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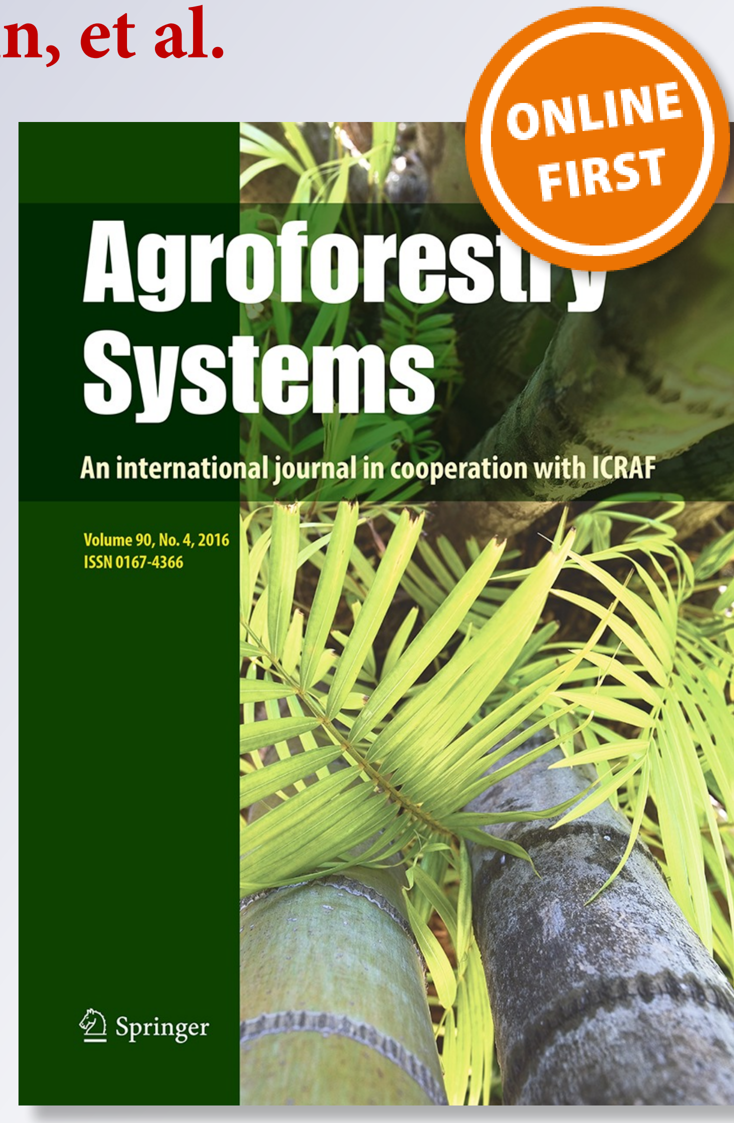


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# Estimating carbon sequestration potential of existing agroforestry systems in India

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**Abstract** India launched National Agroforestry Policy on 10th February, 2014 which has the potential to substantially reduce poverty in rural India and revive wood based industry, besides integrating food production with environmental services. The policy is not only crucial to India's ambitious goal of achieving 33 per cent forest and tree cover but also to mitigate GHG emissions from agriculture sector. Dynamic CO2FIX-v3.1 model has been used to estimate the carbon sequestration potential (CSP) of existing agroforestry systems (AFS) for simulation period of 30 years in twenty six districts from ten selected states of India. The observed number of trees on farmers' field in these districts varied from 1.81 to 204 per hectare with an average value of 19.44 trees per hectare. The biomass in the tree component varied from 0.58 to 48.50 Mg DM $ha^{-1}$, whereas, the total biomass (tree and crop) ranged from 4.96 to 58.96 Mg DM $ha^{-1}$. The soil organic carbon ranged from 4.28 to 24.13 Mg C $ha^{-1}$. The average estimated carbon sequestration potential of the AFS, representing varying edapho-climatic conditions, on farmers field at country level was 0.21 Mg C $ha^{-1}yr^{-1}$. At national level, existing AFS are estimated to mitigate 109.34 million tons $CO_2$

Dharmendra Tripathi, R.R.Shakhela, A.G.Patel,V.V.Dalvi, A.K.Saxena, A.K.S.Parihar, M.R.Backiyavathy, R.J.Sudhagar, C.Bandeswaran and S.Gunasekaran provided raw data at district level through survey as per formats of ICAR-CAFRI, Jhansi.

Ajit (✉)
ICAR-Indian Agricultural Statistics Research Institute (IASRI), Pusa, New Delhi 110 012, India
e-mail: ajit@icar.gov.in;
ajit@iasri.res.in;
umaajitgupta123@gmail.com

S. K. Dhyani · A. K. Handa · R. Newaj · S. B. Chavan · B. Alam · R. Prasad · A. Ram · R. H. Rizvi · A. K. Jain · Uma
ICAR-Central Agroforestry Research Institute (CAFRI), Jhansi 284 003, Uttar Pradesh, India

D. Tripathi
Agricultural Research Station, Fatehpur-Shekhawati 332301, Rajasthan, India

R. R. Shakhela · A. G. Patel
S.D.Agriculture University, Banaskhantha, Sardar Krushinagar 385 506, Gujarat, India

V. V. Dalvi
Dr. B.S. Konkan KrishiVidyapeeth, Ratnagiri, Dapoli 415 712, Maharashtra, India

A. K. Saxena · A. K. S. Parihar
N.D.University of Agriculture & Technology, Faizabad 224 229, Uttar Pradesh, India

M. R. Backiyavathy · R. J. Sudhagar
Tamilnadu Agricultural University, Coimbatore 641003, Tamil Nadu, India

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annually, which may offsets one-third (33 %) of the total GHG emissions from agriculture sector.

**Keywords** GHG-mitigation · Tree-biomass · Soil-carbon · CO2FIX model · Agroforestry-systems (AFS) · Carbon-sequestration-potential (CSP)

| | |
|---|---|
| AFS | Agroforestry-Systems |
| CSP | Carbon-Sequestration-Potential |
| GHG | Green-House-Gases |
| SCS | Soil-Carbon-Sequestration |
| ICAR | Indian Council of Agricultural Research |
| ISFR | India State of Forest Report |
| INCCA | Indian Network for Climate Change Assessment |
| MPTs | Multi-purpose trees |
| NAP | National Agroforestry Policy |
| NAPCC | National Action Plan on Climate Change |
| NICRA | National Initiative on Climate Resilient Agriculture |

## Introduction

Indian agriculture is facing diverse challenges and constraints due to growing demographic pressure, increasing needs of food, feed, pulp, fodder and timber, depletion of natural resources and climate change (Dhyani et al. 2013, NRCAF 2013). India thus, recognizes that for ensuring sustainability in agriculture and country's food security, appropriate mitigation and adaptation strategies have to be developed. The country has initiated timely action to address the problems of climate change. On June 30, 2008, India launched first National Action Plan on Climate Change (NAPCC) outlining existing and future policies and programs addressing climate mitigation and adaptation. The plan identifies eight core "national missions" (www.moef.nic.in/sites/default/files/Pg01-52_2.pdf), of which six are directly or indirectly related to agriculture (Table 1). Agroforestry has been recognized as a component of climate-smart agriculture and is frequently mentioned for strong potential for climate change adaptation and mitigation.

