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Reduction of global warming potential vis-à-vis greenhouse gases through traditional agroforestry systems in Rajasthan, India

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Abstract

Tree-based systems in arid region of India are an integral part of livelihood and environment security. Traditionally, the maintenance of scattered trees on farm to reap several tangible and intangible benefits is a way of life. Presently, these systems are often known as low-hanging fruit and become a key weapon to fight climate change evil by offsetting greenhouse gas (GHG) emission through carbon sequestration. Therefore, to quantify the offsetting potential of GHG emission and area occupied by these tree-based systems in Rajasthan was undertaken. The study was carried out into two major aspects: estimation of agroforestry area using satellite remote sensing data, and to estimate the carbon sequestration potential of existing agroforestry by using dynamic CO2FIXv3.1 model for a simulation period of 30-years in five districts (20% sampling), namely, Bikaner, Dausa, Jhunjhunu, Pali and Sikar from Rajasthan, India. The estimated area under agroforestry in Rajasthan was 1.49 million ha. The findings revealed that the major tree species existing on farmer's field were *Prosopis cineraria, Tecomella undulata, Capparis decidua, Acacia tortilis, Prosopis juliflora, Azadirachta indica* and *Ziziphus mauritiana* with an observed number of trees in selected districts varied from 1.40 to 14.90 ha^{-1}(with average tree density of 9.71 ha^{-1}). The total biomass (tree + Crop) varied from 2.22 to 19.19 Mg ha^{-1}, whereas the total biomass carbon ranged from 1.00 to 8.64 Mg C ha^{-1}. The soil organic carbon ranged from 4.51 to 16.50 Mg C ha^{-1}. The average estimated carbon sequestration and mitigation potential of the agroforestry were 0.26 Mg C ha^{-1} $year^{-1}$and 0.95 Mg CO_2 eq ha^{-1} $year^{-1}$ on farmers' field of Rajasthan. At the state level, the reduction of GHG emission potential of agroforestry was found to be 1.42 million tonnes annually, which helps to cut carbon footprint and achieve targets of Paris agreement.

Keywords Arid agroforestry · Transect analysis · Carbon sequestration · CO2FIX model · Climate change · Agroforestry area

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Abstract

Tree-based systems in arid region of India are an integral part of livelihood and environment security. Traditionally, the maintenance of scattered trees on farm to reap several tangible and intangible benefits is a way of life. Presently, these systems are often known as low hanging fruit and becoming a key weapon to fight climate change evil by offsetting greenhouse gas emission through carbon sequestration.Therefore, to quantify the offsetting potential of GHG emission and area occupied by these tree-based systems in Rajsthanwas undertaken. The study was carried out into two major aspects: estimation of agroforestry area using satellite remote sensing data, and to estimate the carbon sequestration potential (CSP) of existing agroforestry byusing dynamic CO2FIXv3.1 model for a simulation period of 30 years in five districts (20% sampling) *viz.* Bikaner, Dausa, Jhunjunu, Pali and Sikarfrom Rajasthan, India. The estimated area under agroforestryin Rajasthan was 1.49 million ha. The findings revealed that the major tree species existing on farmer's field were *Prosopis cineraria, Tecomellaundulata, Capparis decidua, Acacia tortilis, Prosopisjuliflora, Azadirachtaindica*and *Ziziphusmauritiana*with an observed number of trees in selecteddistricts varied from 1.40 to 14.90 ha^{-1}(with average tree density of 9.71 ha^{-1}). The total biomass (tree+Crop) varied from 2.22 to 19.19 Mg ha^{-1}, whereas, the total biomass carbon ranged from 1.00 to 8.64 Mg C ha^{-1}.The soil organic carbon ranged from 4.51 to 16.50 Mg C ha^{-1}. The average estimated carbon sequestration and mitigation potential of the agroforestry were 0.26 Mg C $ha^{-1}yr^{-1}$and 0.95 Mg CO_2eq $ha^{-1}yr^{-1}$ on farmers' field of Rajasthan. At the state level, the reduction of GHG emission potential of agroforestry found to be 1.42 million tonnes annually, which helps to cuts carbon footprint of the state as well as national level.

Keywords: Arid agroforestry, Transect analysis, Carbon sequestration, CO2FIX model, Climate change, agroforestry area

Introduction

Arid agro-ecosystem is categorized by scarce natural resources and an inhospitable climate spread over 18.8 % areas throughout the world. India has about 31.8 million ha (12%) hot arid areasspread in parts of Rajasthan (61%), Gujarat (20%), Andhra Pradesh and Karnataka (10%), and Punjab and Haryana (9%) and cold arid zone (7%). The largest area is occupied by Rajasthan states (20 million ha) and which is popularly known as "IndianThar desert" (Behera and France, 2016). The arid regions is climatically and edaphically most fragile and unpredictable agro-ecosystem, which characterized as an erratic rainfall ranges from 100 to400 mm, experiences extremes of temperature fluctuations (-2 to 48°C), high strong wind velocity (30–40 km/h) escalates higher evaporations (1500-2000 mm/year) and sandyrocky gravely to saline soils having poor fertility and low water retention (<0.15), extremes of aridity (-70 to -90) and low biomass producing conditions (Bhati and Faroda, 2001, Kar, 2014;Rathode*et al.* 2019). With such distressed conditions also, thelocal habitants of IndianThar Desert (known as world's most populated arid zone, with a density of 101 persons/km^2 against the world average for arid zones of 6–8 persons/km^2) evolved a sustainable farming system as a drought protective mechanism based on centuries-old experiences, descending from one generation to next generation. Traditionally, thisregion is endowed with many indigenous crops, trees, shrubs and grasseswhich have played a pivotal role in ecological equilibrium to act asa life-support system of local's livelihoodthrough multiple products and services (Bhati et al. 2017). Among such systems, trees are occupied an essential part in resource scare arid zone in India as well as world.

