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Exploration of green house gas emissions, avoided deforestation potential and carbon trade: insights from prominent agroforestry systems of Indian Himalaya

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The present study is reported from the central region of Indian Kashmir Himalayas with the aim of (i) identifying and documenting tree species in the agroforestry systems along with the preferred usage, (ii) quantifying green house gas (GHG) emissions and avoided deforestation potential, and (iii) assessing biomass and carbon stock for their trade potential. Purposive, multi-stage, and random sampling procedures were followed for the selection of sampling units based on the availability of agroforestry land use systems. A total of 19 tree species belonging to 9 families and 12 genera were documented. Species like *Populus deltoides*, *Populus nigra*, *Salix alba*, and *Salix fragilis* were found to be highly preferred for fuelwood, fodder, and small timber extraction. The total green house gas (GHG) emission potential of this extracted material is 64.35 tC and 235.95 tCO₂, with the maximum CO₂ emission from *Salix alba* (28.05 tCO₂). A total quantity of 143 quintals of biomass is extracted annually from the 19 tree species utilized for fuelwood, fodder, and small timber, resulting in an average avoided deforestation potential of 75.26 m³. The highest offset value of US\$ 1492.79/Mg was recorded for Horti-silvi-pastoral systems, followed by Homegardens (US\$ 1414.51/Mg), and the minimum offset value of US\$ 626.38/Mg was recorded for Boundary plantations. On an average, a single sampled household helps to sequester 4.7 Mg of carbon annually in the present study. Therefore, a cluster-based approach by bundling villages together in the entire Ganderbal district would result in approximately sequestering 213,196 Mg CO₂e and hence would yield US\$ 536,620 per annum. The present study's estimation of carbon stock and carbon offset values could act as a baseline for the future implementation of CDM, REDD, and REDD++ projects in J&K.

KEYWORDS

carbon trading, climate change, deforestation, fuel wood, sequestration

1 Introduction

Agroforestry has a great potential of reducing atmospheric CO₂ through carbon sequestration (Rizvi et al., 2019; Ghale et al., 2022). The scattered trees on farmlands hold a high potential of carbon storage (Gebrewahid et al., 2018) which may greatly contribute to the climate resilience, green economy strategy and to reducing CO₂ emissions by avoiding burning of forest-based fuelwood and helping in avoiding deforestation (Murthy et al., 2013). To mitigate the adverse climate change effects, agroforestry is known to have a great potential in the short run through natural resources and microclimate moderation and by sequestering carbon in the long run (Rao et al., 2007; Sahoo et al., 2022). Evidences are now emerging that agroforestry systems are promising management practices to increase aboveground and soil carbon stocks to mitigate greenhouse gas emissions (Pandey, 2007). Information on the potential costs of reducing deforestation globally (Sohngen et al., 2008) is very limited. There is a real potential to generate unprecedented funds for deforestation prevention however, it also reveals several challenges (Ebeling and Yasue, 2008). In addition to reduction of harmful GHG emissions through REED, this mechanism could also provide lots of co-benefits for human development and biodiversity. Results of various studies (Nair et al., 2010; Soto-Pinto et al., 2010; Pala et al., 2020) demonstrated the value of agroforestry systems as a potential strategy for avoiding deforestation and tree cover recovery and carbon sequestration, and suggest that adequate planning, incentives and capacity-building efforts can lead to better conservation practices (Berkes, 2007; Wisudayati et al., 2021).

The change in climatic conditions and alterations in temperature have developed a need for the sustainable landuse system that will be more productive (FAO, 2016). Agroforestry landscapes be the response of society, consisting primarily of meeting the urgent human needs for food, fuel, animal feed, shelter etc. (Dove, 1992). Tree cover on agricultural landscape varies globally (Gebrewahid et al., 2018). Agroforestry systems, trees on farms, and trees outside the forest (Foresta, 2013; Khan et al., 2024) can be a good alternative for achieving sustainable goals by improving microclimate, water qualities, soil properties and carbon sequestration (Schroth and Sinclair, 2003; Sarvade, 2014). Rehabilitation and control of degraded lands with suitable agroforestry techniques is a substantial opportunity which has not been realized, particularly in the attempt to lessen the accumulation of green house gases in the atmosphere (Unruh et al., 1993). According to Leakey and Sanchez (1997), approximately 1.2 billion people (20%) of the world population relies upon agroforestry products and services in developing countries that could provide goods and services, which can offset 5–20% of deforestation.