Agriculture is a significant contributor (10–12 %) to global anthropogenic emissions of GHGs (Smith et al. 2008), while IPCC recognized agroforestry with high potential for sequestering carbon under the climate change mitigation strategies (Watson et al. 2000; Chauhan et al. 2009). Agroforestry in developing countries has attracted increasing attention for both adaptation to climate change and greenhouse gas mitigation. Agroforestry practices stores more carbon compared to conventional plantations, and thus mitigates GHG emissions (Hergoualc'h et al. 2012; Chauhan et al. 2010a, 2010b). Agroforestry, in India, is practiced in both irrigated and rain-fed conditions where it produces fuel, fodder, timber, fertilizer, fibre, and contributes to food, nutritional and ecological security, sustains livelihoods, alleviates poverty and promotes productive and resilient cropping and farming environments. Agroforestry has been receiving greater attention by researchers, policy-makers and others for its perceived ability to contribute significantly to economic growth, poverty alleviation and environmental quality (DAC 2014) and recognized as an important part of the 'evergreen revolution' movement in the country. India, on 10th February 2014, became the first country in the world to adopt a National Agroforestry Policy (http://ccafs.cgiar.org/publications/indias-new-national-agroforestry-policy). There would be an investment of US $30–40 million attached to this National Agroforestry Policy–2014 (http://www.worldagroforestrycentre.org/newsroom/highlights/india-leads-way-agroforestry-policy).

The agroforestry policy is not seen only as crucial aspect to achieve India's ambitious goal of 33 per cent forest and tree cover but also to balance the GHG emissions from agriculture sector. However, there is limited understanding about the large scale potential of agroforestry systems for greenhouse gas emission reductions. Most of the recently reported carbon sequestration potential (CSP) estimates of tree based systems in India are based on tree biomass productivity only barring soil component (Pandya et al. 2013; Suryawanshi et al. 2014; Gupta and Sharma, 2014; Aggarwal 2014; Sharma et al. 2016), though some studies considered soil component as well (Kanime et al. 2013; Murthy et al. 2013; Arora and Chaudhary 2014; Goswami et al. 2014;) and only a few considered all the three carbon pools under agroforestry systems viz. tree, soil and crop (Chauhan et al. 2011,2012;

C. Bandeswaran · S. Gunasekaran
Tamilnadu Veterinary & Animal Science University, Kattupakkam 603 203, Tamil Nadu, India

**Table 1** National action plan on climate change (NAPCC) and their objectives in relation to agriculture and agroforestry in India

| S.No. | National action plan | Objectives related to agriculture and agroforestry |
|---|---|---|
| 1. | National water mission | 20 % Improvement in water use efficiency |
| 2. | National mission for sustaining the himalayan ecosystem | To conserve biodiversity, forest cover, and other ecological values in the Himalayan region |
| 3. | National mission for a green India | Afforestation of 6 million ha of degraded forest lands |
| | | 3 million ha of degraded lands and fallows to be brought under agroforestry/social forestry |
| | | Achieve target of 33 % tree cover from present less than 25 % of total geographical area |
| 4. | National mission for sustainable agriculture | Climate adaptation in agriculture through the development of climate-resilient crops, |
| | | Emphasis on soil & water conservation, water use efficiency, soil health management and rainfed area development |
| | | Expansion of weather insurance mechanisms and agricultural practices |
| | | Promote tree based land use system as crop diversification strategy. Presently Agroforestry as submission of NMSA is housed at DAC. |
| 5. | National mission for enhanced energy efficiency | Renewable energy through biofuel, biogas and biomass |
| | | 20 % blending of biofuels both for bio-diesel and bioethanol |
| 6. | National mission on strategic knowledge for climate change | Better understanding of climate science, impacts and challenges |
| | | Climate science research fund, |
| | | Improved climate modeling and Increased international collaboration |

Mangalassery et al. 2014; Sharma et al. 2016). Moreover, all these studies fall under the category of "One-Time-Harvest-Assessment". Regarding the future prediction of carbon sequestered over a period of time, falling under the category of "Simulation-Studies", the published literature in Indian context is very scanty barring Kaul et al. (2010) for some selected tree species and Gera et al. (2006); Ajit et al. (2013) for agroforestry systems in Indo-Gangetic-Plains of India.

This study on mitigation potential of existing agroforestry systems on farmers' field at district level in India was initiated in 2011 at Central Agroforestry Research Institute (CAFRI), Jhansi (Uttar Pradesh), India under the National Initiative on Climate Resilient Agriculture (NICRA) Project. The basic objective of this study was to simulate the CSP of existing AFS on farmers' field at district level. This article also elaborates the potential of existing agroforestry systems on farmers' fields in India in mitigating the total annual GHG emissions from agriculture sector at the state and country level using CO2FIX model. The validation of the CO2FIX model simulated results with the real time observed data under Indian conditions has been attempted by Ajit et al. (2013). Recently, Negash and Kannienen (2015) compared long-term simulated and measured C stocks for biomass, soil and total (biomass plus soil) under three agroforestry systems for a period of 10–40 years and concluded that the CO2FIX model accurately predicts the soil and total C stocks, however the prediction of the biomass C stocks can be improved through availability of accurate inputs for running the model. The results of this study can provide firsthand information on the potential of agroforestry systems in C sequestration at district/state level, which in turn, could be used as an input for the managers and planners for small-holder agroforestry systems.

## Materials and methods

CO2FIX model v3.2 (Masera et al. 2003; Groen et al. 2006), a process based carbon estimation model, has been used in this study for simulation purpose. CO2FIX v3.2 is available free of charge for academic/research institutions (http://www.efi.int/projects/casfor/CO2FIX/register32.php) and more detailed information on CO2FIX is available at http://www.efi.int/projects/casfor. CO2FIX was preferred over other reported models used in estimating changes in carbon stock for forestry and plantation projects viz. PROCOMAP, CO2FIX, CENTURY and ROTH for the present study since only CO2FIX can simulate the carbon dynamics of single/multiple species simultaneously, and can handle trees with varied ages and agroforestry systems (AFS). Follow Ajit et al. (2013) for brief description and input parameters of the model.

## Basic data required for running the CO2FIX model

For the purpose of simulating carbon stocks under 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 name of the 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. The secondary data includes the growth rates of tree biomass components (stem, branch, foliage and root) for various species on annual basis as well as the productivity of different crops grown in that region.

District wise survey were conducted in ten states viz. Himachal Pradesh, Punjab, Haryana, Uttar Pradesh, Bihar, Gujarat, Rajasthan, Maharashtra, Tamil Nadu and West Bengal of the country to record data on tree, crop and soil component under the existing AFS. Twelve villages were selected from each district using two stage random sampling for comprehensive primary survey. Number of trees were counted, species wise, in each village. Mean of these 12 villages was taken for obtaining the average number of trees in one village of the district. This was multiplied by the total number of villages, for computing the total number of trees in one district. The total number of trees in the district were divided by the total crop sown area of the district for calculating the number of trees per hectare in each district.

