0.804	0.49	0.499
Chhattisgarh	0.601	0.19	1.140
Total/ Mean	15.73	0.35	7.230

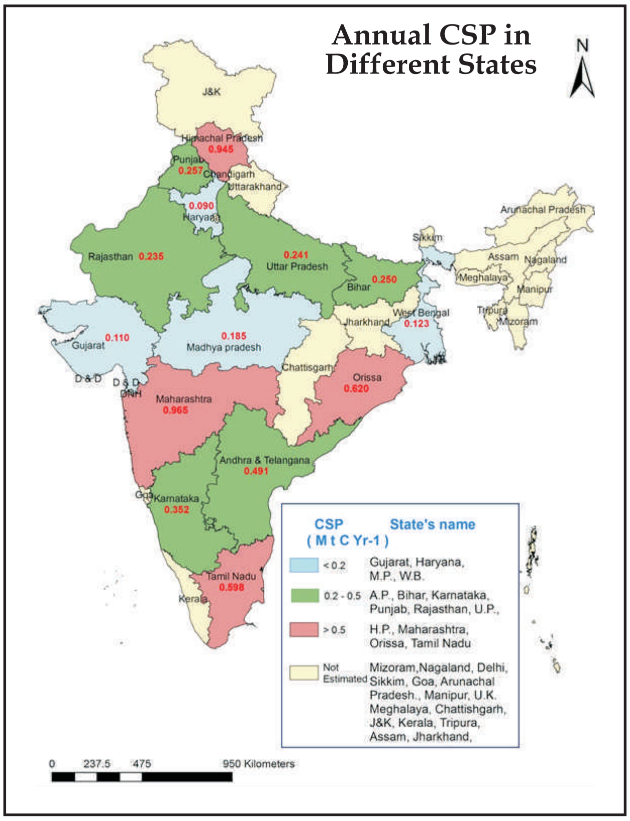


Figure 11.Annual carbon sequestration potential in different states

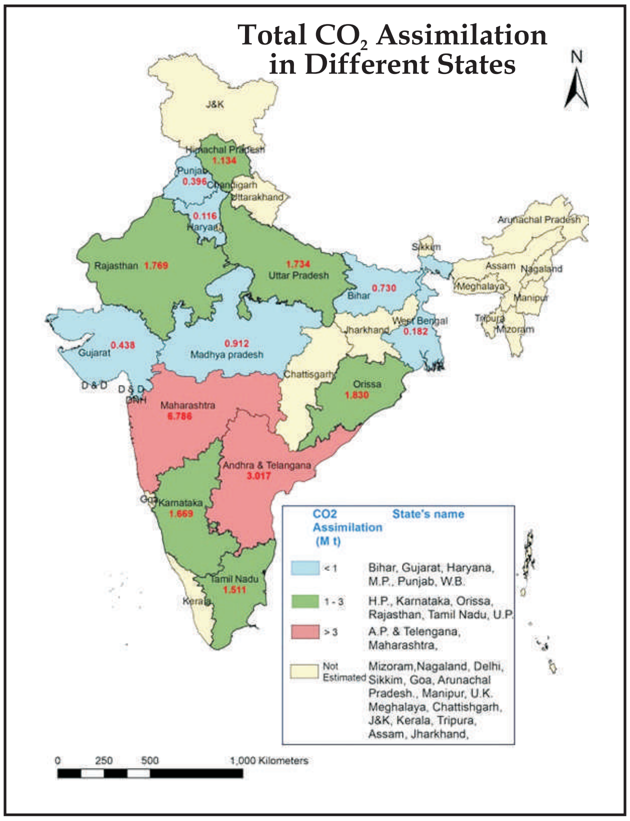


Fig. 13. CO_2 equivalent C sequestration by agroforestry systems in different states