Agroforestry conserves biodiversity and makes the landscape suitable for forest species by decreasing frequency and intensity of fires and providing buffer zones to protected areas (Pandey, 2002). In addition to biodiversity conservation, agroforestry increases farm income (Kaushal et al., 2017) and gives food security through amplification in the yield of products and services from biodiversity rich agro-ecosystems (Khan et al., 2024). The introduction of trees in the agricultural landscapes often improves the productivity of

systems while providing opportunities to create carbon sinks and provide suitable ways to reduce CO₂ emissions in the atmosphere (Chauhan et al., 2015, 2016). The potential of trees on farmlands to sequester carbon depends upon the woody species composition, age of trees, geographic location, agro-ecological conditions, management regimes and soil characteristics (Bunker et al., 2005; Henry et al., 2009; Newaj et al., 2016). Trees on farmlands or agricultural landscape if primarily designed to sequester carbon is a unique opportunity to increase carbon stocks in the terrestrial biosphere (Albrecht and Kandji, 2003). Agroforestry has importance as a carbon sequestration strategy because of carbon storage potential in its multiple plant species and soil and as well as its applicability in both agricultural and reforestation lands (Ruark et al., 2003; Nair et al., 2009, 2010).

The important role of Agroforestry in sequestration of carbon has raised the global interest in controlling the emissions of green house gases (Pala et al., 2020). Woodlands sequester more carbon as compared to other systems and are thus an important natural means to monitor climate change (Gibbs et al., 2007). The mechanisms for avoiding deforestation have been considered by the United Nations Framework Convention for Climate Change, but the economic potential of avoided deforestation has yet to be addressed. The concept of creating a program that gives incentives to countries to lower their deforestation rates has not been widely considered, although it has been discussed in academic literature. Agroforestry meets the ever-increasing demands of fuelwood and fodder by increasing the number of trees on arable/non-arable farmlands (Kaushik et al., 2015; Sharma et al., 2021). Most of the fuelwood demand is associated with rural households and some observers (e.g. Gregersen et al., 1989) believe that the key to solving fuelwood problem can be found by encouraging farm families to develop agroforestry systems.

Therefore, unlike in tree plantations and other monoculture systems, agroforestry seems to have a unique advantage in terms of carbon sequestration, many of these assumptions have, however, not been systematically tested and validated (Montagnini and Nair, 2004; Amare and Darr, 2020). Their ability to address smallholder' livelihood needs and simultaneously store large quantities of carbon make tree-rich smallholder agroforestry systems possible prototypes for CDM-type projects (Roshetko et al., 2002) and REDD projects and policies (Pala et al., 2020). The Union Territory of Jammu & Kashmir has most of its area under tree-based cultivation having 09 types of agroforestry systems (Banyal et al., 2016; Sharma et al., 2024) and hence has immense potential for carbon trade potential. While the literature acknowledges this potential, but the cost of reducing deforestation is very limited and its economic gain has not been documented yet. Therefore, the present study was conducted within the unexplored and high potential context of the central region of Kashmir Himalayas with the aim. (i) To identify and document tree species in the agroforestry systems along with the preference for the usage. (ii) Quantification of GHG emissions and avoided potential deforestation. (iii) Assessment of biomass and carbon stock for trade potential, thereby providing real data to support the economic case for agroforestry as an effective climate solution.

2 Materials and methods

The present research problem was undertaken in the Ganderbal district falling in the central region of UT Jammu and Kashmir, India, located at an elevational range of 1650–3600 m above mean sea level (MSL). The geographical location of the district falls between 34° 2' 9" N Latitude and 74° 6' 8" E Longitude (Figure 1). The district comprises of total 139 villages grouped in six tehsils viz, Gund, Kangan, Ganderbal, Wakura, Lar and Tulmulla and seven blocks (Lar, Ganderbal, Kangan, Wakura, Sheripathri, Safapora and Gund Ganderbal) and further divided into 112 Panchayat Halqas. The population of the district is 321,139 (estimated as per aadhar uidai.gov.in Dec 2020 data). The district covers a total area of 1,46,295 ha, and has contributions from Forest (50,362.29 ha), Forest Scrub (12,721.60 ha), Grassland (14,301.10 ha), Snow cover (25,892.4 ha), Tree outside forest (TOF) (9,905.62 ha), Wasteland (14,153.44 ha), Waterbodies (2,246.47 ha) and Wetland (1,783.21 ha) (Wani et al., 2020). Soil types vary from silt clay loam to clay loam. The average annual precipitation is 1002.8 mm in the form of rain and snow. The climate is temperate type with the upper reaches receiving heavy snowfall during winter.

Agriculture is the main occupation of the economy in the district with more than 80% of the involvement of population. The agro-climatic conditions allow cultivation of major fruit crops like apple, pear, cherry, walnut apart from rare and special crops like grapes, strawberry, persimmon etc. The agriculture and horticultural crops are mostly grown on same lands making it a strong case of properly existing agroforestry systems with varying crop components within households. Adoption and practice of these agroforestry systems depends on the edapho-climatic, socio-economic status and need of the resources. These attributes lead to variation in the structure and composition of recommended technologies and existing agrarianism.