Different tree species, planted/retained by the farmers on croplands, exhibit varying nature of growth behavior. The actual number of tree species observed at district level during the field survey in different states of the country ranged from 17 to 32. As the basic requirement of any simulation tree growth model, the CAI of the stem growth pattern with respect to the DBH (diameter at breast height) for each of the observed tree species should be known i.e. the equations/models relating stem volume to DBH should be known (either through the primary data or from published studies). However, for majority of the 32 observed species, the published equations for Volume-DBH relations under Indian conditions were not available. This compelling constraint necessitated to group the tree species, observed during the survey, into three broad categories and to develop generalized equations for stem volume-DBH for these categories. Accordingly, 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 etc.) set for the tree cohorts have been detailed in Table 2. Relative growth of various tree components with respect to stem growth for tree cohorts over years has been detailed in Table 3. 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 (i.e. the generalized equations), the volume equations published in India State of Forest Report-2013 (Ministry of Environment and Forests, Government of India, http://fsi.nic.in/cover_2013/annexure.pdf) were used as the secondary data.

Readers may refer Ajit et al. (2013) for detailed description on parameterization of the tree/crop cohorts and soil module.

## Biophysical and climatic sketch of surveyed states

The 26 districts of the ten states, where the present study was undertaken to cover nine agro-climatic zones, out of the 15 broad agro-climatic zones based on physiography and climate of the country. Details of the site characteristics, dominant tree species and crops alongwith climate of the study area is presented in Table 4.

## Statistical analysis of data

The Statistical analysis of data has been done using SAS-9.3 (SAS Institute's Inc. @ 2011, Cary, North Carolina-27513, USA). Proc-UNIVARIATE was used

**Table 2** Input parameter used in CO2FIX model for simulating tree biomass components in various tree cohorts (uniform for all 26 districts)

| Cohorts | Slow growing trees[a] | Medium growing trees[b] | Fast growing trees[c] |
|---|---|---|---|
| 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 |

Estimated from [a] Negi (1984); Kumar et al.(2011); [b] Jha (1995); [c] Bargali et al. (1992); [*] Haripriya (2001)

for computing the basic descriptive statistics, trimmed & winsorized means and proc-CORR was used for computing correlation coefficients.

## Results and discussion

### CO2FIX simulated tree and crop biomass/carbon stocks

The base line (current) tree biomass (above plus below ground) at the district level was lowest (0.58 Mg DM ha$^{-1}$) in Faridkoat (Punjab) and highest (48.5 Mg DM ha$^{-1}$) in Ratnagiri (Maharashtra) respectively (Table 5). The value in Ratnagiri district was high because of the highest tree density (204 trees ha$^{-1}$). In general, the baseline (current) tree biomass increased linearly with tree density ($R^2_{(\text{observed vs predicted})} = 0.84$) implying thereby that tree density plays a convincing role in governing the base line tree biomass. The tree biomass (above plus below ground) is expected to increase from the base line range of 0.58–48.5 Mg DM ha$^{-1}$ to the simulated range of 0.96–109.75 Mg DM ha$^{-1}$ over the simulated period of 30 years (Table 6). The rate of increase in tree biomass at district level is expected to range from 0.013 to 2.04 Mg DM ha$^{-1}$yr$^{-1}$ as the tree density increases from 1.94 to 204 trees ha$^{-1}$. The current total biomass (tree and crop together) ranged from 4.96 to 58.96 Mg DM ha$^{-1}$ and is expected to increase to the range of 7.18–120.5 Mg DM ha$^{-1}$. The 30 years simulation results of CO2FIX model revealed that biomass carbon would enhance to the tune of 3.33–57.30 Mg C ha$^{-1}$ from the present baseline range of 2.24–27.78 Mg C ha$^{-1}$.

### CO2FIX simulated soil carbon stocks

The observed base line (current) surface soil carbon in different districts ranged from 4.28 to 24.13 Mg C ha$^{-1}$ for Sikar (Rajasthan) and Dahod (Gujarat), respectively (Table 6). Amongst the district wise values, the lowest was observed for Rajasthan and the higher values for Himachal Pradesh, Bihar, Maharashtra and Gujarat. During the 30 year simulation period, the soil carbon is expected to increase to the tune of 7.34–29.66 Mg C ha$^{-1}$ in different districts. The net estimated increase in soil carbon was maximum for Ludhiana district (Punjab). The estimated rate of soil carbon sequestration (SCS) under the existing AFS at district level ranged from 0.003 to 0.51 Mg C ha$^{-1}$ yr$^{-1}$(during the 30 year simulation period) for different districts. The higher values of SCS rate in Ludhiana (0.51 Mg C ha$^{-1}$ yr$^{-1}$) may be attributed to higher tree density of fast growing trees (*Populus deltoides*-53.25 %, *Eucalyptus tereticornis*-28.25 % and *Melia azedarach*-14.98 %) as they alone contribute 97 % in the total tree density. Moreover, the management itself is not uniform, it plays significant role at farmers field.

**Table 3** Relative growth of various tree components with respect to stem growth for tree cohorts over years (uniform for all 26 districts)

| Slow growing[a] | | Medium growing[b] | | Fast growing[c] | |
|---|---|---|---|---|---|
| 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 |
| 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 |
| 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 |

Estimated from [a]Negi (1984), Kumar et al. (2011), Pande and Patra (2010); [b]Jha (1995); [c]Bargali et al. (1992)

## CO2FIX simulated carbon sequestration potential (CSP) of existing AFS at district level

A very clear cut trend was observed across all surveyed districts (irrespective of state boundaries) that with increasing number of trees per hectare, the value of CSP increased proportionally. A high positive correlation (r = 0.89, significant at 1 per cent level of significance), was observed in between tree density and CSP at district level. Although, even with almost equal number of trees per hectare in some districts viz.Nawansahar (6.2), Sultanpur (6.14) and Uttar Dinajpur (6.2) varying values of CSP viz. 0.16, 0.11 and 0.12 Mg C $ha^{-1}yr^{-1}$, respectively may be attributed to be influenced by site's climatic factors like average temperature, total precipitation with its distribution over different months and evapo-transpiration, and management.

The total carbon sequestered under AFS basically comprises of two pools viz. biomass carbon and soil carbon. As far as the biomass carbon is concerned, it is predominantly the tree biomass carbon that matters most, since bulk of the crop biomass is exported out of the system and the crop residue biomass only accounts in total CSP. Moreover, it is observed that as the tree density increases, tree biomass increases and in turn the tree biomass carbon increases. Accordingly, tree density is expected to play an important role in CSP of AFS. It is clear from the breakup depicted in Table 6 that biomass carbon constitutes a larger portion of the total carbon as compared to soil carbon. A clear increasing trend was observed between total carbon sequestered and tree density as the pearson's correlation coefficient was highly significant with a high positive value (r = 0.89, p = 0.00). However, such a strong trend could not be observed in between soil carbon and tree density as the correlation was not only weak but also non-significant (r = 0.34, p = 0.20). Although a similar trend, as recorded with total carbon, was observed in between the tree biomass carbon and tree density with highly significant and high correlation value (r = 0.92, p = 0.00).

The estimated range for CSP of existing AFS at district level ranged from 0.05 to 1.03 Mg C $ha^{-1}$ $yr^{-1}$ and the observed tree density (trees $ha^{-1}$) ranged from 1.81 (Patan, Gujarat) to 204 (Ratanagiri, Maharashtra) (Table 6). The average values of trees $ha^{-1}$ was 19.44 and the average value of CSP was 0.21 Mg C $ha^{-1}yr^{-1}$. The Trimmed mean values of trees $ha^{-1}$ was 7.64 and CSP was 0.16 Mg C $ha^{-1}yr^{-1}$ and Winsorized mean values of trees $ha^{-1}$ was 8.68 and CSP was 0.18 Mg C $ha^{-1}yr^{-1}$.

