Assessment of carbon storage potential and area under agroforestry systems in Gujarat Plains by CO2FIX model and remote sensing techniques

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Agroforestry is a traditional and ancient land use practice, having deliberate integration of trees with crop and livestock components. In India, agroforestry practices are prevalent in different agro-ecological zones and occupy sizeable areas. These practices have great potential for climate change mitigation through sequestration of atmospheric CO_2. Carbon sequestration potential was studied in four districts of Gujarat (Anand, Dahod, Patan and Junagarh), for which field survey was conducted to collect primary data on existing agroforestry systems. The extent of agroforestry area in these districts was estimated by sub-pixel classifier using medium resolution remote sensing data (RS-2/LISS III). By sub-pixel classifier, the highest area under agroforestry was estimated in Dahod (12.48%) followed by Junagarh district (10.95%) with an average of 9.12%. Sapota (*Manilkara zapota*) based agroforestry was also mapped in Junagarh district, which occupied an area of 1.13%. An accuracy of 87.2% was found by sub-pixel classifier in delineation of sapota-based agroforestry in the district. Dynamic CO2FIX model has been used to estimate total carbon (biomass + soils) and net carbon sequestered in existing agroforestry systems. Net carbon sequestered over a simulated period of 30 years in Anand, Dahod, Patan and Junagarh districts was found to be 2.70, 6.26, 1.61 and 1.50 Mg C ha^{-1} respectively. Total carbon stock in all four districts for baseline and simulated period of 30 years was estimated to be 2.907 and 3.251 million tonnes respectively. Thus, agroforestry systems in Gujarat have significant potential in carbon storage and trapping atmospheric CO_2 into biomass and soils. Hence, CO2FIX model in conjunction with remote sensing techniques can be successfully applied for estimating carbon sequestration potential of agroforestry systems in a district or a region.

Keywords: Agroforestry, geospatial, remote sensing, sub-pixel, tree cover.

AGROFORESTRY has traditionally been a way of life and livelihood in India for centuries. Now it is a modern science inviting deliberate management of trees on farms and surrounding landscape[1,2]. The growing awareness of the importance and potential of agroforestry has resulted in invaluable increase of site-specific case studies[3]. In India, the diagnostic survey and appraisal of agroforestry practices in the country revealed that there are innumerable practices in different agro-ecological zones[4]. These systems/practices occupy sizeable areas in various regions of India. Some estimates of area and production of wood for the tree cover outside forests are available[5], but these estimates include trees on canal side, roadside, and in urban areas and thus do not represent the true agroforestry area[6]. Nair[7] estimated globally 823 M ha area under agroforestry and silvo-pastoral systems, out of these 307 M ha is under agroforestry. However these estimates came from taking the FAO estimate of agricultural land multiplied by an estimate of 20% covered by agroforestry. But this value of 20% is not based on objectively measured data. Zomer[8] stated that agroforestry is widely spread and almost half of the world's agricultural lands have at least 10% tree cover. Manual (traditional) methods of mapping take a relatively longer time and cost more. An accurate assessment of the area under agroforestry systems in different agro-climatic regions of India can be done with the help of remote sensing. However, using remote sensing data for estimation of the agroforestry area is challenging as well as problematic for several reasons[9].

Remote sensing techniques have been utilized successfully in certain areas of application, including forestry, watershed management, agriculture and related fields, especially in developed countries where agriculture patterns are well defined and methodologies are developed. However, these technologies have yet to be used extensively in agroforestry[10]. In a spatial database approach, suitable areas for agroforestry were estimated in sub-Saharan Africa and suitable areas of *Annona cherimola* agroforestry system were determined in Southern Ecuador[11]. The role of GIS in the characterization and monitoring of agroforestry parks was also highlighted by Bernard and Depommier[12]. Paquette and Domon[13] did spatial analysis of census and geomorphologic data in GIS environment to explore dynamics of agroforestry in the 19th century Canadian landscape. A principal use of remotely sensed data is to produce a classification map of identifiable or meaningful features or classes of land cover types in a scene[14]. As a result, the chief product is a thematic map with themes such as land use, vegetation types and geology. By definition, a thematic map is an informational representation of an image which conveys information regarding the spatial distribution of a particular theme[15].