Throughout the arid zone of the world, many well-proven examples highlight the role of such tree-based systems in the uplifting livelihood of a grief-stricken rural population. Such systems are evolved over a period of time and testified under difficult situation is widely known as indigenous tree-based systems or traditional agroforestry (Vishwanath et al. 2018). These traditional systems include *Faidherbiaalbida* with pearl millets in Africa (Mason et al. 2015), *Vitellariaparadoxa* and *Parkiabiglobosa* trees in semi-arid sub-Saharan Africa (Teklehaimanot, 2004)), *Acacia nilotica*in paddy fields in Central India (Vishwanath et al. 2000), *Azadirachtaindica* with sorghum in Deccan plateau, *Acacia leucopholea* with *Centurusciliaris* in Tamil Nadu and *Prosopis cineraria* with millets in Rajasthan (Shankarnarayan et al. 1987) were intricately oven with social and economic functions and offers several ecosystem services (Jose, 2009; Chavan et al. 2019, Reed et al. 2017;). On this line, agriculture in arid zone of Rajasthan is also gifted with many tree species for numerous needs of local population by providing directs benefits (fodder, fruits, fuelwood, fertilizer, food, and timber) to and indirect benefits (improving soil, microclimate moderation, and carbon sequestration). In Arid zone of

Rajasthan, traditional agroforestry systems are dominated by trees species like *Prosopis cineraria*, *Acacia nilotica*, *Tecomellaundulata, Azadirechtaindica, Zizyphusmauritiana,*and*Ailanthus excelsa*(Roy et al 2011;Keerthika et al. 2015, Tanwar et al. 2019). Among these species,*Prosopis cineraria*-based agroforestry system is a world-famous traditional system of the arid region that evolved over a period of time and providing sustainability to this region and known as 'lifeline of desert' (RadhaKrishan and Jinadal, 2015). It has been proven facts that yield of annual crops (mainly millets) are significantly increased by 10-15 % with or under tree canopy over pure cropping (Kaushik and Kumar 2003; Singh et al. 2007; 2013). In a similar way, other trees like *Tecommelaundulata*, Acacia *nilotica* and *Ailanthus excelsa* also offer life support benefits to the farmers during lean periods. Farmers believe that these tree-based systems in agriculture as a boon in the region particularly during a drought when rainfed crops fail and trees stand the only source of fodder, fruit, vegetable, fuelwood, timber and fiber for sustaining a rural livelihood. Moreover, arid agroforestry provides 62% of the fodder, fuelwood and timber requirement of the rural people (Singh 2011). Also, tree in arid agro-ecosystem acts like insurance against climate vagaries to buffer crop-yield losses, enhance resilience and diversify the system (Newaj et al. 2013; 2015a; Chavan et al. 2015; 2016). Under such circumstances, trees in traditional farming systems formed a better solution to tackle climatic vagaries and supported agriculture by providing a mutual synergistic effect on ecological as well as food security (Chavan et al. 2014; Keerthika et al. 2015).

Apart from this,agroforestry has been recognized as a component of climate-smart agriculture (Newaj et al., 2015) and is frequently mentioned for strong potential for climate change adaptation and mitigation (IPCC 2004, Nair et al. 2009, Ajit et al. 2017), which is extensively lightened under various international initiatives such as Kyoto Protocol of 2001 (Nair et al. 2009), REDD+ mechanism (Minanget al.2011), Sustainable Developmental Gaols (United Nation Assembly 2015) and Paris Agreement (UNFCCC 2015). The Paris Agreement of 21st session of Conference of Parties of UNFCCC (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement) adopted with the aim to maintain the global average temperature below 2 °C of pre-industrial levels and made a huge noise in the international arena. Where in this, India had promised to reduce its emissions intensity—greenhouse gas emissions (GHGs) per unit of GDP— by 33 to 35 percent below 2005 levels by the year 2030. To achieve this target, we would need to create a carbon sink of 2.5 to 3 billion tonnes of carbon dioxide-equivalent by the year 2030 by increasing its forest and tree cover (https://pib.gov.in/newsite/PrintRelease.aspx?relid=128403). But developing such additional sink through the increase in forest areais considered an exceptionally difficult and ambitious task, it possible only by immediate strong political and financial commitment along with policy and institutional reforms. Hence, over past two decades Government of Indiahas also initiated various policies and interventions like Green India Mission 2003, plantation drives through CAMPA (https://pib.gov.in/newsite/PrintRelease.aspx?relid=181889), National Agroforestry Policy 2014 & Submission on agroforestry and bamboo (https://nmsa.dac.gov.in), Green Highway Policy 2015 (https://morth.nic.in/green-highways), six missions of NAPCC (www.moef.nic.in/sites/default/files/Pg01-52_2.pdf) to transformed agroforestry radically to increase tree cover up to 33 % of total geographic area andreduce the impact of climate change.

On the other hand, agroforestry is becoming a well-proven solution to achieve the above-mentioned targets with the fastest pace and having a greater opportunity to increase the tree cover. Because, thecarbon sequestration potential of agroforestry in India ranges from 0.29 to 15.21 Mg C ha^{-1} yr^{-1}(Montanagiri and Nair 2004; Nair et al. 2010; Prasad et al. 2012;Rizvi et al. 2011;Newaj et al. 2016) shows the ability of systems either existing or planted.Even though, existing trees on farmers' field (density varies from 1 in arid zone to 1000 in-home garden) also consist of a crucial part in achieving Nationally Determined Contributions (NDCs) targets and require paradigm shifts to quantify their carbon sinks and area distribution under agroforestry throughout the country. However, proper quantification of carbon sink and area of existing agroforestry practices at state as well as the country level requires urgent attention.