2.1 Sampling techniques

Purposive, multi-stage and random sampling procedures were followed for the selection of sampling units. The three (03) blocks viz., Lar, Ganderbal and Gund were selected from total seven blocks from the district Ganderbal purposively due to the availability of agroforestry land use systems (Figure 2). From each of these blocks, three villages from each respective blocks were randomly selected such as, Fraw, Hakhnaar, Rayil from Gund block, Watlar, Manigam and Chount-waliwar from Lar Block and Shallbough, Wakura and Tulmulla from Ganderbal block. A total of six hundred seventy one (671) households with 10% of sampling intensity were chosen from nine (09) selected villages. The information was collected at the household level based on open and close ended questionnaire and whereas, field data was carried out in the agroforestry fields of the sampled households. The preference of respondents interviewed was either household heads or the eldest members of the family. Before final data collection, entire schedule was pre-tested for elimination, addition and alteration with non-sample respondents of the study area (Pala et al., 2019). For better understanding and exploration of data, we categorized the sampled sites and collected the data on basis of agroforestry systems.

2.2 Data collection

The present study included both quantitative and qualitative methods. Data was collected by using both primary field survey and secondary sources. Primary sources of data involved the dissemination of questionnaires/interview schedules among the sampled households as well as non-participant observation (Kumar, 2012). Secondary sources of data were obtained from literature from various journals, previous published research, annual reports, and online sources like Web of Science, Research gate, Publons, Google scholar and Academia etc. Quadrature method was used to study the diversity and ecological status of the tree in the existing agroforestry systems. In each agroforestry system, 10 m × 10 m (100 m²), 5 m × 5 m (25 m²) and 1 m × 1 m (1 m²) sample quadrats were systematically laid for trees, shrubs and annual crops respectively. A total of 63 quadrats were used to determine density (subsequently converted into density per hectare), number of individuals belonging to each tree species, tree species diversity and number of tree species. Only woody perennials of erect habit with girth at breast height of at least 10 cm were enumerated.