## Carbon sequestration and GHG mitigation through existing AFS at state/country level

Average CSP at state level was more than 0.25 Mg C $ha^{-1}yr^{-1}$ for Maharashtra, Himachal Pradesh and Tamil Nadu, whereas, it was less than 0.20 Mg C $ha^{-1}yr^{-1}$ in Bihar, West Bengal, Haryana and Gujarat. For remaining three states viz. Punjab, Uttar Pradesh

**Table 4** Site characteristics, dominant tree species/crops and climatic data of the study areas

| State | District | Location and soil type | Region and climate | Dominant crops (productivity in Mg ha$^{-1}$) | Dominant trees (contribution in per cent) |
|---|---|---|---|---|---|
| Himachal Pradesh | Mandi | 31.70°N 76.93°E<br>Mountainous & skeletal, calcareous, deep & loam soil | Western Himalayan region<br>Hill temperate region, sub-humid | *Triticum aestivum* (1.82), *Zea mays* (2.82), *Oryza sativa* (1.25) | *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) & *Malus domestica* (3.03) |
| Punjab | Faridkot | 30.40°N 74.45°E<br>Coarse loamy & fine loamy associations & Fine loamy | Trans gangetic plain region<br>Hot semi-arid | *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<br>Coarse loamy & fine loamy soils | Trans gangetic plain region<br>Hot semi-arid, sub-humid (Dry) | *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) |
| | Nawanshahar | 31.12°N 76.11°E<br>Coarse loamy and fine loamy association, Fine loamy | West Himalayan region<br>Hot sub-humid (Dry) | *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 | Kurukshetra | 29.96°N 76.83°E<br>Clayey loam & sandy loam | Upper gangetic plain<br>Hot and humid | *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<br>Sandy to sandy loam, loamy and clay loam | Upper gangetic plain<br>Hot semi-arid | *Oryza sativa* (2.50), *Pennisetum glaucum* (2.23), *Triticum aestivum* (4.62), *Hordeum vulgare* (3.69), *Vigna radiata* (0.46) & *Cicer arietinum* (0.90) | *Eucalyptus tereticornis* (32.61), *Populus deltoides* (28.13), *Dalbergia sissoo* (16.45), *Azadirachta indica* (6.74) |
| Uttar Pradesh | Sultanpur | 26.45°N 82.11°E<br>Silty loam & gray | Middle gangetic plain region<br>Hot sub-humid (dry) | *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), |
| | Gorakhpur | 26.75°N 83.36°E<br>Sandy, Sandy loam or clay loam & khadar soil | Middle gangetic plain region<br>Hot sub-humid (moist) | *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) |
| | Bulandsahar | 28.40°N 77.85°E<br>Loamy sand, sandy loam and sandy silt loam | Upper gangatic plain zone<br>Hot semi-arid | *Oryza sativa* (2.22), *Triticum aestivum* (3.77), Pulses (0.77) & *Saccharum officinarum* (59.4) | *Mangifera indica* (32.64), *Populus deltoides* (28.57), *Psidium guajave* (8.19), *Azadirachta indica* (4.17) |

**Table 4** continued

| State | District | Location and soil type | Region and climate | Dominant crops (productivity in Mg ha$^{-1}$) | Dominant trees (contribution in per cent) |
|---|---|---|---|---|---|
| | Mirzapur | 25.15°N 82.60°E<br>Red lateritic & sandy loam, black soils | Middle gangetic plain region<br>Hot sub-humid (Moist/Dry) | *Oryza sativa* (1.93), *Triticum aestivum* (2.03), Oilseeds (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<br>Silty loam (bhat), alluvial silt loam | Middle gangetic plain region<br>Hot sub-humid (Moist) | *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) |
| Bihar | Darbhanga | 26.17°N 85.90°E<br>Very deep, calcareous fine loamy, loamy | Middle gangetic plain region<br>Hot sub-humid (Moist) | *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<br>Sandy loam, clay loam & loam | Middle gangetic plain region<br>Hot sub-humid (Moist) | *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<br>Sandy loam, clay loam, loam, clay | Mid gangetic plain region<br>Hot sub-humid (Dry) | *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) |
| West Bengal | Uttar Dinajpur | 25.62°N 88.12°E<br>Clay loam, sandy loam & sandy | Lower gangetic plain region<br>Hot sub-humid to humid | *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<br>Gravelly loamy, loam & clay | Lower gangetic plain region<br>Hot sub-humid to humid | *Oryza sativa* (3.01), *Triticum aestivum* (2.31), Zea *mays* (3.30), Pulses (0.85), Oil seeds (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<br>Clay loam & Sandy loam | Gujarat plains & hills region<br>Hot (Moist) | *Oryza sativa* (2.11), *Pennisetum glaucum* (2.65) & *Triticum aestivum* (1.28) | *Azadirachta indica* (70.00), *Mangifera indica* (10.00), *Eucalyptus tereticornis* (10.00) |
| | Dahod | 22.86°N 74.25°E<br>Hilly light soils, sandy loam shallow & deep black | Gujarat plains & hills region<br>Hot semi-arid (Moist) | *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) |

**Table 4** continued

| State | District | Location and soil type | Region and climate | Dominant crops (productivity in Mg ha$^{-1}$) | Dominant trees (contribution in per cent) |
|---|---|---|---|---|---|
| | Junagarh | 21.52°N 70.47°E l<br>Medium to shallow black, Mix red & coastal alluvia | Arid western plains<br>Arid | *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<br>Alluvial sandy to sandy loam & sandy clay loam | Gujarat plains and hills region<br>Hot arid | *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) |
| | Banaskantha | 24.17°N 72.43°E<br>Alluvial sandy to sandy loam & sandy clay loam | Gujarat plains and hills region<br>More or less arid | *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 | Jhunhjunu | 28.13°N 75.40°E<br>Sandy loam & shallow depth red soil | Tropical desert<br>Arid & hot | *Pennisetum glaucum* (1.01), *Hordeum vulgare* (2.72), *Triticum aestivum* (3.26), *Cyamopsis tetragonoloba* (0.26), Pulses (0.31) & *Arachis hypogaea* (1.49) | *Prosopis cineraria* (64.78), *Tecomella undulata* (10.20), *Acacia tortilis* (3.88), *Ailanthus excelsa* (2.92) |
| | Sikar | 27.62°N 75.15°E<br>Sandy loam, shallow depth red soil | Tropical desert<br>Arid & hot | *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) |
| Maharashtra | Ratnagiri | 17.00°N 73.50°E<br>Laterite & alluvial | Western coast plains & ghat region<br>Hot humid-per humid | *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) |
| Tamil Nadu | Coimbatore | 11.01°N 76.97°E<br>Deep black | Eastern ghat<br>Hot semi-arid | *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) |
| | Kanchipuram | 12.82°N 79.71°E<br>Deep black, deep red &very deep black | East coast plains & hills region<br>Hot humid | *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 oliefera* (14.15) |