The most, if not all, agroforestry systems have the potential to sequester carbon. In India, carbon sequestration potential ranges from 1.5 to 3.5 Mg C ha^{-1} in small holding agroforestry systems[16]. Several forms of agroforestry systems like agri-silviculture, agri-horticulture, silvihorticulture and boundary plantations are prevalent in Gujarat

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Table 1. Site characteristics, dominant trees/crops and climate of the study districts

Attributes	Anand	Dahod	Junagarh	Patan
Location	22.55°N, 72.95°E	22.86°N, 74.25°E	21.52°N, 70.47°E	23.83°N, 72.12°E
Rainfall (mm)	761	745	904	539
Climate	Hot (moist)	Semi-arid (moist)	Hot arid	Hot arid
Soil type	Clay loam and sandy loam	Sandy loam shallow, deep black	Medium to shallow black, coastal alluvial	Alluvial sandy loam, sandy clay loam
Dominant crops	*Oryza sativa*, *Pennisetum glaucum* and *Triticum aestivum*	*Oryza sativa*, *Glycine max*, *Triticum aestivum* and *Cicer arietinum*	*Arachis hypogaea* and *Triticum aestivum*	*Pennisetum glaucum*, *Sorghum bicolor*, *Triticum aestivum* and *Sesamum indicum*
Dominant agroforestry trees	*Azadirachta indica*, *Mangifera indica*, *Eucalyptus tereticornis*	*Eucalyptus tereticornis*, *Leucaena leucocephala*, *Tectona grandis*, *Mangifera indica*	*Manilkara zapota*, *Mangifera indica*, *Tectona grandis*	*Ailanthus excelsa*, *Azadirachta indica*, *Leucaena leucocephala*

plains and hill regions. Tree species grown under these systems are mainly *Citrus medica*, *Mangifera indica*, *Manilkara zapota*, *Zizyphus mauritiana*, *Ailanthus excelsa*, *Tectona grandis* and *Azadirachta indica*. The present study is aimed at estimating the area of carbon storage potential under agroforestry systems in four districts of Gujarat, namely Anand, Patan, Dahod and Junagarh. Carbon storage and sequestration for the existing agroforestry systems in these districts have been estimated by CO2FIX V 3.1, a carbon accounting model. Land use and land cover (LULC) analysis has been done using medium resolution remote sensing data (RS-2/LISS III). Area under agroforestry in these districts is estimated by applying sub-pixel method, which is then used for estimating carbon storage potential at district level.

For estimating carbon stock under existing agroforestry systems (AFS) in Gujarat state, four districts namely, Anand, Patan, Dahod and Junagarh were surveyed. From each district, two block and from each block two villages were selected and surveyed. In each village, transect walk was conducted to collect primary data on tree species available on farmlands, their number, diameter at breast height (DBH) and crops grown with trees. Composite soil samples were collected from the existing agroforestry system up to 1.0 m depth with the help of soil augur. These samples were analysed to estimate soil organic carbon (SOC) using Walkley and Black method[17]. Site characteristics, dominant crops and trees in the selected district are given in Table 1.

CO2FIX v. 3.1 is a carbon accounting model developed as part of the CASFOR II project. It is a user-friendly tool for dynamically estimating the carbon sequestration potential of forest management, agroforestry and afforestation projects. The CO2FIX model is a multi-cohort ecosystem-level model based on carbon accounting of forest stands, including forest biomass, soils and products. This model has been used to estimate the dynamics of C-stock and flows for a variety of ecosystems around the world[18] and described in detail by Namburs and Schelhaas[19] and Masera *et al*.[20].