Against this background still, we are lacking to provide basic information like the area under agroforestry, tree density in agroforestry and their contribution towards mitigating climate change. Howevere scattered trees on farmer's fields in India hasalso an enormous potential to reduce GHG emission through sequestrating carbon, which need to be proven. Moreover, most carbon sequestration studies in plantation and systematic agroforestry are limited up to ''One-Time-Harvest-Assessment'' of one or three carbon pools which are local importance but regarding the future prediction of carbon sequestered over a period of time though ''Simulation-Studies'' provides opportunity to quantify future potential based on growth, climate, and edaphic parameters. With this background, study on the reduction of global warming potential vis-à-vis greenhouse gases through traditional agroforestry in Rajasthanwas initiated at ICAR-Central AgroforestryResearch Institute (CAFRI), Jhansi (Uttar Pradesh),India under the National Innovationin ClimateResilient Agriculture (NICRA) Project under Indian Council of Agricultural Research, New Delhi, India. The basicobjective of this study was to simulate the CSP ofexisting agroforestry on farmers' fields at district and state levels; and estimation of area under agroforestry for Rajasthan using GIS and remote sensing. This paper also highlights the potential of existing agroforestrysystems on farmers' fields to mitigate the total annual GHG emissions at the state and country-level usingthe CO2FIX model.

Material and Methods

Field survey

A field survey of selected districts viz.,Bikaner, Dausa, Jhunjunu, Pali and Sikar districts of Rajasthan (Fig 1) 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 Field survey of study area 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.Detailed methodology has been published by Ram Newaj et al (2017) http://cafri.res.in/Technical_Bulletins/NICRA_Technical_Bulletin.pdf

Tree density (tree ha^{-1}): Number of trees were counted, species wise, in each village. Mean of sampled 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 (Ajitet al.2017).

Soil sampling

Soil organic carbon is very important to quantify carbon sequestrations potential of the systems. The soil samples were collected from agroforestry as well as pure agriculture with the help of soil augur. The soil sampling was done up to the depth of 90 cm as recommended. The standard methodology was used to estimate soil organic carbon (Walkley and Black 1934).

Assessment of C stock through the simulation model

The CO2FIX V 3.1 is a dynamic carbon accounting model (http://dataservices.efi.int/casfor/models.htm) consists of six modules *viz.*,biomass, soil, products, bioenergy, financial and carbon accounting module (Masera et al. 2003). It is an ecosystem-level simulation model that quantifies the C stocks and fluxes in the forest using the so-called full carbon accounting approach, i.e. calculating changes in carbon stocks in all carbon pools over time. In the present study, three modules three modules namely biomass, soil and carbon accounting modules were taken into consideration to estimate biomass, soil carbon and C sequestered in the agroforestry system.

The main input parameters relevant to CO2FIX model are the cohort wise values for the stem-CAI (current annual increment in m^3 ha^{-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 °C). Tree species being grown on farmland were classified in to three cohorts namely slow, medium and fast growing trees as per the growth rate and nature of the species. The CSP of agroforestry systems is simulated for 30 years. The detailed methodology has been described by Ajit et al. (2013); Ram Newaj et al. (2014) was followed to estimate biomass (Mg ha^{-1}), biomass carbon (Mg ha^{-1}), soil carbon (Mg ha^{-1}) and carbon sequestration potential (Mg C $ha^{-1}yr^{-1}$).

Agroforestry area mapping

Mapping of agroforestry area in selected districts was done by procuring Resourcesat-2/LISS III multispectral remote sensing data (spatial resolution 23.5 m) from National Remote Sensing Centre, Hyderabad for the period 2012–2013. Thesedate were analyzed for land uses and land covers using the supervised method of maximum likelihoodwith the help of using ERDAS Imagine 11.0 software. From this land use/land cover, agricultural area (cropland + fallowland) has been masked because agroforestry exists on agricultural land only.Then sub-pixel classifier method was applied in this agricultural area, which gave output in the form of classes as per the tree cover (20-30, 30-40,……, 90-100 per cent) within a pixel. The total area of such pixels yielded an estimate of area under agroforestry in the district (Figure 2). Classification accuracy was compared with the help of ground checkpoints collected on agroforestry from farmers' fields. Thematic maps for land use land cover and agroforestry (Sub-pixel basis) were prepared usingArcGIS 10.0 software.In case of Bikaner districts, method of maximum likelihood was used due to unavailability of sub-pixel data. The detailed methodologoly of Rizvi et al (2016) were followed for the estimation of agroforestry area in Rajasthan.

Global Warming Potential (GWP)

Global Warming Potential was developed to allow comparison of the global warming impacts of different gases. It is a measure of how much energy emission of one tonne of gas will absorb over a given period of time, relative to the emission of one tonne of carbon dioxide. Carbon dioxide equivalents (CO_2-e) provide universal standard of measurement of GWP ofgreenhouse gases. The GWP of a given gas describes its effect on climate change relative to a similar amount of CO_2. As the base unit, CO_2 is 1 (Johnson and Coburn, 2010). A quantity of GHG can be expressed as CO_2eq by multiplying the amount of the GHG by its GWP. The global warming potential values are compared with India's total greenhouse gas emission (CO_2-equivalent) to know the potential of agroforestry systems of Rajasthan to mitigate greenhouse gasses emission.Carbon sequestered for selected districts has been multiplied by a factor of 44/12 (or 3.67) to get the *CO_2-eq* per ha (IPCC 2003). These values were then multiplied by area under agroforestry for estimation of *CO_2-eq* at district level and extrapolated for overall state.

$$GWP\ (CO2\text{-}eq) = Carbon\ sequestration\ (Mg\ C\ ha^{-1})*3.67$$

Estimated rate of carbon sequestration potential (Mg C $ha^{-1}yr^{-1}$) for selected districts through the CO2FIX model has been multiplied by a factor of 44/12 (or 3.67) to quantify CO_2 eq. absorption/mitigation per ha (IPCC 2003). Also, their agroforestry area of respective districts was multiplied with CO_2eq.for each district. For state-level scenarios, the district-wise agroforestry area was extrapolated to get agroforestry area of Rajasthan and total CO_2 eq. absorption was presented for meaningful information.