2.2.1 Avoided deforestation potential (fuel wood, fodder and timber) and GHG emission

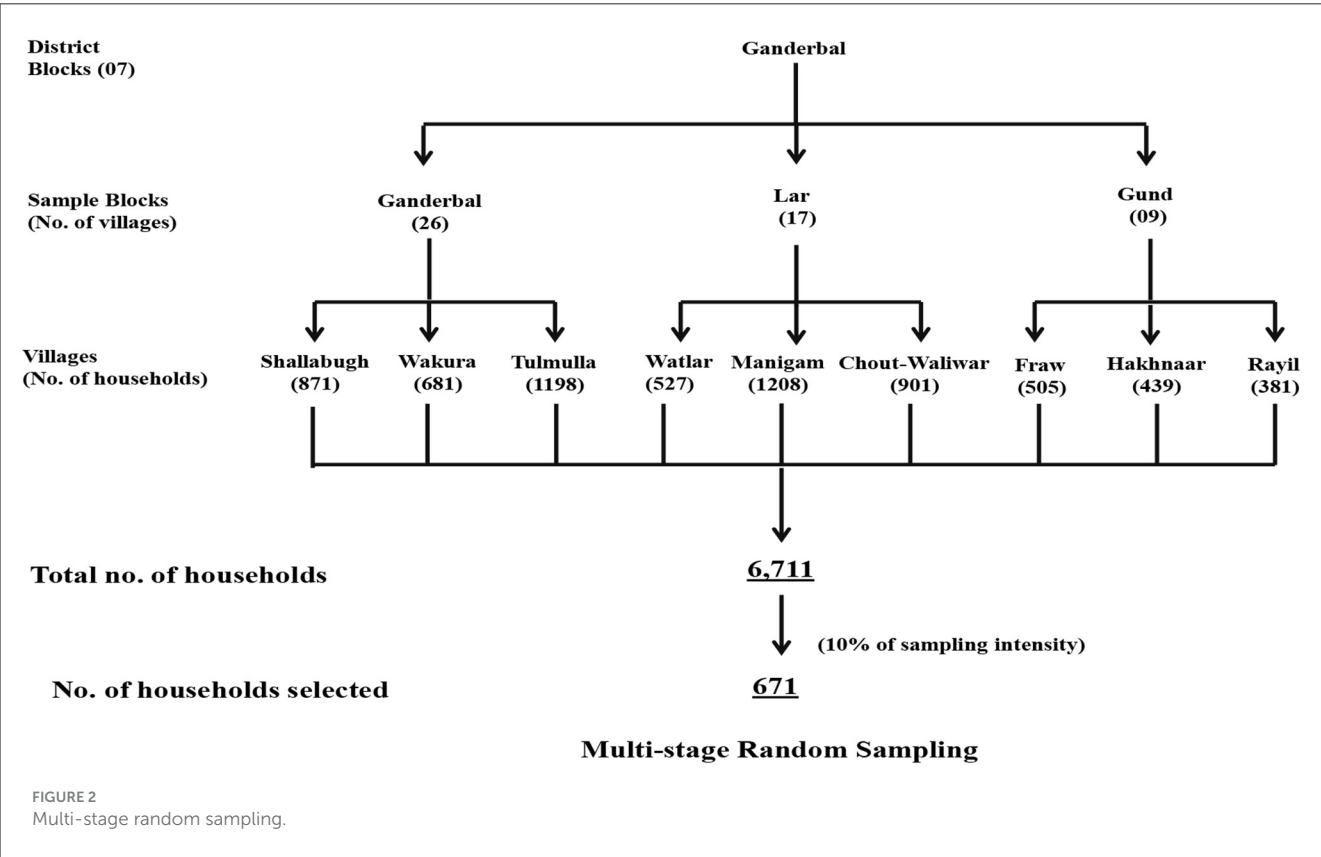
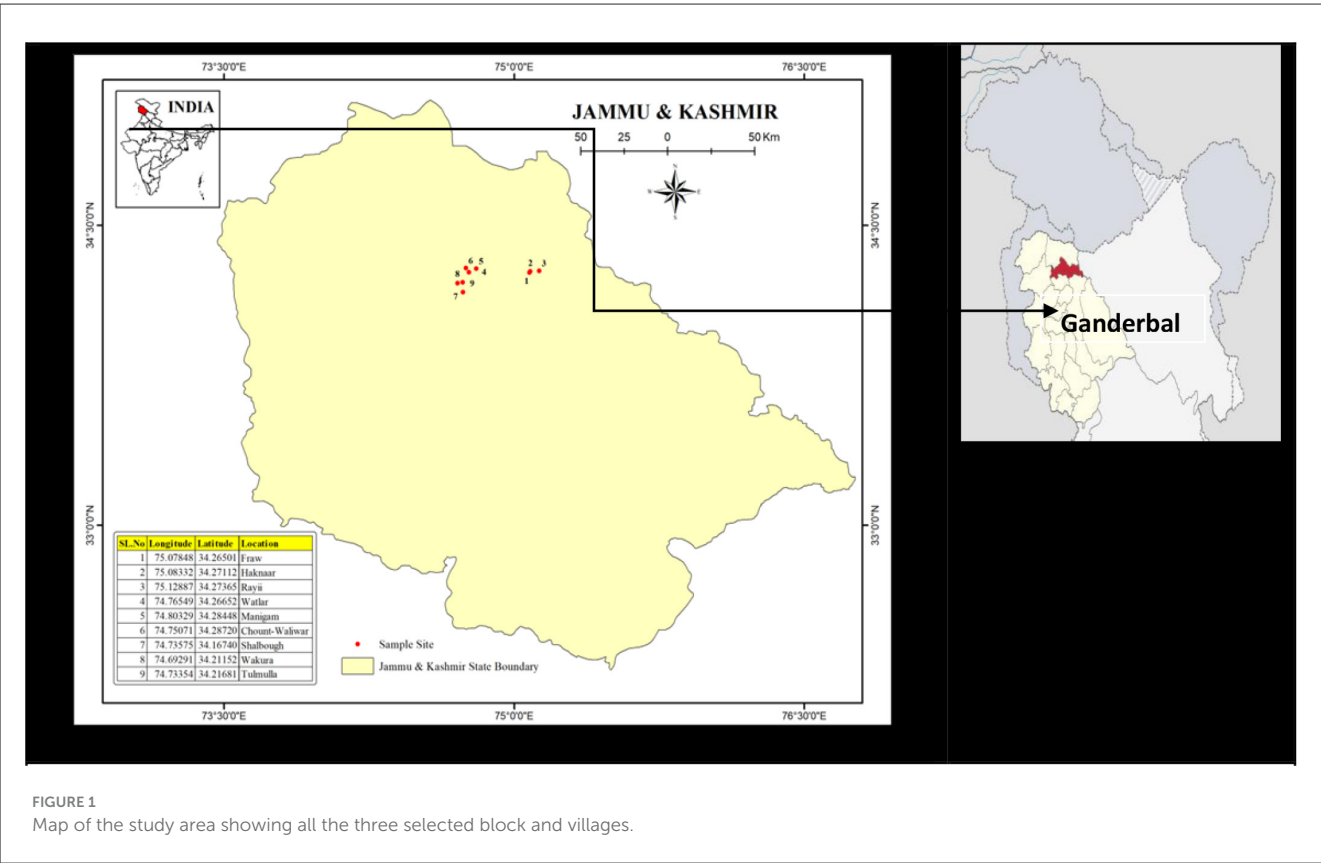
The avoided deforestation potential is the significant decrease in GHG emissions and the generation of ecosystem services such as, fuelwood, fodder and timber, preventing forests from being cut down (Delacote et al., 2016). The avoided deforestation potential represent the volume of wood that is sourced from the agroforestry systems, thereby acting as a proxy for the volume of wood that would otherwise need to be extracted from nearby forest resources. This calculation quantifies the avoided harvesting pressure on natural forests. For this, the respondents were asked to specify their preferences for fuelwood, fodder and timber/small timber species. The identification of major fuelwood, fodder and timber species were mainly based on interviews, informal discussions and observations (Martin, 1995). The quantity of fuelwood and fodder collection was estimated over a period of 24 h using a weight survey method (Mitchell, 1979). Fuelwood consumption per capita per day was calculated on the basis of total fuelwood consumed by a family, divided by the total number of family members (Gupta et al., 1997). The annual rate of avoided deforestation and rate of emission of greenhouse gases per year as a result of burning of fuelwood was evaluated following Tahir et al. (2010).