For simulating carbon stock under AFS for this study, three modules, namely biomass, soil and carbon accounting modules were considered. CO2FIX 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 includes tree species on farmlands along with their numbers, DBH (in cm), crops grown along with their productivity, area coverage, etc. Secondary data includes growth rate of tree biomass components (stem, branch, foliage, root) for tree species on an annual basis. The same input parameters as mentioned by Ajit *et al*.[21] were used in CO2FIX model for simulating tree biomass components in various tree cohorts.

Multispectral remote sensing images of Resourcesat-2/LISS III (spatial resolution 23.5 m) were analysed for land use and land cover patterns. Geo-referenced standard LISS III scenes for the period 2011–12 were procured from the National Remote Sensing Centre, Hyderabad. Pre-processing of these scenes includes layer stacking, subsetting with district boundary and mosaicing. Shape file of district boundaries was obtained from Survey of India, Dehradun.

Maximum likelihood method of supervized classification was applied for assessment of LULC in selected districts. These scenes were classified into 10 classes, viz. cropland, grassland, wasteland, plantation, agroforestry, forest, scrub land, built-ups, water bodies and sandy area (Figure 1). In this classification, only agri-silviculture/agri-horticulture systems and block plantations are accounted for in agroforestry class since medium resolution data is used. Other agroforestry systems like boundary plantations or scattered trees on farmlands are missed out because tree canopy cover within pixel is less than 50%. To overcome this constraint, Imagine Sub-pixel Classifier was applied.

Agricultural land including cropland and fallow land was masked from False Color Composite with the help of LULC map of the district. On this agricultural area, sub-pixel classifier was applied because agroforestry exists on

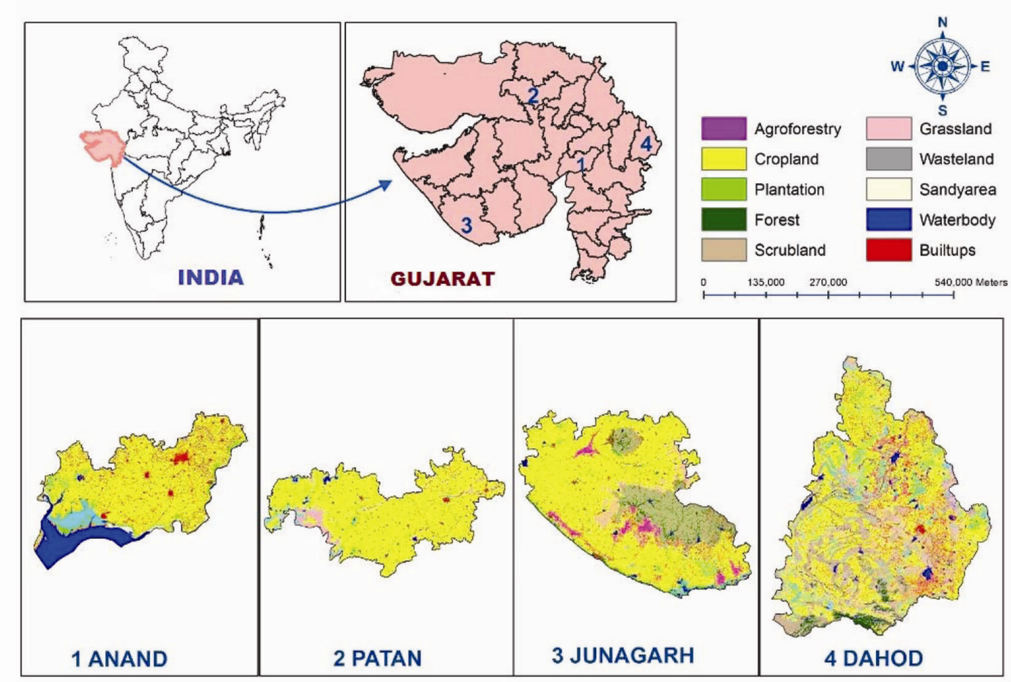

Figure 1. Location and land use land cover maps of selected districts in Gujarat.