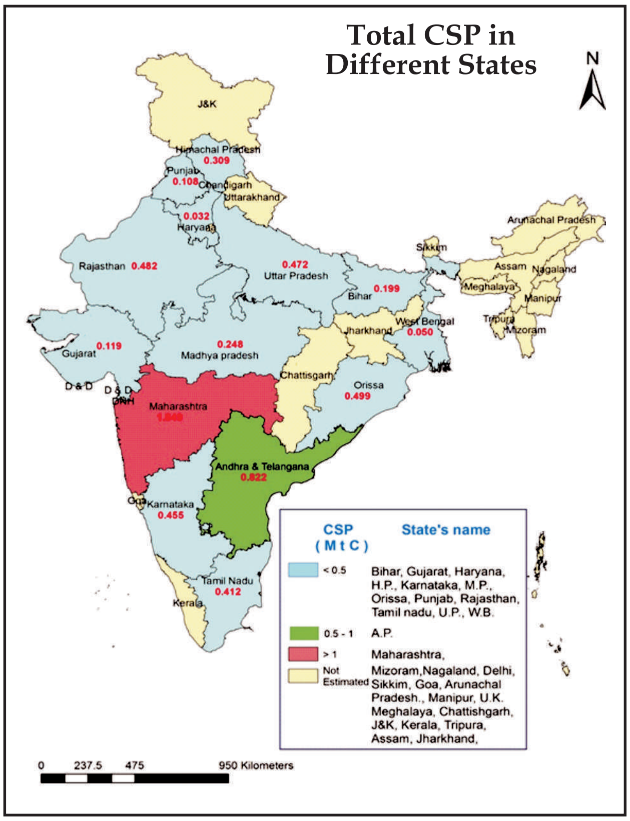


Figure 12. Total carbon sequestration potential in different states

3.5 Estimation of soil organic carbon

The studies on soil organic carbon (SOC) stock in existing agroforestry system on farmer's field was also done. Composite soil samples were collected from different soil depths (0-15, 15-30, 30-60 and 60-90 cm) with the help of soil augur from existing agroforestry system and crop fields. Soil bulk density measurements (0-15, 15-30, 30-60 and 60-90 cm) were made using soil core sampler carefully driven into the soil to avoid compaction. Bulk density was calculated from oven dried soil core weight and volume.

The soil samples were subsequently brought to the laboratory and air dried followed by grinding and then sieving through 2 mm sieve. These samples were analyzed to estimate soil organic carbon SOC. SOC stock was calculated from the following formula:

SOC stock (Mg ha^{-1}) = SOC x BD x SD x 10 ------ (i)

Where, SOC = Soil organic carbon (g kg^{-1})

BD = Bulk density (g cc^{-1})

SD = Soil depth (m)

10 is conversion factor

Soil organic carbon (SOC) was estimated in 0-90 cm soil layer under agroforestry system existing on farmer's field in different states (Rajasthan, Maharashtra, Madhya Pradesh, Karnataka, Telangana Andhra Pradesh, Bihar and Himachal Pradesh). The soil carbon stock under agroforestry varied from 46.59 to 100.13Mg C ha^{-1} in different states (Figure 14). Among these states, two states (Maharashtra and Telangana) having higher SOC and in other states SOC content in soil is almost similar.

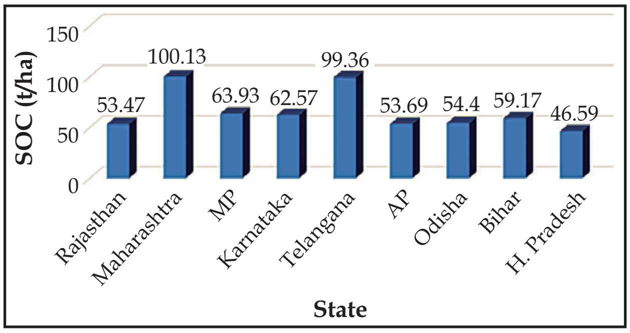


Fig. 14. Soil organic carbon in agroforestry existing on farmer's field (0-90 cm soil depth)

4. Studies on thermo-tolerance in MPTs of agroforestry importance

In connection with the studies on thermos-tolerance of crops and agroforestry important multipurpose tree species (MPTs) for climate resilient agriculture, various experiments were initiated under temperature gradient tunnel (TGT) and in ambient condition in 2011-12 at ICAR-Central Agroforestry Research Institute, Jhansi (Uttar Pradesh). The target temperature inside TGT was 5°C above than ambient condition with a step gradient of 1°C through sector 1 to sector 5. Most emphasis in the initial experiments was to study and monitor the environmental variables as obtained inside the TGT along with the experiments conducted with select crops and tree saplings.