For woody biomass, a conversion factor of 0.5 t C/t dm is used (Intergovernmental Panel on Climate Change (IPCC), 2006). The emission of CO₂ from fuelwood burning was estimated by converting total carbon content (t C) to carbon dioxide content (t CO₂) using the conversion ratio of 44 t CO₂/12 t C (Intergovernmental Panel on Climate Change (IPCC), 2006). This may be given by the following equations:

$$Ct = Mt \times Mf \quad (1)$$

$$Co_2 = Mt \times Mf \times Mc \times (44/12) \quad (2)$$

where in Equation (1), Ct is the carbon content of woody biomass (0.5 t C/t dm), Mt is the total biomass (TB) burnt (t dm), Mf is the fraction of biomass oxidized (0.9) and in Equation (2),



CO₂ equals the total CO₂ (t CO₂) released from the fuelwood burning and Mc equals the biomass carbon content (0.5 t C/t dm) (Intergovernmental Panel on Climate Change (IPCC), 2006).

Non-CO₂ gas emissions include CO, CH₄, NO, N₂O, NO_x and will be estimated using the equations (Delmas, 1994).

$$\text{CO emissions (tCO)} = \text{Carbon released (tC)} \times \text{Emission ratio (0.060)} \times 28/12 \quad (3)$$

$$\text{CH}_4 \text{ emissions (tCH}_4\text{)} = \text{Carbon released (tC)} \times \text{Emission ratio (0.012)} \times 16/12, \quad (4)$$

$$\text{NO emissions (tNO)} = \text{Carbon released (tC)} \times \text{Emission ratio (0.121)} \times \text{N/C ratio (0.01} \times 30/14) \quad (5)$$

$$\text{N}_2\text{O emissions (tN}_2\text{O)} = \text{Carbon released (tC)} \times \text{Emission ratio (0.007)} \times \text{N/C ratio (0.01)} \times 44/28 \quad (6)$$

$$\text{NO}_x \text{ emissions (tNO}_x\text{)} = \text{Carbon released (tC)} \times \text{Emission ratio (0.121)} \times \text{N/C ratio (0.01)} \times 46/14 \quad (7)$$

The data on fodder extraction from various agroforestry systems and consumption was based on the daily household extraction/consumption of fodder, which was calculated using Adult Cattle Unit (ACU). The Adult Cattle Unit refers to: 1 cow/bullock = 1 ACU, 1 buffalo = 2 ACU, 1 goat/sheep = 0.5 ACU, 1 calf = 0.75 ACU, 1 horse = 1 ACU, (Khanna, 1982). The data related to extraction of small timber from various types of agroforestry systems for different purposes *i.e.* housing and roofing, cattle shed/store house, rural furniture/packing cases, agricultural implements, fencing and others was calculated. The average length and diameter of the small timber collected and consumed was recorded and volume was determined using Smalian's formula (Gray, 1943) as follows:

$$V = \frac{(S_b + S_t)}{2} \times L \quad (8)$$

Where, S_b and S_t are the basal area of the butt and top end of the bole, L is the length and V the volume of the bole.

The carbon estimation was done using the specific gravity values from available literature (Rajput et al., 1985).

$$\text{Total dry biomass (t)} = \text{Total volume (m}^3\text{)} \times \text{Specific gravity} \quad (9)$$

$$\text{Carbon (t)} = \text{Dry biomass (t)} \times 0.50 \quad (\text{Negi et al., 2003}) \quad (10)$$

2.2.2 Total carbon stock for offset values and potential carbon market

We measured the height and dbh (diameter at breast height) of all trees within sampling quadrats. After laying quadrats, we measured individual trees. Tree height was measured using a Ravi's multimeter. Trees with dbh ≥ 10 cm were considered (Knight, 1963). The growing stock density (GSVD) was estimated using volume tables or volume equations developed by Forest Research Institute (FRI) and Forest Survey of India (FSI) publications for the respective species (Chaturvedi, 1973; Iqbal et al., 2020). The estimated GSVD ($\text{m}^3 \text{ha}^{-1}$) was then converted into above ground biomass density (AGBD) of tree components, which was calculated

by multiplying GSVD of the tree species by appropriate biomass expansion factors, BEF (Brown et al., 1999).