Results and Discussion

Agroforestry area in Rajasthan

Rajasthan is the largest state located in the north-western part of the country, constituting 10.41% of the total geographic area. The state has a varied climate from semi-arid to arid. Such a difficult situation made agriculture very complex and dependent on rainfall. The scattered presence of trees in agricultural land helps to diversify the traditional agricultural systems, but it arises difficulty in estimation of agroforestry area. The total geographic area, agroforestry area and their percentage of selected districts viz., Bikaner, Dausa, Jhunjunu, Pali and Sikar of Rajasthan wereindicated in Table 1. The estimated area under agroforestry was found highest in Pali (84149.97 ha) followed by Bikaner (79752.21 ha), Sikar (38792.56 ha), Jhunjunu (37100.97) and Dausa (22630.59 ha).The agroforestry area of Dausa, Jhunjhunu, Pali and Sikar was mapped by using sub-pixel classifier, whereas due to unavailability of requisite data images of Bikaner was mapped on the basis of maximum likelihood classification (Fig 1). The agroforestry area obtained for selected districts (20 per cent) districts of Rajasthan was extrapolated for entire state. The area under agroforestry in Rajstjhan was estimated to be 1.49 million ha. The figure arised for Rajasthan was on higher side than FSI (2013) reports, which has mentioned 0.84 million ha. This is due to significant variation in the methodology adopted by the institutes

(Dhyani 2014; Chavan et al. 2015).

Tree density and major tree species existing on farmer's field

A primary field survey was undertaken in five districts of Rajasthan to gather information on number of different tree species (nos.), DBH (cm), age (years) and their tree density (ha^{-1}) on farmers field during 2013–2014 (Table 1 and 2). Out of five districts, Bikaner districts had the highest number of tree species (24nos) followed by Jhunjhunu (19 nos.), Dausa and Sikar (17 nos), howerverlowerstnumber of tree species was found in Pali (11) (Table 2). These tree species were classified as slow, medium and fast-growing based on their growth habits and mean annual increment (MAI).Also, the age of these tree species was estimated based on pre-developed DBH-age relationships. The average age of the existing trees was 49.90, 14.90 and 8.28 yearsfor slow, medium and fast categories, respectively. These values of DBH and tree densities were taken as input for the CO2FIX model to estimate biomass and carbon stock for slow, medium and fast-growing trees.

The major tree species existing in farmer's field were*Prosopis cineraria, Tecomellaundulata, Capprisdeciduas*, *Acacia tortilis*, *Prosopisjuliflora*, *Azadirachtaindica*, *Dalbergiasissoo*and *Ziziphusmauritiana.* The native *Prosopis cineraria*were the most dominant tree species in four districts except Dausa, where *Azadirachtaindica* was dominant. Other tree species such as *Tecomellaundulata*, *Capparis decidua, Acacia tortilis, Ailanthus excelsa*and *Prosopisjuliflora*are also common in the desert landscape (Fig 3&5). In Rajasthan, the minimum tree density was1.40 tree ha^{-1}(Bikaner) and maximum was 14.9 tree ha^{-1}(Dausa) with the average density of 9.71 trees ha^{-1} (Table 2).*Prosopis cineraria* wasfound to be the most dominant tree species on farmers field in Bikaner, Jhunjhunu, Sikar and Pali districts, which consists of 45.17 to 64.78% over total tree species. The Dausa district was dominated by*Azadirachtaindica*(31%) as the edaphic as well as climatic conditions does not favours*Prosopis cineraria*. The results of the present study are in line witherlier studies of Shankarnarayan et al (1987), Tiwariand Singh (2006) and Roy et al (2011). Singh (2011) clearly reported that the *Prosopis cineraria* based systems were dominant in about 47% and also *Ziziphusnummularia* based agroforestry occupy about 28% of the total area of western Rajasthan. The tree density of *Prosopis cineraria*varied from 5 to 50 tree ha^{-1}through out the Rajasthan (Tiwari et al.2014).

The secondary data on crop productivity was obtained from surveyed farmers, Districts Statistical officers and NIC (National Informatics Centre, Ministry of Communications and Information Technology, Govt. of India, New Delhi) and used as fourth cohort in CO2FIX model. The secondary data includes production, productivity and average yield of district along with land use pattern also collected for biomass and carbon simulation. The agriculture of Rajasthan mainly dominated with wheat (*Triticumaestivum*), Pearlmillet

(*Pennisetumglaucum*), mustard (*Brassica juncea*), groundnut (*Arachishypogaea*), barley (*Hordeumvulgare*), Gaur (*Cyamopsistetragonoloba*) and chickpea(*Cicerarientinum*) and presented in Table 1.For example, productivity of wheat varied from 0.97 Mg ha^{-1} (Bikaner) to 5.00 Mg ha^{-1} (Dausa) due to climatic and edaphic factors of arid ecosystem. The trees in studied districts of Rajasthan are mostly occurs either on field bund or scattered in agriculture fields. There was no systematic symmetry of trees in agriculture field but farmers are purposefully retaining trees for fuelwood, fodder and benefits of agricultural crop (Fig 4&5).

***Assessment of* carbon sequestration potential**

Assessment of carbon sequestration potential (CSP) of agroforestry system existing on farmer's field was done through simulation model CO2FIX in five districts of Rajasthan. Tree biomass, total biomass (tree +crop), biomass carbon, soil carbon, net carbon sequestered over simulated period of 30-yearsand carbon sequestration potential (CSP) of surveyed districts has been given in Table 4 and detailed explained in following subheads.