In the initial phase of the studies MPTs namely Pongamia pinnata and *Dalbergia sissoo* and crops namely wheat and mustard were grownin polythene bags inside and outside TGT. The major purposes to include the crops for thermotolerance were for rapid evaluation of physiological traits and further use of the traits in evaluation of thermotolerance of MPTs. Differential responses of elevated temperature inside TGT were reflected in the growth and physiology of MPTs and crops. Canopy temperature depression (CTD) increased under elevated temperature than the ambient indicating adaptive responses of MPTs and crops. Collar diameter and biomass index of both the MPTs relatively decreased under elevated temperature. Physiological indices such as rate of CO_2 assimilation (Amax) and thylakoid electron transport rate (ETR) were also decreased as the temperature increases. Although the adverse effects on all the physiological and growth traits were relatively less at the elevated temperature of about 2°C than the ambient, but alarming effects were noted at the elevated level of 5°C above ambient. Increase in malondialdehyde (MDA) concentration in the leaves of MPTs and crops reflected higher cellular level oxidative stress mechanism under elevated temperature. Various other leaf level components like leaf area index (LAI), leaf pigment concentration and anti-oxidant enzyme activities were also influenced under elevated temperature.

Studies on agroforestry important multipurpose tree species were expanded with the addition of two more MPTs *Albizia procera* and *Butea monosperma* in 2014-15 and *Azadirecta indica* in 2016. Physio-biochemical indices as emerged from the previous and ongoing experiments have been utilized to assess the growth, carbon assimilation and its association with thermos-tolerance with respect to elevated temperature (Figure 15 A-G).

Under prevailing ambient climate, there is clear temporal variation with respect to seasonal changes. There are two extremes namely winter for low temperature and summer with extremely high atmospheric temperature. These provided a basis also for analyzing the physiological responses at temporal scale *viz.* pre-winter, winter and post-winter seasons for determining growth, carbon assimilation and thermos-tolerance.