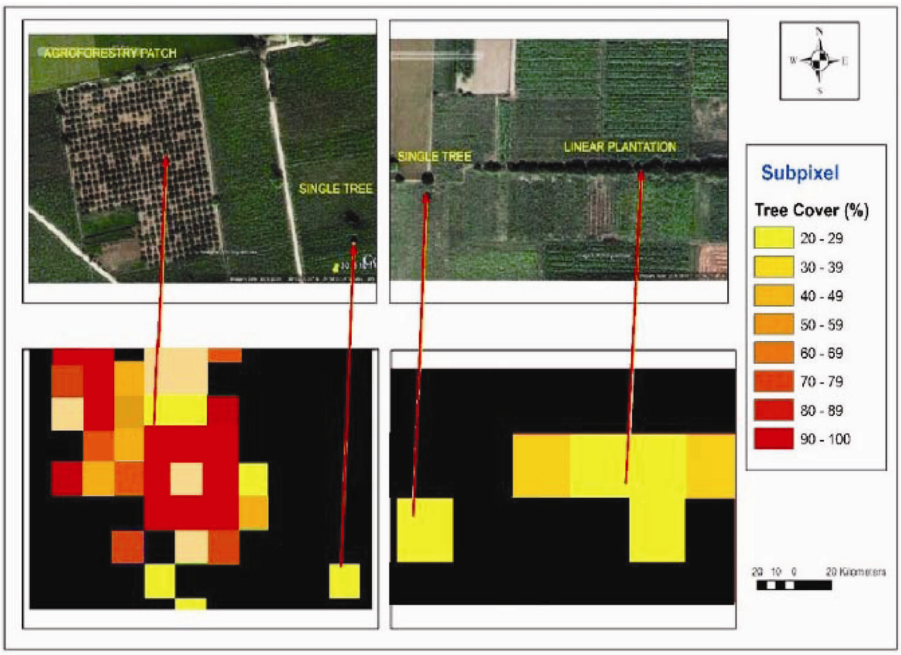

Figure 2. Agroforestry systems (scattered, linear and block plantations) identified through sub-pixel.

agricultural lands only. For sub-pixel classification, signatures were generated from referenced data collected by GPS from farmers' fields during survey. The resultant image consists of pixels of five categories: (i) pixels covering trees plus cropland, (ii) pixels covering trees plus fallow land, (iii) pixels covering only trees, (iv) pixels covering cropland only; and (v) pixels covering only fallow land. Pixels of first three categories are considered for estimation of area under tree cover and agroforestry. This method was adopted by Rizvi *et al.*[22] for mapping agroforestry in two districts of Punjab. The advantage of using sub-pixel classifier is that all types of agroforestry systems, viz. scattered trees on farmlands, linear, block plantations, etc., can be identified (Figure 2). Sapota-based

Table 2. Number of trees and their observed DBH in surveyed districts of Gujarat

District	Estimated age of existing trees (years)			Observed DBH of existing trees (cm)			No. of trees ha^{-1}
	Slow	Medium	Fast	Slow	Medium	Fast	
Anand	51.2	19.6	8.0	37.40	31.38	21.10	4.85
Dahod	50.7	17.4	7.7	37.05	26.92	18.65	7.11
Junagrah	53.8	15.0	7.6	39.24	25.13	18.88	2.07
Patan	62.1	15.2	8.1	45.63	24.21	20.89	1.81
Average	54.4	16.8	8.1	39.83	26.91	19.88	

Table 3. Estimated biomass, carbon and carbon sequestered by trees in agroforestry