Estimation of tree stem biomass

The following biomass regression was used for estimating stem biomass per tree (Brown et al., 1989):

$$\text{Fruit tree: } Y = \exp\{-2.4090 + 0.9522 \ln(D^2HS)\} \quad (11)$$

Where, Y = biomass per tree in kg, D = dbh in cm for trees and collar diameter for fruit trees, H = tree height in cm and S = wood density ($0.57 \text{ t m}^{-3} = \text{g cm}^{-3}$).

2.2.3 Root biomass

Below ground biomass of forest trees was estimated by using default value of 0.25 for converting above ground biomass into below ground biomass (Schulze, 1983). Below ground biomass of fruit trees was estimated by multiplying the above ground biomass with default root: shoot ratio of 0.33 for converting above ground biomass into below ground biomass (Singh, 2010). Above ground biomass and below ground biomass were added to get the total biomass density (TBD).

2.2.4 Estimation of carbon stock

The calculation of carbon stock was determined by multiplying total biomass by a conversion factor that represents the average carbon content in biomass. The coefficient of 0.45 for the conversion of biomass to carbon was used. Therefore, the total carbon stock (C) present in the calculated total biomass was presented as $C = 0.45 \times \text{Biomass (total)}$ (Woomer, 1999). The mitigation potential of the system has been worked out by calculating equivalent carbon dioxide (CO₂e) as per formula of Dury et al. (2002).

$$\text{CO}_2\text{e} = C \times 3.67 \quad (12)$$

Soil samples with three replicates were collected from each sample quadrat and mixed to form a composite one at each depth. The soil samples were collected from two depths *i.e.*, 0–30 and 30–60 cm, using soil core sampler of dimension 1 inch in diameter and 10 inches in length. A total of 126 soil samples were collected from selected agroforestry systems. Each sample was thoroughly mixed, air dried, grinded with pestle and mortar, sieved through a 2 mm mesh screen. The sieved soil samples were stored in paper bags for chemical analysis. The soil organic carbon stock was estimated by Walkley and Black's rapid titration method (and expressed as mega grams per ha^{-1}) for a specific depth and was computed by multiplying the soil organic carbon with bulk density and depth (Medeiros et al., 2017; Khan et al., 2025).

The total carbon stock (above ground, below ground and soil) is multiplied by the C-CO₂e conversion factor of 3.67 to get Offset/MgCO₂e (tons of carbon dioxide emissions per hectare). In the present study the average price (US\$ 2.5/MgCO₂e) is taken into account as applied by Asian Offset suppliers (Hamrick and Goldstein, 2016) to quantify the carbon trade benefits (Pala et al., 2020).

2.2.5 Statistical analysis

For this study both quantitative and qualitative data analysis technique were used. Descriptive statistics methods such as Shannon and Wiener index for species diversity and Sorensen's Index of similarity were used to analyze the data collected in sample quadrats and Biomass (Quintals/year); Avoided Deforestation Potential (m^3); Carbon content in biomass (t C per t dry matter); Total carbon released; Total carbon-dioxide emissions; Total carbon-monoxide emissions; Total methane emissions; Total nitric oxide emissions; Total nitrous oxide emissions; Total nitrogen oxide emissions for biomass extraction and potential GHG emissions, etc. were presented in MS excel and their means were evaluated.

3 Results

3.1 Agroecological description of various agroforestry systems

A total of seven agroforestry systems viz., Home gardens, Horti-agriculture, Boundary plantation, Horti-silvi-pasture, Horti-silviculture, Horti-silvi-agriculture and Silvi-pastoral systems were identified from the study area (Supplementary material). However, Home gardens, Horti-agriculture and Boundary plantations were found to be practiced by majority of the farmers. In Home gardens, there were 12 prominent trees with Shannon–Weiner index (H') of 2.5 & Simpson's dominance index (D) as 0.08, and 13 crop species ($H' = 2.52$ & $D = 0.08$) were recorded. In Horti-agricultural systems, 7 prominent trees ($H' = 1.99$ & $D = 0.16$), and 8 crops were recorded with values of $H' = 2.02$ & $D = 0.14$ respectively. There were 5 prominent tree species and 3 crops in Boundary plantations, with $H' = 1.53$ & 0.96 and D as 0.23 & 0.41, while in Silvi-pastoral systems, 7 prominent tree species were recorded with the values of $H' = 1.80$ and $D = 0.19$ and 7 prominent grass species ($H' = 1.88$ & $D = 0.16$) were reported. In Horti-silvi-pastoral systems, 11 trees ($H' = 2.16$ & $D = 0.09$) and 5 grass species ($H' = 1.6$ & $D = 0.21$) were recorded. In Horti-silvicultural systems, 10 tree species ($H' = 2.23$ & $D = 0.11$) were recorded and whereas in Horti-silvi-agricultural systems, 10 tree species ($H' = 2.20$ & $D = 0.11$) and 12 crop species ($H' = 2.40$ & $D = 0.09$) were present under this agroforestry system.