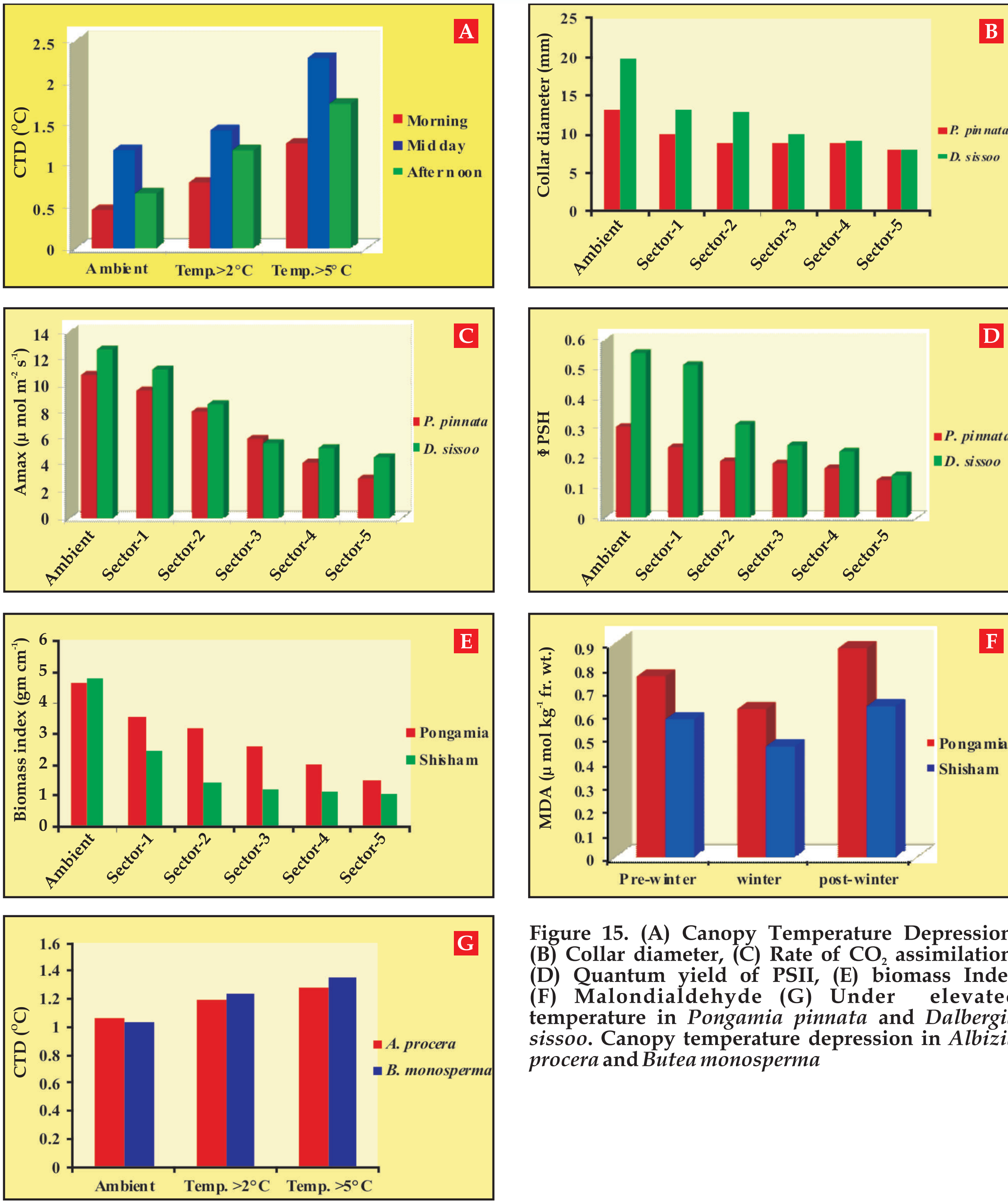


Figure 15. (A) Canopy Temperature Depression, (B) Collar diameter, (C) Rate of CO_2 assimilation, (D) Quantum yield of PSII, (E) biomass Index (F) Malondialdehyde (G) Under elevated temperature in *Pongamia pinnata* and *Dalbergia sissoo*. Canopy temperature depression in *Albizia procera* and *Butea monosperma*

5. Summary

The institute is working on three aspects under NICRA project *viz.*, assessment of carbon sequestration potential of agroforestry system existing on farmer's field in different agro-climatic regions through simulation model (CO2Fix model), mapping of agroforestry area using GIS and Remote Sensing technique and study on thermos-tolerance. The assessment of carbon sequestration potential (CSP) has been completed in 51 districts covering 16 states (U.P., Gujarat, Bihar, West Bengal, Rajasthan, Punjab, Haryana, Himachal Pradesh, Maharashtra, Tamil Nadu, Andhra Pradesh, Karnataka, Madhya Pradesh, Chhattisgarh, Orissa and Telangana). The number of trees on farmer's field is 18.42 trees per hectare in these states. The net carbon sequestered in agroforestry system existing on farmer's field under different states is 11.35Mg C ha^{-1} from baseline over simulated period of 30-year. The carbon sequestration potential (CSP) of agroforestry system is 0.35 Mg C ha^{-1} yr^{-1} and total CSP is 7.230 million tones C in these states.

The soil organic carbon (SOC) in agroforestry system existing on farmer's field in different states (Rajasthan, Madhya Pradesh, Maharashtra, Andhra Pradesh, Karnataka and Telangana) was higher than pure crop. The SOC in agroforestry systems under these states varied from 53.47 to 100.13 Mg C ha^{-1} in 0-90 cm soil depth.

Land use and land cover (LULC) analysis for the selected districts in ten agro-climatic regions (Lower Gangetic Plains, Middle Gangetic Plains, Upper Gangetic plains, Trans-Gangetic plains, Gujarat plains & hill region, Central Plateau & Hill Region, Central Plateau & Hill Region, Western Dry region, Western Plateau & Hill Region and Southern plateau & Hill Region) was done using RS2/ LISS-3 data. The total area under agroforestry in these regions was estimated to be 16.60 million ha of total geographical area (207.90 million ha) of these regions.

Studies on thermotolerance at elevated temperature 1 to 5°C from ambient under temperature gradient tunnel (TGT) indicated that the *Pongamia pinnata* and *Delbergia sissoo* both are able to tolerate an elevated temperature up to 2°C from ambient. But *Pongamia pinnata* relatively having better thermo-tolerance capability than *Dalbergia sissoo*.

Agroforestry system existing on farmer's field in Chittoor, Andhra Pradesh

Common agroforestry on farmers' field in Bellary

Agroforestry systems existing on farmers' field in Tumkur district of Karnataka

Common agroforestry existing on farmers'fields in Maharashtra

Common agroforestry existing on farmers' in Gujarat and Indo-Gangetic plain

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