**Table 5** Primary survey results for the tree species observed in different districts in the selected states of India

| State | District | Observed average number of trees (trees/ha) | | | | Estimated age of existing trees (years) | | | Observed DBH of existing trees (cm) | | | Observed no. of tree species in the district |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Slow | Medium | Fast | Total | Slow | Medium | Fast | Slow | Medium | Fast | |
| Himachal Pradesh | Mandi | 21.84 | 18.91 | 10.16 | 50.91 | 36.52 | 14.01 | 8.03 | 26.66 | 22.14 | 18.96 | 15 |
| Punjab | Faridkot | 0.15 | 0.33 | 1.46 | 1.94 | 27.53 | 11.93 | 5.68 | 20.09 | 18.85 | 13.42 | 16 |
| | Nawasahar | 0.31 | 2.03 | 11.51 | 13.85 | 27.95 | 16.50 | 8.55 | 20.40 | 26.07 | 20.18 | 23 |
| | Ludhiana | 0.17 | 1.00 | 36.78 | 37.95 | 40.00 | 16.00. | 3.00 | 29.20 | 25.28 | 7.50 | 17 |
| Haryana | Hisar | 0.04 | 0.85 | 1.27 | 2.17 | 54.81 | 18.20 | 9.98 | 40.01 | 28.75 | 23.57 | 17 |
| | Kurukshetra | 0.23 | 0.57 | 5.78 | 6.59 | 58.05 | 17.69 | 9.06 | 42.37 | 27.95 | 21.48 | 21 |
| Uttar Pradesh | Bulandshar | 1.31 | 3.09 | 2.39 | 7.00 | 31.36 | 15.47 | 6.56 | 22.88 | 24.44 | 15.48 | 21 |
| | Gorakhpur | 0.77 | 13.22 | 1.77 | 15.78 | 44.24 | 22.24 | 8.19 | 32.29 | 35.14 | 19.32 | 16 |
| | Mirzapur | 0.46 | 8.40 | 1.29 | 10.00 | 51.01 | 20.59 | 9.26 | 37.24 | 32.53 | 21.96 | 16 |
| | Sultanpur | 0.90 | 2.88 | 2.36 | 6.14 | 40.00 | 16.00 | 8.00 | 29.20 | 25.28 | 18.88 | 20 |
| | Faizabad | 3.69 | 10.21 | 6.03 | 19.94 | 46.88 | 18.91 | 9.13 | 34.22 | 29.88 | 21.64 | 16 |
| Bihar | Darbhanga | 0.18 | 1.98 | 0.29 | 2.50 | 47.32 | 18.63 | 7.45 | 34.54 | 29.44 | 17.65 | 13 |
| | Purnia | 0.48 | 2.86 | 0.63 | 4.00 | 57.28 | 19.06 | 8.23 | 41.82 | 30.12 | 19.51 | 15 |
| | Nawada | 0.92 | 27.5 | 0.79 | 30.0 | 47.93 | 15.55 | 7.00 | 34.98 | 24.57 | 16.59 | 14 |
| West Bengal | Uttar Dinajpur | 0.24 | 4.04 | 1.93 | 6.20 | 50.00 | 13.00 | 9.00 | 36.50 | 20.54 | 21.24 | 32 |
| | Bardhman | 0.39 | 2.91 | 1.39 | 5.00 | 54.01 | 14.44 | 8.37 | 39.42 | 22.84 | 19.85 | 21 |
| Gujarat | Anand | 0.58 | 2.86 | 1.41 | 4.85 | 51.24 | 19.86 | 8.90 | 37.40 | 31.38 | 21.10 | 18 |
| | Dahod | 0.34 | 1.57 | 5.19 | 7.11 | 50.76 | 17.04 | 7.87 | 37.05 | 26.92 | 18.65 | 19 |
| | Junagrah | 0.32 | 1.66 | 0.08 | 2.07 | 53.76 | 15.90 | 7.96 | 39.24 | 25.13 | 18.88 | 25 |
| | Patan | 0.86 | 0.90 | 0.03 | 1.81 | 62.51 | 15.32 | 8.81 | 45.63 | 24.21 | 20.89 | 21 |
| | Banaskhanta | 0.21 | 3.90 | 0.19 | 4.32 | 40.74 | 20.46 | 9.71 | 29.74 | 32.33 | 23.03 | 26 |
| Rajasthan | Jhunjhnu | 6.03 | 0.76 | 0.16 | 6.95 | 38.14 | 10.62 | 7.13 | 27.84 | 16.79 | 16.91 | 19 |
| | Sikar | 9.21 | 2.58 | 0.62 | 12.42 | 39.40 | 12.44 | 9.02 | 28.76 | 19.66 | 21.38 | 17 |
| Maharashtra | Ratnagiri | 10.18 | 116.66 | 78.03 | 204.0 | 31.32 | 16.50 | 8.14 | 22.86 | 26.07 | 19.30 | 33 |
| Tamil Nadu | Kanchipuram | 0.65 | 5.08 | 3.53 | 9.26 | 48.24 | 14.95 | 6.99 | 35.21 | 23.63 | 16.57 | 10 |
| | Coimbatore | 4.54 | 33.72 | 3.96 | 42.23 | 41.13 | 15.33 | 6.60 | 30.02 | 24.22 | 15.64 | 32 |

and Rajasthan, average CSP ranged from 0.20 to 0.25 Mg C $ha^{-1}yr^{-1}$. Indeed, these estimates are based on the data from 26 districts in ten states. The existing number of districts in these 10 surveyed states of the country ranges from 12 to 75. However due to the constraints of manpower, time, money and resources, the number of sampled districts per state ranged from 1 to 5 in this study. Undeniably with all these known limitations, these are the first hand reported estimates of CSP under existing AFS at state level in India.

Comparing the district level values, the CSP of existing AFS in the surveyed districts ranged from 0.05 to 1.03 Mg C $ha^{-1}$ $yr^{-1}$ with the mean value of 0.21 Mg C $ha^{-1}yr^{-1}$. Based on this study, estimated value of trees $ha^{-1}$ was 19.44 and average CSP of existing AFS at country level was 0.21 Mg C $ha^{-1}yr^{-1}$. Expressing in terms of carbon dioxide equivalent, AFS in India has the potential to mitigate 0.77 Mg $CO_2$ equivalent $ha^{-1}yr^{-1}$. Smith et al.(2008) used the latest datasets and techniques to make the first estimates of agricultural GHG mitigation potential for 2030 that include all GHGs with breakdowns for all global regions and all gases. They divided the opportunities for mitigating GHGs in agriculture into three broad categories based on the underlying mechanism viz reducing emissions, enhancing removals and avoiding emissions.