Tree-crop biomass& carbon

The CO2FIX model was used to quantify baseline as well as simulated carbon on the basis of primary and secondary data during study. The base line (2014) tree biomass (above+belowground) at the district level was lowest (0.86 Mg ha^{-1}) in Bikaner and highest (11.25 Mg ha^{-1}) in Pali, respectively(Table 4 &Table 5). The biomass of Pali district was higher due to highest tree density (14.90 trees ha^{-1}). The results further indicates that the increase in the tree density increases tree biomass. This is well supported by Singh (2011) in *Prosopis cineraria* and Gupta et al. (2019) in *Hardwickiabinata* that tree density has an strong influencial factor on tree biomass production.Morever, tree biomass (above+below ground) is expected to increase from the base line range of 0.86–11.25Mg $ha^{-1}$to the simulated range of 0..87–28.59Mg ha^{-1}over the simulated period of 30 years (Table 4). The baseline total biomass (tree+crop) ranged from 2.22 to 19.19 Mg ha^{-1} and is expected to increase to the range of 4.27–39.11 Mg ha^{-1}. A clear increasing trend was observed between total biomass and tree density as the pearson's correlation coefficient was found to be highly significant with a high positive value ($r = 0.97$, $p = 0.00$).The similar range of existing biomass production from the well-established agroforestry systems in arid zone of Rajasthan isalso reported by Tanwar et al. (2019). They reported a biomass production of 1.77 to 22.56 Mg ha^{-1} at tree density of 45 to 145 ha^{-1} after 19 years of age tree dominated system (*Prospois cineraria, Hardwickia binate, Z. mauritiana and Acacia tortolis*with grasses), respectively.In the study, the highest and lowest total baseline biomass carbon (tree + crop) was recorded in Sikar (8.64 Mg C ha^{-1}) and Bikaner districts (1.00 Mg C ha^{-1}) of Rajasthan. The simulation results of total carbon (biomass+soil) through CO2FIX model revealed that total carbon would enhance to the tune of 13.32–35.39 Mg C $ha^{-1}$from the present baseline range of 9.00–24.45 Mg C ha^{-1}.

Soil Organic Carbon (SOC)

For the estimation of soil carbon in selected ditricts, soils up to 90 cm depth was sampled and analysed. Soil organic carbon is also used as one of the cohort for CO2FIX model.In the study, maximum SOC was found in Pali (16.51 Mg ha^{-1}) and Dausa (16.49 Mg ha^{-1}) followed by Bikaner (8.00 Mg ha^{-1}), Jhunhunu (4.51 Mg ha^{-1}) and Sikar (4.28 Mg ha^{-1}). The average soil carbon of Rajasthan state was 9.96 Mg $ha^{-1}$and it ranged from 4.28-16.5 Mg ha^{-1} (Table 4). The similar findings of soil carbon have been reported by Mangalasset et al. (2014) and Singh (2005) for different agroforestry systems of arid zone.The simulated SOC is expected to increase from 4.28-16.51 Mg ha^{-1} to 7.34-17.01 Mg ha^{-1} over simulated period of 30 years..The variation in the soil organic carbon is due to tree density, type of soil, type of tree species, rainfall and other management practices. Many authors clearly pointed out that leaf litter production is function of increase in SOC, but the heavy lopping of xerophytic vegetation for fodder purposes reduces the availability of leaf litter in arid zone (Yadav et al. 2008, Tanwar et al. 2019, Singh et al. 2012). However, correlation between observed SOCand tree density was not only weak but also non-significant ($r = 0.57$, $p = 0.32$).

Carbon sequestration Potential existing agroforestry systems

Basically, the total carbon sequestered under agroforestry comprises of two main pools viz. biomass carbon and soil carbon (Ajit et al. 2017).Total carbon (biomass + soil) in Pali, Dausa, Sikar, Jhunjunu and Bikaner districts was estimated to be 24.45, 22.58, 12.92, 12.09 and 9.00 Mg C ha^{-1}, respectively, for baseline. This total carbon would tend to increase to 35.39, 31.56, 21.45, 31.56, 18.96 and 13.32 Mg C ha^{-1} in these districts, respectively, for a simulated period of 30 years (Table 4). In this way, net carbon sequestered by agroforestry in simulated period of 30 years will be 10.94, 8.94, 8.53,6.87 and 4.32Mg C ha^{-1} in these districts, respectively.However, for clear picture on district level net carbon sequestered is estimated by multiplying agroforestry area of district with net carbon sequestration of that district and expressed in million tonnes (Figure 3). The highest net carbon sequestered by Pali district (0.92 million tonnes) followed by Bikaner (0.34 million tonnes) and Sikar (0.33 million tonnes) (Figure2).

CSPof agroforestry system was calculated by dividing net carbon sequestration by simulated years (30). However, CSP of existing agroforestry system has been assessed to be as 0.36 Mg C ha^{-1} yr^{-1} in Pali, 0.29 Mg C ha^{-1} yr^{-1}in Dausa, 0.28 Mg C ha^{-1} yr^{-1} in Sikar, 0.22 Mg C ha^{-1} yr^{-1} in Jhunjhunu and 0.14 Mg C ha^{-1} yr^{-1}in Bikaner (Table 4; 5& Fig. 3).Comparatively similar trendis reported by Gupta et al (2019), Tanwar et al (2019) and Singh et al. (2015) that average rate of CSP in agroforestry systems in arid zone varies from 0.28–0.70Mg C ha^{-1} yr^{-1}over a period of 20-25 years.However, a very clear trend was observed across all surveyed districts that as the tree density increases, tree biomass increases and in turn the tree biomass carbon increases. Based on this study, estimated value of CSPfor the entire Rajasthan state was 0.26 Mg C ha^{-1} yr^{-1} at average tree density of 9.71 ha^{-1}.