Baseline and simulated biomass/carbon		Anand	Dahod	Junagarh	Patan
Total biomass (tree + crop) Mg DM ha^{-1}	Baseline	6.85	5.63	8.5	6.84
	Simulated	11.94	7.18	11.77	7.57
Soil carbon (Mg C ha^{-1})	Baseline	11.75	24.13	23.38	10.02
	Simulated	12.03	29.66	23.49	11.17
Biomass carbon (Mg C ha^{-1})	Baseline	3.10	2.60	3.73	3.02
	Simulated	5.52	3.33	5.28	3.37
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline	14.85	26.73	27.11	13.04
	Simulated	17.55	32.99	28.77	14.54

Table 4. Estimated area under tree cover and agroforestry by sub-pixel classifier

District	Tree cover		AF area	
	ha	%	ha	%
Anand	16658.40	5.11	26667.42	8.19
Dahod	27860.99	7.62	45631.70	12.48
Junagarh	58062.37	6.58	96606.09	10.95
Patan	25472.85	4.31	51330.24	8.69
Total	128054.61		196235.45	–
Average	–	5.95	–	9.12

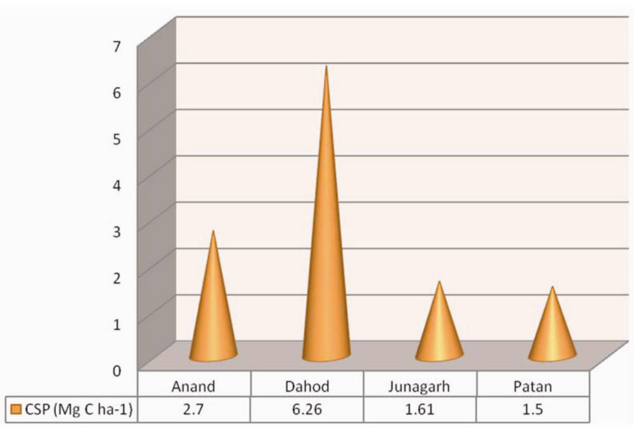

Figure 3. Carbon sequestration potential in AFS over the simulated period of 30 years in surveyed districts.

agri-horticulture system was dominant in Junagarh district. Area under this system was also mapped and estimated.

Tree species found on farmlands during survey of Anand, Dahod, Junagarh and Patan districts have been grouped into slow, medium and fast growing trees. Their observed DBH and number of trees per ha are presented in Table 2. Highest tree density was found in Dahod (7.11 trees ha^{-1}) followed by Anand (4.85 trees ha^{-1}), Junagarh (2.07 trees ha^{-1}) and Patan (1.81 trees ha^{-1}). Average DBH for slow, medium and fast growing trees was found to be 39.83, 26.91 and 19.88 cm respectively (Table 2). These values of DBH and tree densities were taken as input for CO2FIX 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 and simulated period of 30 years using carbon accounting module. Soil carbon has also been simulated using soil module of CO2FIX model by taking soil organic carbon as input. Biomass and soil carbon were then added to get the estimated total carbon in existing agroforestry systems.

Total biomass (tree + crop) under agroforestry systems (AFS) in Anand, Dahod, Junagarh and Patan districts was estimated to be 6.85, 5.63, 8.50 and 6.84 Mg DM ha^{-1} respectively for baseline by CO2FIX model. Baseline biomass carbon was estimated to be 3.10, 2.60, 3.73 and 3.02 Mg C ha^{-1} in these districts respectively, which is simulated to be 5.52, 3.33, 5.28 and 3.37 Mg C ha^{-1} for 30 years respectively. Soil carbon in these districts came out to be 11.75, 24.13, 23.38 and 10.02 Mg C ha^{-1} respectively (Table 3). Baseline total carbon (soil + biomass) in Anand, Dahod, Junagarh and Patan districts were estimated to be 14.85, 26.73, 27.11 and 13.04 Mg C ha^{-1} respectively. This total carbon has been simulated for a 30-year period, which came out to be 17.55, 32.99, 28.77 and 14.54 Mg C ha^{-1} respectively, in these districts. Net carbon sequestered in AFS simulated for the period of 30 years was estimated to be 2.70, 6.26, 1.61 and 1.50 Mg C ha^{-1} in Anand, Dahod, Junagarh and Patan districts respectively (Figure 3). Thus the total carbon sequestration potential under agroforestry systems would be