3.2 Tree species composition and usage preference

The total number of plant species reported from the present study was 48 belonging to 17 families and 34 genera. Among the total recorded 48 species, trees and agricultural crops were dominating and represented by 19 and 20 species respectively, followed by 9 species of grasses. The reported 19 species of trees were belonging to 9 families and 12 genera, and those of agricultural crops to 8 families and 13 genera. The nine grass species were of 4 families and 8 genera. The species like *Populus deltoides*, *Populus nigra*, *Salix alba* and *Salix fragilis* were found to be highly preferred for fuelwood, fodder and small timber extraction (Figure 2). *Robinia pseudoacacia* was highly preferred

for both fuelwood and fodder and *Ailanthus altissima*, *Ailanthus excelsa*, *Aesculus indica*, *Prunus domestica* and *Prunus armeniaca* were moderately preferred for fodder but had least preference for fuelwood and zero for timber. *Juglans regia* was moderately preferred for timber, least for fuelwood and had zero preference for fodder. The study indicated that most of the tree species under agroforestry were maintained for fuelwood and fodder, and only a few species were providing timber to the households (Figure 3). These tree species produce good fuelwood, nutritive fodder and good amounts of small timber.

3.3 Biomass extraction status and GHG emissions

A total quantity of 143 quintals of biomass extracted from 19 tree species present in these agroforestry systems is utilized for fuelwood, fodder and small timber annually with an average avoided deforestation potential of 75.26 m^3 (Table 1). These 19 species are *Populus deltoides*, *Populus nigra*, *Salix alba*, *Salix fragilis*, *Ulmus wallichiana*, *Ailanthus altissima*, *Ailanthus excelsa*, *Aesculus indica*, *Robinia pseudoacacia*, *Juglans regia*, *Malus domestica*, *Pyrus communis*, *Prunus amygdalus*, *Prunus domestica*, *Prunus armeniaca*, *Punica granatum*, *Prunus persica*, *Diospyros kaki* and *Prunus avium*. The total green house gas (GHG) emissions of 64.35 and 235.95 of tC and tCO_2 are emission potentials of this extracted material. The maximum CO_2 emission was recorded from *Salix alba* (28.05). An average value of 9.009, 1.030, 0.167, 0.007 and 0.256 of tCO, tCH₄, tNO, tN₂O and tNO_x respectively were recorded for non- CO_2 emissions. Among these recorded nineteen species the maximum biomass extraction was reported from *Salix alba* (17 Q/yr) followed by *Populus deltoides* (15 Q/yr) with avoided deforestation potential of (8.95 m^3) and (7.89 m^3) respectively. The minimum quantity of 1 Q/yr is being extracted from *Diospyros kaki* and *Punica granatum* each with avoided deforestation potential of 0.53 m^3 . The maximum CO_2 emission was recorded from *Salix alba* (28.05) because of its higher extraction of biomass. An average value of 9.009, 1.030, 0.167, 0.007 and 0.256 of tCO, tCH₄, tNO, tN₂O and tNO_x respectively were recorded for non- CO_2 emissions.

3.4 Agroforestry system wise biomass extraction and GHG emission

The average highest biomass extraction was recorded for Horti-silvi-pastoral systems (121 Q/yr), followed by Homegardens (101 Q/yr) and whereas, the minimum was recorded for Horti-agricultural systems (29 Q/yr). The highest avoided deforestation potential value of 63.68 Q/yr was recorded for Horti-silvi-pastoral systems, followed by Homegardens (53.16 Q/yr) (Table 2). The minimum avoided deforestation potential was recorded for Horti-agricultural systems (15.26 Q/yr). This indicates that the Horti-silvi-pastoral systems and Homegardens play an important role in avoiding deforestation from the nearby forests in the study area.

The greenhouse gas emissions were recorded maximum for Horti-silvi-pastoral systems (60.50, 54.45 and 199.65 of CB, tC and tCO_2 respectively). The non- CO_2 emissions were recorded