Mitigation of GHG emission through agroforestry

The district level CSP and area under agroforestry have been extrapolated for entire states and presented in Table 5.The mean CSP value of all surveyed districts (20% sampled districts) i.e. 0.26 Mg C ha^{-1} yr^{-1} was considered as CSP of Rajasthan state. The carbon-di-oxide absorption/mitigationpotential was also quantified for each district by multiplying 3.67 factor (44/17) with mean CSP (Mg C ha^{-1} yr^{-1}). The average GHG mitigation potential of Bikaner, Dausa, Jhunjhunu, Pali and Sikar was 0.51, 1.06, 0.81, 1.32 and 1.03 Mg CO_2 eq. ha^{-1} yr^{-1}, respectively (Table 4).Total GHG mitigation potential of agroforestry (tonne yr^{-1}) at district level was also computed by multiplying CO_2 absorption/mitigation (Mg CO_2eq ha^{-1} yr^{-1}) with agroforestry area in the district (Table 5). The highest GHG mitigation potential was observed for Pali (111178.94 Mg CO_2eq yr^{-1}) followed by Bikaner (40976.69 Mg CO_2eq yr^{-1}), Sikar (39863.24 Mg CO_2eq yr^{-1}), Jhunjunu (29955.32 Mg CO_2eq yr^{-1}) and Dausa (23872.88 Mg CO_2eq yr^{-1}). The stae-level GHG or global warming mitigation potential of Rajsthan was found to be 0.95 million tonnes of CO_2eq $yr^{-1}$from 1.49 million ha of agroforestry (Table 5).

As mentioned earlier, precise and accurate estimates of carbon sequestration potential and area under agroforestry arethe need of the hour to achieve various challenges of climate change. In India, trees are grown and maintained on farmlands for various reasons but not yet quantified in terms of area and their carbon stock. The information on these aspects will help to achieve Indias's pledge in Paris for creating an additional carbon sink of 2.5-3 billion tonnes up to 2030 (UNFCCC 2015). Interestingly, the present study quantified the existing carbon stock (Biomass carbon + soil) of 24.26 million tonnes from 1.49 million agroforestry areas of Rajasthan. The agroforestry of Rajasthan has huge potential to offset global warming i.e. GHG emission at a rate of 1.42 million tonnes of CO_2-eq yr^{-1}. AFOLU (Agriculture, Forestry and Other Land Use) sector of Rajasthan was emitted 24.45 million tonnes CO_2-eq in the year 2015. Considering the reported GHG emissions from AFOLU (Agriculture, Forestry and Other Land Use) sector as 24.45 million tons of CO_2 equivalent in Rajasthan (GHG platform India; Dhingra and Mehata, 2017), the tree-based systems on farmers' fields are quantified to offset 5 % of total GHG emissions from AFOLU sector annually. From these facts, we can conclude that traditional tree farming in India has the huge potential to offset their total emission and pave the way towards carbon neutral as assessed in Rajasthan.

Conclusion

Agroforestry, or the intentional use of trees in the cropping system, has been proposed by many practitioners as a potential strategy to minimize carbon footprint and could be a potent instrument to achieve the targets of Paris agreement. The study concluded that arid agroforestry could be sequestered at a rate of 0.26 Mg C ha^{-1} yr^{-1} at a tree density of 9.71 ha^{-1} in Rajasthan. This potential of carbon sequestration can be further enhanced by increasing tree density to offset GHG emission from AFOLU (Agriculture, Forestry and Other Land Use) sector. However, the information generated from this study will be helpful to develop high biomass producing agroforestry models, carbon management and incentives for ecosystem services.

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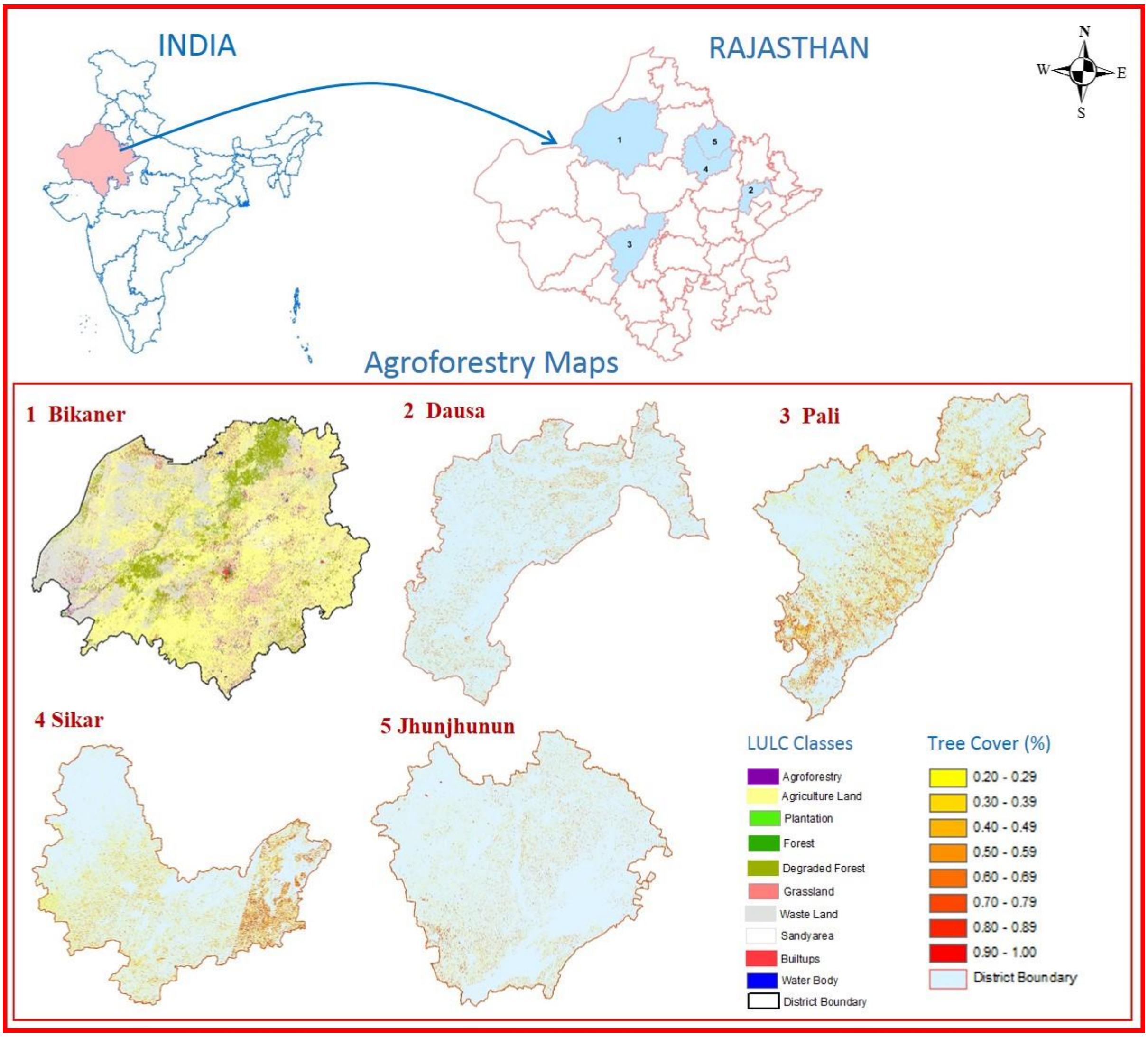