**Table 6** Biomass accumulated in the tree/crop components and carbon sequestered under existing AFS in various districts of selected states of India (simulated using CO2FIX model)

| Parameters | | | Observed number of existing trees per hectare in agroforestry systems at district level are given in parenthesis | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Himachal Pradesh | Punjab | | | Haryana | | Uttar Pradesh | | |
| | | | Mandi (50.91) | Faridkot (1.94) | Ludhiana (37.95) | Nawansahar (13.85) | Hisar (2.17) | Kurukshetra (6.59) | Sultanpur (6.14) | Bulandsahar (7.01) | Gorakhpur (15.78) |
| Tree biomass (above and below ground) Mg DM ha$^{-1}$ | Baseline | Biomass | 10.69 | 0.58 | 2.88 | 6.70 | 0.78 | 0.97 | 2.56 | 2.71 | 18.20 |
| | Simulated | | 24.86 | 0.96 | 4.67 | 6.71 | 2.40 | 3.00 | 8.24 | 8.65 | 31.66 |
| Total biomass (tree + crop) Mg DM ha$^{-1}$ | Baseline | | 26.77 | 12.18 | 25.97 | 23.91 | 17.54 | 7.96 | 11.14 | 6.95 | 19.66 |
| | Simulated | | 41.39 | 12.91 | 28.41 | 24.94 | 19.63 | 10.18 | 17.05 | 13.20 | 34.5 |
| Soil carbon (Mg C ha$^{-1}$) | Baseline | Carbon | 22.28 | 9.02 | 9.12 | 6.95 | 10.31 | 9.1 | 8.13 | 10.65 | 9.89 |
| | Simulated | | 24.98 | 10.32 | 24.51 | 11.31 | 12.89 | 9.75 | 8.63 | 11.26 | 11.01 |
| Biomass carbon (Mg C ha$^{-1}$) | Baseline | | 12.05 | 5.27 | 11.21 | 10.30 | 7.58 | 3.48 | 4.92 | 3.11 | 9.30 |
| | Simulated | | 19.04 | 5.61 | 12.45 | 10.90 | 8.57 | 4.53 | 7.75 | 6.11 | 16.41 |
| Total carbon (biomass + soil) (Mg C ha$^{-1}$) | Baseline | | 34.33 | 14.29 | 20.43 | 17.25 | 17.89 | 12.49 | 13.05 | 13.76 | 19.19 |
| | Simulated | | 44.02 | 15.93 | 36.96 | 22.21 | 21.46 | 14.28 | 16.38 | 17.37 | 27.42 |
| Net carbon sequestered in AFS over the simulated period of 30 years (Mg C ha$^{-1}$) | | Carbon sequestered | 9.69 | 1.64 | 16.53 | 4.96 | 3.57 | 1.80 | 3.33 | 3.61 | 8.23 |
| Estimated annual carbon sequestration potential of AFS in different districts of surveyed states (Mg C ha$^{-1}$ yr$^{-1}$) | | | 0.32 | 0.05 | 0.55 | 0.16 | 0.12 | 0.06 | 0.11 | 0.12 | 0.32 |

**Table 6** continued

| Parameters | | | Uttar Pradesh | | Bihar | | | West Bengal | | Gujarat |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mirzapur (10.00) | Faizabad (19.94) | Nawada (30.00) | Darbhanga (2.50) | Purnia (4.00) | Bardhman (5.00) | Dinajpur (6.20) | Anand (4.85) |
| Tree biomass (above and below ground) Mg DM $ha^{-1}$ | Baseline | Biomass | 8.68 | 15.50 | 6.97 | 1.95 | 3.40 | 2.76 | 2.45 | 3.02 |
| | Simulated | | 20.45 | 31.45 | 21.77 | 4.85 | 6.72 | 6.43 | 8.22 | 8.00 |
| Total biomass (tree + crop) Mg DM $ha^{-1}$ | Baseline | | 12.38 | 44.44 | 11.02 | 4.96 | 8.75 | 7.70 | 12.10 | 6.85 |
| | Simulated | | 24.28 | 61.20 | 25.93 | 7.95 | 12.22 | 11.58 | 17.59 | 11.94 |
| Soil carbon (Mg C $ha^{-1}$) | Baseline | Carbon | 13.76 | 4.60 | 16.67 | 14.73 | 17.38 | 11.76 | 8.16 | 11.75 |
| | Simulated | | 14.45 | 11.17 | 17.11 | 15.22 | 18.65 | 13.47 | 9.28 | 12.03 |
| Biomass carbon (Mg C $ha^{-1}$) | Baseline | | 4.17 | 19.90 | 5.09 | 2.24 | 3.94 | 3.45 | 5.33 | 3.10 |
| | Simulated | | 9.82 | 27.87 | 12.24 | 3.67 | 5.58 | 5.30 | 8.00 | 5.52 |
| Total carbon (biomass + soil) (Mg C $ha^{-1}$) | Baseline | | 5.25 | 24.50 | 21.53 | 16.97 | 21.32 | 15.21 | 13.49 | 14.85 |
| | Simulated | | 11.47 | 39.04 | 29.35 | 18.89 | 24.23 | 18.77 | 17.28 | 17.55 |
| Net carbon sequestered in AFS over the simulated period of 30 years (Mg C $ha^{-1}$) | | Carbon sequestered | 6.22 | 14.54 | 7.82 | 1.92 | 2.91 | 3.56 | 3.79 | 2.70 |
| Estimated annual carbon sequestration potential of AFS in different districts of surveyed states (Mg C $ha^{-1}$ $yr^{-1}$) | | | 0.21 | 0.48 | 0.26 | 0.06 | 0.09 | 0.11 | 0.13 | 0.09 |

Observed number of existing trees per hectare in agroforestry systems at district level are given in parenthesis

| Parameters | | | Gujarat | | | | Rajasthan | | Maharashtra | Tamil Nadu | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Dahod (7.11) | Junagrah (2.07) | Patan (1.81) | Banaskantham (4.32) | Jhunjhunu (6.95) | Sikar (12.42) | Ratnagiri (204.00) | Coimbatore (42.23) | Kanchipuram (9.26) |
| Tree biomass (above and below ground) Mg DM $ha^{-1}$ | Baseline | Biomass | 3.43 | 1.30 | 1.58 | 3.74 | 4.33 | 7.62 | 48.5 | 9.43 | 4.93 |
| | Simulated | | 4.92 | 4.36 | 2.16 | 9.30 | 10.04 | 18.74 | 109.75 | 30.61 | 12.36 |
| Total biomass (tree + crop) Mg DM $ha^{-1}$ | Baseline | | 5.63 | 8.50 | 6.84 | 19.24 | 17.13 | 19.19 | 58.96 | 24.28 | 23.77 |
| | Simulated | | 7.18 | 11.77 | 7.57 | 25.24 | 23.2 | 30.64 | 120.5 | 45.88 | 31.73 |
| Soil carbon (Mg C $ha^{-1}$) | Baseline | Carbon | 24.13 | 23.38 | 10.02 | 11.11 | 4.51 | 4.28 | 20.60 | 10.65 | 8.58 |
| | Simulated | | 29.66 | 23.49 | 11.17 | 12.64 | 8.48 | 7.34 | 21.63 | 11.41 | 10.43 |
| Biomass carbon (Mg C $ha^{-1}$) | Baseline | | 2.60 | 3.73 | 3.02 | 8.47 | 7.58 | 8.64 | 27.78 | 10.92 | 10.47 |
| | Simulated | | 3.33 | 5.28 | 3.37 | 11.31 | 10.48 | 14.11 | 57.3 | 21.25 | 14.27 |

**Table 6** continued

| Parameters | | Observed number of existing trees per hectare in agroforestry systems at district level are given in parenthesis | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Gujarat | | | | Rajasthan | | Maharashtra | Tamil Nadu | |
| | | Dahod (7.11) | Junagrah (2.07) | Patan (1.81) | Banaskantham (4.32) | Jhunjhunu (6.95) | Sikar (12.42) | Ratnagiri (204.00) | Coimbatore (42.23) | Kanchipuram (9.26) |
| Total carbon (biomass + soil) (Mg C $ha^{-1}$) | Baseline | 26.73 | 27.11 | 13.04 | 19.58 | 12.09 | 12.92 | 47.84 | 21.57 | 19.05 |
| | Simulated | 32.99 | 28.77 | 14.54 | 23.95 | 18.96 | 21.45 | 78.93 | 32.66 | 24.70 |
| Net carbon sequestered in AFS over the simulated period of 30 years (Mg C $ha^{-1}$) | Carbon sequestered | 6.26 | 1.61 | 1.50 | 4.37 | 6.87 | 8.53 | 31.09 | 11.09 | 5.65 |
| Estimated annual carbon sequestration potential of AFS in different districts of surveyed states (Mg C $ha^{-1}$ $yr^{-1}$) | | 0.21 | 0.06 | 0.05 | 0.14 | 0.22 | 0.28 | 1.03 | 0.36 | 0.18 |