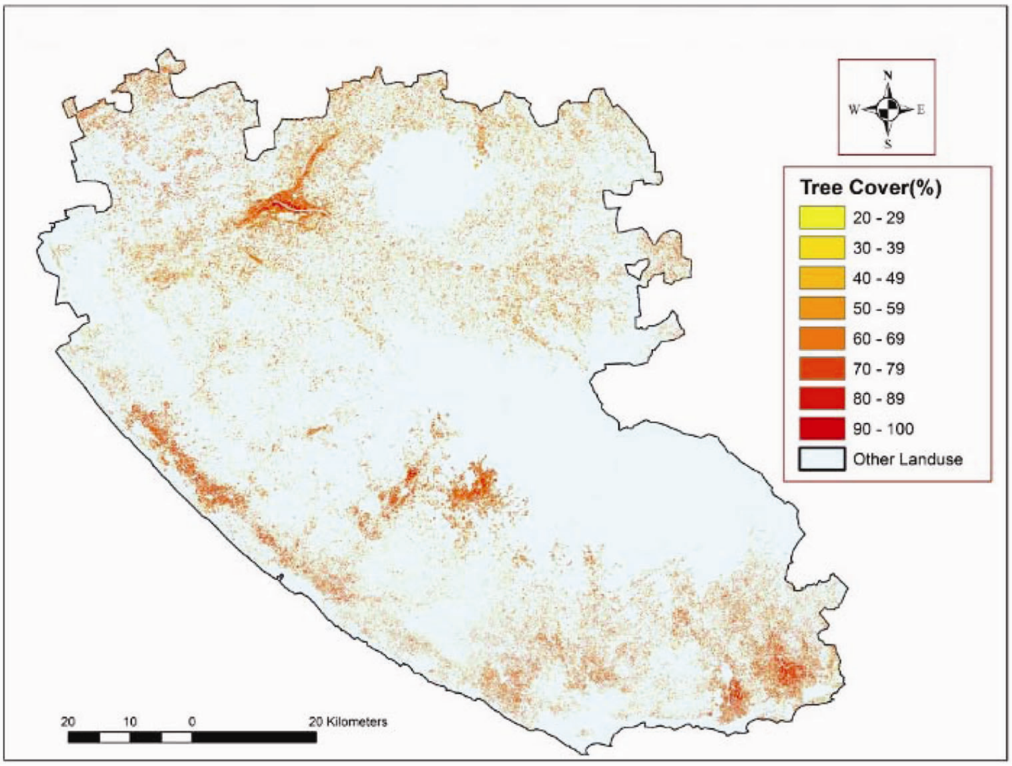

Figure 4. Distribution of agroforestry area in Junagarh district obtained by sub-pixel classifier.