Figure 1. Study site and agroforestry area maps of surveyed districts of Rajasthan

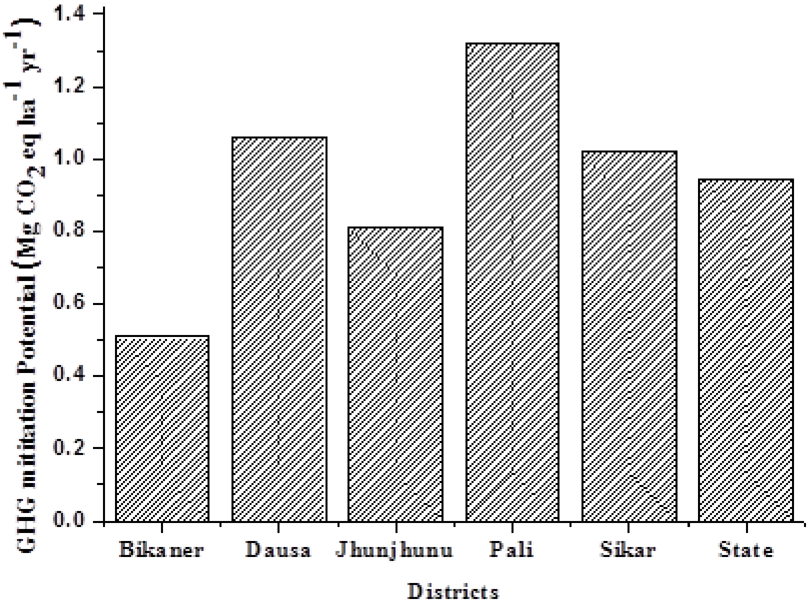

Figure 2: District-wise GHG mitigation potential of agroforestry (Mg CO_2-eq ha^{-1} yr^{-1}) in Rajasthan

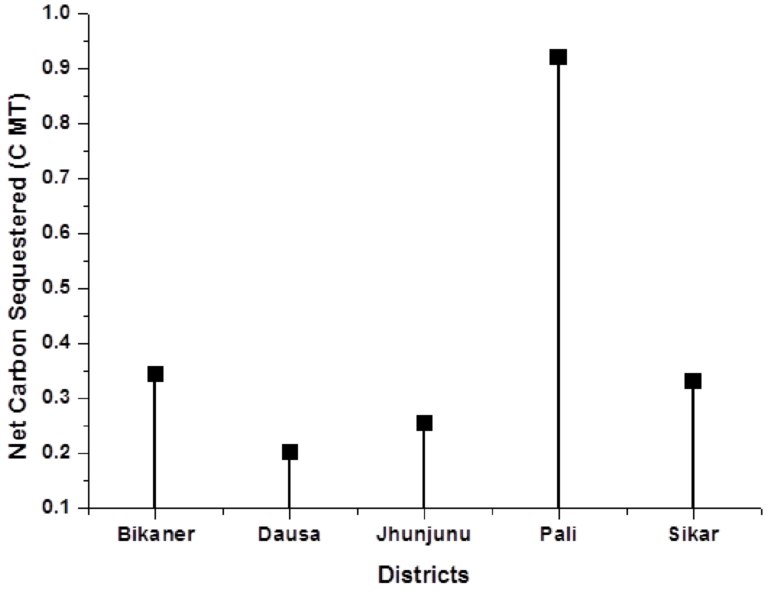

Figure 3District-wise net carbon sequestered (C million tonnes) in agroforestry of Rajasthan

Fig 4.*Prosopiscineraia*-based agroforestry with *Arachis hypogaea*(a) and *Brassica juncea* (b)

Fig 5.Pennisetumglaucum with *Acacia nilotica* (a) and *Ailathanusexcelsa (b)*

Table 1Site characteristics, dominant tree species and their density/crops and climatic data of the study areas