Agroforestry as a land use pattern has been included in the second category of enhancing removals. It has been reported that the mean annual mitigation potential (tons $CO_2$-eq. $ha^{-1}$ $yr^{-1}$) through agroforestry practices ranges from 0.17 to 0.72 in different climatic regions. The highest values has been reported up 1.89 tons $CO_2$-eq. $ha^{-1}$ $yr^{-1}$. Accordingly, our estimated figure of GHG mitigation potential of 0.77 $CO_2$-eq. $ha^{-1}$ $yr^{-1}$ at the country level seems reasonable.

Since for computing the number of trees per hectare in each district, the total number of trees in the district were divided by the total crop sown area of the district, therefore for scaling up this district level GHG mitigation estimate to the country level, we have multiplied it by the net sown area of the country (142 million hectare). Accordingly, AFS in India are estimated to mitigate 109.34 million tons of $CO_2$ equivalent annually. Considering the reported GHG emissions from agriculture sector as 334.41 million tons of $CO_2$ equivalent in India (Indian Network for Climate Change Assessment, Report-2010, Govt. of India), the existing agroforestry systems on farmers' fields are estimated to offset one-third (33 %) of the total GHG emissions from agriculture sector annually at the country level.

## Soil carbon sequestration

The estimated rate of soil carbon sequestration (SCS) under the existing AFS at district level ranged from 0.003 to 0.51 Mg C $ha^{-1}$ $yr^{-1}$(during the 30 year simulation period) for different districts in which the tree density ranged from 1.94 to 204 trees $ha^{-1}$. These results are in line with the report of Post and Kwon (2000), who reported that the average rate of SCS under tree based systems ranged between 0–3 Mg C $ha^{-1}$ $yr^{-1}$ (with 0.3 Mg C $ha^{-1}$ $yr^{-1}$ as the average value). Swamy and Puri (2005) have also reported that the rate of SCS was 0.42 Mg C $ha^{-1}$ $yr^{-1}$ in *Gmelina arborea* (576 trees $ha^{-1}$) based AFS in Raipur (Chhattisgarh) at 5 years of age. Although the rate of SCS appears to be affected by tree density to some extent, but there are a large number of other factors influencing SCS under AFS viz. precipitation, temperature, evapo-transpiration, decomposition rates, litter fall, decay rates of tertiary tree roots, crop residue, chemical properties of the litter etc.

Carbon sequestration potential

The estimated rates of CSP for the existing AFS's under the various districts in this study ranged from 0.05 to 1.03 Mg C $ha^{-1}yr^{-1}$ (with average value of 0.21 Mg C $ha^{-1}yr^{-1}$). From the perspective of CSP, AFS (crop with trees) lies in between pure cropping system (only crop without trees) and pure tree plantations on crop lands (only trees without crop). Accordingly, to examine the accuracy of simulated estimates of CSP values, comparison was done with CSP values of pure cropping and pure tree plantation systems in addition to planted AFS. The published value of CSP for AFS (crop/pasture/forage/grasses with trees) usually involved tree density ranging from 300 to 1500 trees $ha^{-1}$ or even more in some cases. Whereas, the tree density observed in this study during the primary survey of the 26 districts across 10 states of the country usually ranged from 2 to 204 trees $ha^{-1}$ (with average value of 19.44 trees $ha^{-1}$).

Pathak et al. (2011) have analyzed the CSP of 26 long-term experiments on different cropping systems in India in different agro climatic zones and reported that C sequestration rate varied from 0.02 to 1.2 Mg C $ha^{-1}$ $yr^{-1}$ in general (whereas for the 4 long term pure cropping experiments of almost 30 years duration, CSP ranged from 0.02 to 0.10 Mg C $ha^{-1}$ $yr^{-1}$ with an average value of 0.062 Mg C $ha^{-1}$ $yr^{-1}$).

The CSP of various AFS in different parts of the country have been compiled and presented in Table 7. The reported CSP varied from 0.49 to 12.15 Mg C $ha^{-1}$ $yr^{-1}$ for the most common tree density in the range of 400–800 trees per hectare (usually preferred by the farmers in AFS). For the complete range of all the reported studies considered together (irrespective of tree densities), the CSP varied from 0.39 to 15.91 Mg C $ha^{-1}$ $yr^{-1}$ (age varying from 2.5 to 30 years). Nair et al. (2010) have also reported that the estimate of carbon stored in AFS's in different parts of the world, ranged from 0.29 to 15.21 Mg C $ha^{-1}$ $yr^{-1}$ in above ground, and 30–300 Mg C $ha^{-1}$ up to 1 m depth in the soil (the age varied from 4 to 35 years).

Although, we could compare the CSP values obtained in this study with those reported for pure cropping systems, pure tree plantations and some systematically planned farm level AFS. However, the basic difference between this study and the other published articles on CSP of AFS was the type of situation, process of recording data and sampling design. To elaborate it further, first village level data were collected (a minimum of 10 surveyed villages from each district for primary data) and then averaged it out to arrive at district level figures. Whereas in the reported CSP of AFS from other studies, the data pertains to farm level AFS within a specified experimental area usually with single planted tree species along with one/two crops grown for a limited period of time (generally ranging from 5 to 12 years). In this study, a number of tree species were observed on per hectare basis at district level with varied nature of growth, varying ages and different crops. In a recently published review article on CSP of AFS in India, Murthy et al. (2013) have also reported some primary survey data recorded on the baseline tree biomass stocks of existing trees at village level (for 8 villages from Tamilnadu and Karnataka states of India). This village level data was recorded using almost the same approach as adopted in our study and thus the data sets are comparable at the basic level. However, Murthy et al. (2013) have reported only tree biomass stocks at base line, but not the CSP, accordingly comparison was made for base line tree biomass stocks only. They reported that the base line tree biomass stocks in the existing trees at village level varied from 1.33 to 13.17 Mg DM $ha^{-1}$ with the average value of 6.46 Mg DM $ha^{-1}$. In the present study, the base line tree biomass stocks observed at district level (as average of 10 villages) varied from 0.58 to 48.50 Mg DM $ha^{-1}$ with the average value of 6.75 Mg DM $ha^{-1}$. Interestingly, the average value of base line tree biomass stocks in the existing trees at village level obtained in this study (in fact representing the average value of more than 260 diverse villages selected randomly from 10 different states of the country encompassing northern and central parts of India) almost coincides with the value as reported by Murthy et al. (2013) (obtained as average of 8 villages from 2 southern states). Although the observed range in this study was a bit larger (0.58–48.50) as compared to the range (1.33–13.17) reported by Murthy et al. (2013), this may be attributed to very large number of observations (more than 260 village level data sets) in our data set representing very diverse biophysical and climatic conditions. Thus the model simulated estimates of CSP for existing AFS at district level obtained in this study are in line with those reported by Murthy et al. (2013) through ground field measurements, confirming the accuracy of these simulated CSP estimates.