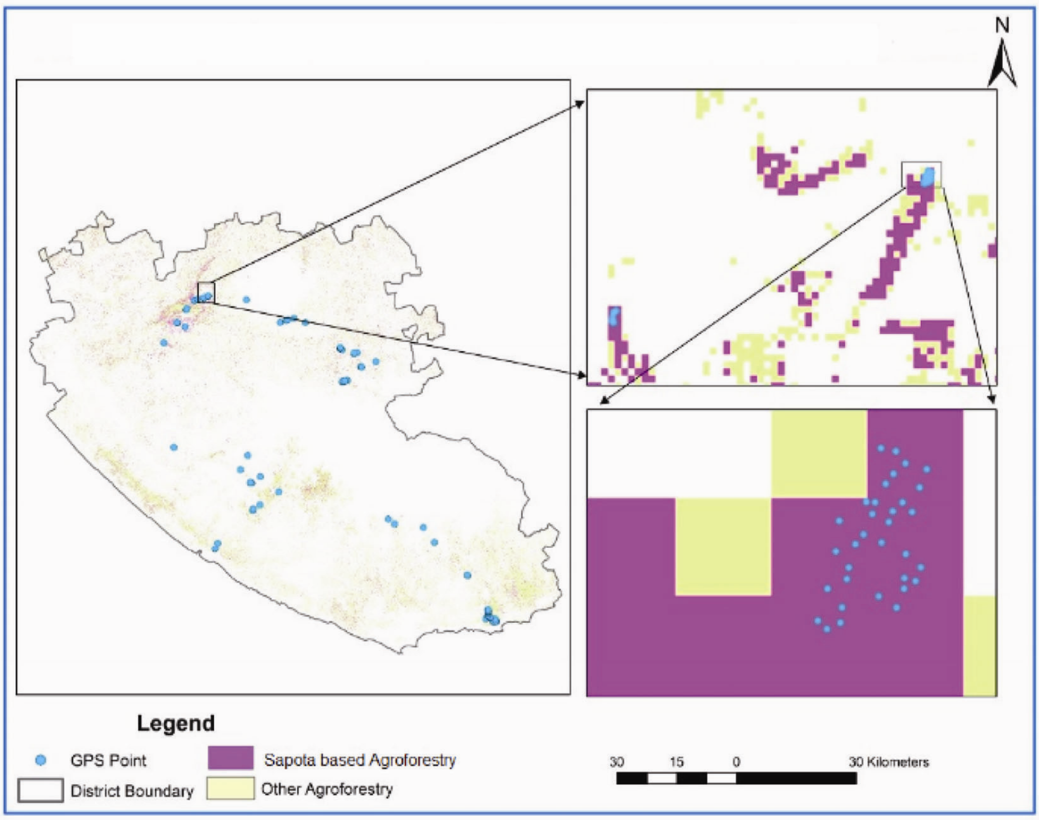

Figure 5. Sapota-based agroforestry system in Junagarh delineated by sub-pixel classifier.

Table 5. Total estimated carbon stock in four selected districts of Gujarat

District	Geographical area (M ha)	Total (biomass + soil) carbon stock (Mt)		Increase (%)
		Baseline	Simulated	
Anand	0.326	0.247	0.292	18.2
Dahod	0.365	0.745	0.919	23.3
Junagarh	0.882	1.574	1.670	6.09
Patan	0.578	0.332	0.370	11.4
Total	2.151	2.907	3.251	11.8

12.07 Mg C ha^{-1} in all four districts of Gujarat. Carbon storage and sequestration potential (CSP) of selected tree species in forests[23] and under agroforestry systems in Indo-Gangetic plains[21] have been estimated using CO2FIX model. CSP was estimated to be 0.11, 0.13 and 0.55 Mg C ha^{-1} yr^{-1} for Sultanpur, North-Dinajpur and Ludhiana districts in Indo-Gangetic plains.

Sub-pixel classifier gives an output in the form of percent tree canopy ranging from minimum 20% to maximum 100% within a pixel. All such pixels were considered for estimation of area under tree cover and agroforestry in a district. Estimated area under tree cover was highest in Dahod (7.62%) followed by Junagarh (6.58%) district. Average area under tree cover in these four districts was 5.95%, which is quite similar to the green tree cover in Gujarat reported by FSI[4]. Area under agroforestry in Anand, Dahod, Junagarh and Patan districts by sub-pixel classifier was estimated to be 8.19, 12.48, 10.95 and 8.69% (Table 4). Average area under agroforestry in these districts was found to be 9.12% of total geographical area.