Particulars	**Bikaner**	**Dausa**	**Jhunjunu**	**Pali**	**Sikar**
Location	28°01′00″N 73°18′43″E	26.88°N 76.33°E	28.13°N 75.40°E	30 0 3’N76 03’E	27.62°N 75.15°E
Rainfall (mm)	100-350	500-700	300-500	350-650	300-500
Climate	Hyper arid partial irrigated zone (1C)	Semi-arid eastern plains (IIIA)	Internal drainage dry zone (IIA)	Transitional plain of Luni basin (IIB)	Internal drainage dry zon
Soil type	sandy and loamy-coarse in texture & calcareous	Deep brown loam and sandy	Sandy loam, shallow depth red soil	Light yellowish brown Sandy and loamy	Sandy loam, shallow depth
Dominant crops (Mg ha^{-1})	*Triticumaestivum (0.97),Brassica juncea(0.47),Arachishypogaea(0.80), Cicerarietinum(0.85), Cyamopsistetragonoloba(0.98)*	*Triticumaestivum (5.0), Pennisetumglaucum (5.0), Mustard (3.2), Arachishypogaea (3.1), Brassica nigra(2.9)*	*Pennisetumglaucum*(1.01), *Hordeumvulgare (2.72), Triticumaestivum (3.26), Cyamopsistetragonoloba* (0.26), Pulses (0.31)&*Arachishypogaea (1.49)*	*Triticumaestivum (1.78), Cicerarietinum(3.1), Millet (5.4), Arachishypogaea (1.74), Hordeumvulgare (1.7)*	*Pennisetumglaucum* (1.03), *Triticumaestivum*(2.98),*Hordeum* Pulses (0.34), *Cyamopsistetragonoloba*(0.44)&*A (1.49)*
Dominant trees in field (%)	*Prosopis cineraria (45.17), Acacia nilotica (28.65), Ziziphusmauritiana (4.57), Prosopisjuliflora (15.93), Dalbergiasissoo (2.95), Azadirachtaindica (1.40)*	*Azadirachtaindica (30.9), Acacia nilotica (19.44), Prosopis cineraria (8.05), Dalbergiasissoo (6.51), Prosopisjuliflora (2.5)*	*Prosopis cineraria (64.78), Tecomellaundulata (10.20), Acacia tortilis (3.88), Ailanthus excelsa (2.92)*	*Prosopis cineraria (59.52), Prosopisjuliflora (16.31), Ziziphusmauritiana (8.55), Azadirechtaindica*(7.84),*Dalbergiasissoo(3.92), Acacia nilotica(2.96)*	*Prosopis cineraria (46.19),Cappa (16.06),Tecomellaundulata (7.27), (7.02)*
Tree density (tree ha^{-1})	1.40	12.87	6.95	14.90	12.42

Table 2 Number of tree species, their age and observed DBH in surveyed districts of Rajasthan

Districts	Observed no. of tree species in the district	Observed average number of trees (trees/ha)				Estimated age of existing trees (years)			Observed DBH of existing trees (cm)		
		Slow	Medium	Fast	Total	Slow	Medium	Fast	Slow	Medium	Fast
Bikaner	24	0.09	1.26	0.04	1.4	44.66	15.73	8.69	32.6	24.85	20.59
Dausa	17	0.08	12.52	0.26	12.87	67.93	19.37	8.41	49.58	30.6	19.93
Jhunjhnu	19	6.03	0.76	0.16	6.95	38.14	10.62	7.13	27.84	16.79	16.91
Pali	11	0.75	14	0.14	14.9	59.46	16.71	8.13	43.4	26.24	19.26
Sikar	17	9.21	2.58	0.62	12.42	39.4	12.44	9.02	28.76	19.66	21.38

Table 3.Estimated agroforestry area of selected districts of Rajasthan (ha)

Districts	Geographic area (ha)	Agroforestry area (ha)	Agroforestry area (%)	Tree density (tree ha^{-1})
Bikaner	3025824.48	79752.21	2.64	1.40
Dausa	343223.92	22430.59	6.54	12.87
Jhunjunu	591350.63	37100.97	6.27	6.95
Pali	1254939.81	84149.97	6.71	14.90
Sikar	777215.06	38792.56	4.99	12.42
Rajasthan*	**34223900.00**	**1497593.01**	**4.38**	**9.71**

* Agroforestry area for state-level is extrapolated based on survey districts (20% of total districts of state)

Table 4.Estimated biomass, carbon and carbon sequestered under existing agroforestry systems in various districts of Rajasthan

Parameters			**Bikaner (1.40)**	**Dausa (12.87)**	**Jhunjhunu (6.95)**	**Pali (14.90)**	**Sikar (12.42)**
Tree Biomass (above and below ground) Mg DM ha^{-1}	Baseline	Biomass	0.86	11.01	4.33	11.25	7.62
	Simulated		2.87	28.59	10.04	33.00	18.74
Total Biomass (tree+ crop) Mg DM ha^{-1}	Baseline		2.22	12.88	17.13	17.19	19.19
	Simulated		4.27	30.51	23.20	39.11	30.64
Soil carbon (Mg C ha^{-1})	Baseline	Carbon	8.00	16.49	4.51	16.5	4.28
	Simulated		11.34	17.01	8.48	16.92	7.34
Biomass carbon (Mg C ha^{-1})	Baseline		1.00	6.09	7.58	7.95	8.64
	Simulated		1.98	14.55	10.48	18.47	14.11
Total carbon (biomass + soil) (Mg C ha^{-1})	Baseline		9.00	22.58	12.09	24.45	12.92
	Simulated		13.32	31.56	18.96	35.39	21.45
Net carbon sequestered in AFS over the simulated period of thirty years (Mg C ha^{-1})		Carbon sequestered	4.32	8.98	6.87	10.94	8.53
Estimated annual carbon sequestration potential of AFS in different districts of Rajasthan (Mg C $ha^{-1}yr^{-1}$)			0.14	0.29	0.22	0.36	0.28
GHG mitigation potential (Mg CO_2 eq. $ha^{-1}yr^{-1}$)			0.51	1.06	0.81	1.32	1.02

Table 5 Carbon sequestration and GHG mitigation potential of agroforestry in Rajasthan

Districts	Agroforestry area (m ha) (LISS-IV images) (A)	CSP (Mg C $ha^{-1}yr^{-1}$) (CO2FIX model) (B)	GHG mitigation Potential (Mg CO_2 $ha^{-1}yr^{-1}$) (CO2FIX model) (C)	Total CSP (Mg C yr^{-1}) (A*B)	GHG mitigation potential agroforestry (A*C)	
					Mg CO_2 eq. yr^{-1}	Million tonne CO_2 eq. yr^{-1}
Bikaner	79752	0.14	0.51	11165.3	40976.7	0.04
Dausa	22431	0.29	1.06	6504.87	23872.9	0.02
Jhunjunu	37101	0.22	0.81	8162.21	29955.3	0.03
Pali	84150	0.36	1.32	30294	111179	0.11
Sikar	38793	0.28	1.03	10861.9	39863.2	0.04
Rajasthan*	**1497593**	**0.26**	**0.95**	**386379**	**1418011**	1.42

*Extrapolated for state level based on surveyed districts