**Table 7** Reported carbon sequestration potential (Mg C $ha^{-1}yr^{-1}$) of various agroforestry systems in India

| Location | Agroforestry system | Tree species | No. of tree per hectare | Age (year) | CSP (Mg C $ha^{-1}yr^{-1}$) | References |
|---|---|---|---|---|---|---|
| Uttarakhand | Agri-silviculture | *D. hamiltonii* | 1000 | 7 | 15.91 | Kaushal et al. 2014 |
| Himachal Pradesh | Agri-silviculture | Fruit trees | 69 | – | 12.15 | Goswami et al. 2014 |
| Khammam, Andhra Pradesh | Agri-silviculture | *L. leucocephala* | 4444 | 4 | 14.42 | Prasad et al. 2012 |
| | | | 10000 | 4 | 15.51 | |
| Uttarakhand | Agri-silviculture | *P. deltoides* | 500 | 8 | 12.02 | Singh and Lodhiyal 2009 |
| SBS Nagar, Punjab | Agri-silviculture | *P. deltoides* | 740 | 7 | 9.4 | Chauhan et al. 2010a, 2010b; Chauhan et al. 2015 |
| Ladhowal, Ludhiana, Punjab | Agri-silviculture | *P. deltoides* | 493 | 6 | 6.22 | Chauhan et al. 2011 |
| Kurukkhetra, Haryana | Silvipasture | *A. nilotica* | 1250 | 7 | 2.81 | Kaur et al. 2002 |
| | | *D. sissoo* | 1250 | 7 | 5.37 | |
| | | *P. juliflora* | 1250 | 7 | 6.5 | |
| Tripura | Silviculture | *T. grandis* | 444 | 20 | 3.32 | Negi et al. 1990 |
| | | *G. arborea* | 452 | 20 | 3.95 | |
| Tarai central division Uttarakhand | Silviculture | *T. grandis* | 570 | 10 | 3.74 | Negi et al. 1995 |
| | | | 500 | 20 | 2.25 | |
| | | | 494 | 30 | 2.87 | |
| Jhansi, Uttar Pradesh | Agrisilviculture | *A. procera* | 312 | 7 | 3.7 | Ramnewaj and Dhyani 2008 |
| Jhansi, Uttar Pradesh | Agrisilviculture | *A. pendula* | 1666 | 5.3 | 0.43 | Rai et al. 2002 |
| Jhansi, Uttar Pradesh | Silviculture | *procera* | 312 | 10 | 1.79 | Rai et al. 2000 |
| | | *A. amara* | 312 | 10 | 1.00 | |
| | | *A. pendula* | 312 | 10 | 0.95 | |
| | | *D. sissoo* | 312 | 10 | 2.55 | |
| | | *D. cinerea* | 312 | 10 | 1.05 | |
| | | *E. officinalis* | 312 | 10 | 1.55 | |
| | | *H. binata* | 312 | 10 | 0.58 | |
| | | *M. azaderach* | 312 | 10 | 0.49 | |
| Hydarabad, Andhra Pradesh | Silviculture | *L. leucocephala* | 2500 | 9 | 10.32 | Rao et al. 2000 |
| | | *E. camaldulensis* | 2500 | 9 | 8.01 | |
| | | *D. sissoo* | 2500 | 9 | 11.47 | |
| | | *A. lebbeck* | 625 | 9 | 0.62 | |
| | | *A. albida* | 1111 | 9 | 0.82 | |
| | | *A. tortilis* | 1111 | 9 | 0.39 | |
| | | *A. auriculiformis* | 2500 | 9 | 8.64 | |

**Table 7** continued

| Location | Agroforestry system | Tree species | No. of tree per hectare | Age (year) | CSP (Mg C $ha^{-1}yr^{-1}$) | References |
|---|---|---|---|---|---|---|
| Raipur, Chhattisgarh | Agrisilviculture | *G. arborea* | 592 | 5 | 3.23 | Swamy and Puri 2005 |
| Coimbatore, Tamilnadu | Agrisilviculture | *C. equisetifolia* | 833 | 4 | 1.57 | Viswanath et al. 2004 |
| Kerala | Home garden | Mixed tree spp. | 667 | 71 | 1.60 | Saha et al. 2009 |

Moreover, the validation of CO2FIX model simulated tree biomass with an independent data set has already been reported by Ajit et al. (2013) in a previous article of this series on CSP simulation under AFS for Indo-Gangetic-Plains of India. This independent data set referred to actual harvested tree biomass data for poplar based agroforestry system (Ajit et al. (2011) for data set and other details) planted at Samastipur, Bihar (India) along an age series of 9 years with 1 year interval. The sensitivity analysis of the model results has also been reported by Ajit et al. (2013).

## GHG mitigation potential of existing AFS at country level

On an average, AFS in India has the potential to mitigate 0.77 Mg $CO_2$ equivalent $ha^{-1}yr^{-1}$. Based on this study, the existing agroforestry systems on farmers' fields are estimated to mitigate one-third (33 %) of the total GHG emissions (in terms of $CO_2$ equivalent) from agriculture sector annually at the country level. Recently, Ogle et al. (2014) have reported 'agroforestry-systems' as agriculture management practices that mitigates GHG emissions to the tune of 3.5–10.8 Mg $CO_2$ equivalent $ha^{-1}yr^{-1}$ (in case of intercropped *Gliricidia sepium* with maize and multistrata coffee). The comparatively higher GHG mitigation values reported in this multistrata coffee AFS are due to much larger number of planted trees on per hectare in that experiment as compared to present study. However, the potential of agroforestry systems in reducing atmospheric GHG emissions varies depending upon the tree species planted, age of trees, tree per hectare, planting geometry, trees composition, crop productivity, geographic location, soil health, local climatic factors and management regimes etc. The potential can be enhanced substantially once enabling environment is created for promotion of agroforestry in the country as envisaged in the NAP 2014. Since an approved Policy is a mirror reflection of government's priority wishes, and expects all concerned to support its recommendations, therefore, efforts are already on to promote agroforestry in the country. In order to ease out regulatory regime for promotion of agroforestry, guidelines have been issued for felling and transit regulations for tree species grown on non-forest/private lands recently (www.moef.nic.in). This is the first step to denotify at least 20 tree species commonly used in agroforestry from felling and transit regulation which was a major hurdle for the growers. Similar efforts are going on to address the recommendations of the NAP to ease the farmers for harvesting and transit permits.

## Conclusions

An average estimated value of 0.21 Mg $ha^{-1}yr^{-1}$ carbon sequestration potential of the agroforestry systems (AFS) at country level was recorded equivalently to 0.77 Mg $ha^{-1}yr^{-1}$ $CO_2$ mitigation. Considering the reported GHG emissions from agriculture sector as 334.41 million tons of $CO_2$ equivalent in India (Indian-Network-for-Climate-Change-Assessment-Report-2010, Govt. of India), the AFS on farmers' fields are estimated to offset one-third (33 %) of total GHG emissions from agriculture sector annually and more than 6 % of total GHG emissions at the country level. No estimate of GHG mitigation potential of existing trees on croplands (excluding the documented forest cover) through agroforestry systems at the country level in India was yet available.

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