In Junagarh district, fruit as well as timber species were found under agroforestry, Sapota (*Manilkara zapota*) and mango (*Mangifera indica*) were the dominant tree species among them. For species level classification, agroforestry area already obtained by sub-pixel classifier (Figure 4) was again used and reclassified for sapota-based and other agroforestry systems. A total of 195 GPS points were collected for sapota trees from the farmers' fields in Vanthalli and Una blocks of Junagarh district. Some of these points were used for making MOI (material of interest) which generated signatures for sapota species and the remaining points were used for finding classification accuracy.

Area under sapota-based agroforestry was found to be 9966.76 ha (1.13%) of the total area under agroforestry (Figure 5). The accuracy of this classification was 87.2% for sapota species. The remaining 9.82% area was under other agroforestry systems like mango, aonla and ber (Indian plum)-based agri-horticulture systems. Sub-pixel classification was used for coconut trees by Palaniswami *et al.*[24] and for Alder species by Oki *et al.*[25]. They applied linear mixture model to find the coverage of species within pixel.

Total carbon (biomass + soil) given in Table 3 was multiplied with estimated area under tree cover given in Table 4 to get the estimates of total carbon stock under existing AFS in four districts. Total carbon stock in baseline was estimated to be 0.247, 0.745, 1.574 and 0.332 million tonnes (Mt) in Anand, Dahod, Junagarh and Patan respectively. Junagarh district has the highest total carbon stock under existing AFS because it has the largest geographical area as well as the highest total estimated carbon compared to the other three districts. Estimated total carbon stock simulated for 30 years in Anand, Dahod, Junagarh and Patan districts was 0.292, 0.919, 1.670 and 0.370 Mt, respectively (Table 5). In this way, total carbon stock for baseline and a simulated period of 30 years was 2.907 and 3.251 Mt in all four districts. Highest percentage change in total carbon stock under existing AFS was observed in Dahod district (23.3%).

Rizvi *et al.*[26] estimated carbon stock under poplar based agroforestry systems in north-western India. Carbon stock was estimated to be 27–32 t ha^{-1} under boundary plantation and 66–83 t ha^{-1} under agri-silviculture system for a rotation period of 7 years.

Agroforestry is land use where trees are integrated with crops and/or animals on farmlands. With adequate management of trees on farmlands, a significant fraction of atmospheric CO_2 could be captured and stored in plant biomass and in the soils. To know the carbon sequestration potential of agroforestry systems, accurate estimation of area under agroforestry is essential. For mapping and delineating agroforestry using medium resolution data, pixel based methods do not give accurate results and considerable area is missed out. By sub-pixel classifier, all types of agroforestry systems (scattered trees, boundary and block plantations) can be identified and accounted for classification and it also gives a more accurate estimate of area under agroforestry systems.

In the plain belt of Gujarat, various agroforestry systems exist with considerable area and also a significant amount of carbon is sequestered by them in tree biomass and soils. CO2FIX – a carbon accounting model can be used for accurate estimation of carbon sequestration potential of agroforestry systems on a hectare basis. CO2FIX model in conjunction with remote sensing technology would help in estimating carbon stock and carbon sequestration potential under existing agroforestry systems for any district or region.

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ACKNOWLEDGEMENTS. This study was conducted under the National Initiative on Climate Resilient Agriculture Project. We thank the Indian Council of Agricultural Research (ICAR), New Delhi for financial and other support to this project.

Received 30 October 2015; revised accepted 20 January 2016

doi: 10.18520/cs/v110/i10/2005-2011

Green synthesis of copper bionanoparticles to control the bacterial leaf blight disease of rice

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Copper bionanoparticles were successfully synthesized using leaf aqueous extract of *Datura innoxia* from copper sulphate. Nanoparticles were characterized with the help of UV–Vis spectroscopy, Field Emission Scanning Electron Microscopy (FESEM), Energy Dispersive X-ray Spectroscopy and Fourier Transform Infrared Spectroscopy. FESEM analysis showed that the particles were spherical in shape with size ranging

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