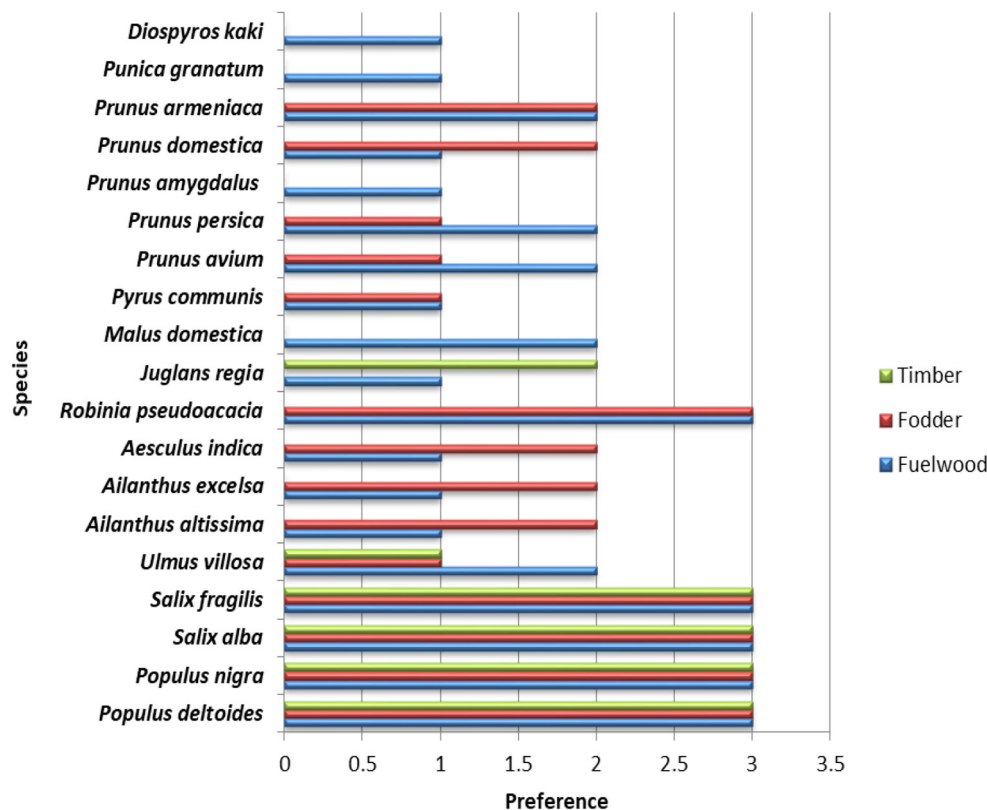


FIGURE 3
Species preference for fuelwood, fodder and small timber.

maximum for Horti-silvi-pastoral systems (7.62, 0.87, 0.14, 0.0060 and 0.216 of tCO₂, tCH₄, tNO_x, tN₂O and tNO_x respectively). Horti-agricultural systems were recorded for minimum values of GHG emissions (14.50, 13.05 and 13.05 of CB, tC and tCO₂ respectively) and minimum non-CO₂ emissions (1.83, 0.21, 0.03, 0.0014 and 0.052 tCO₂, tCH₄, tNO_x, tN₂O and tNO_x respectively respectively).

3.5 Biomass and carbon stock status

Among the nineteen species found in the study area, the maximum total biomass (TB) was recorded for *Juglans regia* with a value of 27.89 tons/ha, followed by *Populus deltoides* (27.65 tons/ha). *Diospyros kaki* with a value of 23.17 tons/ha was recorded for minimum total biomass. In the study area, the total carbon stock was recorded as 216.06 tons/ha. The carbon stock was recorded maximum for *Juglans regia* with a value of 12.55 tons/ha, followed by *Populus deltoides* (12.44 tons/ha). The minimum value of carbon stock was recorded for *Diospyros kaki* (10.43 tons/ha; Table 3).

3.6 Agroforestry system wise carbon stock for offset values

The soil organic carbon was found maximum for Horti-silvi-pastoral systems (39.19 t/ha), followed by Horti-silvicultural

systems (37.57 t/ha) and whereas, minimum was recorded for Boundary plantations (10.79 t/ha) (Table 4). The total carbon stock was recorded maximum for Horti-silvi-pastoral systems (162.70 t/ha), followed by Homegardens (154.17 t/ha). In our study, Homegardens were having the highest tree density as compared to other systems and were thus recorded for highest carbon stock. The minimum total carbon stock was recorded for Boundary plantations (68.27 t/ha). The maximum CO₂ equivalent of 597.12 Mg was recorded for Horti-silvi-pastoral systems and whereas, minimum was recorded for Boundary plantations (250.55 Mg). The highest offset value of US\$ 1492.79/Mg was recorded for Horti-silvi-pastoral systems, followed by Homegardens (US\$1414.51/Mg) and the minimum offset value of US\$ 626.38/Mg was recorded for Boundary plantations.

4 Discussion

4.1 Tree species composition and usage preference

The total number of plant species reported from the different agroforestry systems have proven the fact that these systems are rich in plant diversity and the usage and preference varies from household to household *Juglans regia* was moderately preferred for timber, least for fuelwood and had zero preference for fodder.

TABLE 1 Biomass extraction and potential GHG emissions of the study area.

Tree species	BM (Q/yr)	ADP (m ³)	GHG emissions			Non-CO ₂ emissions				
			CB (tC t dm)	tC	tCO ₂	tCO	tCH ₄	tNO	tN ₂ O	tNO _x
<i>Populus deltoides</i>	15	7.89	7.5	6.75	24.75	0.945	0.108	0.018	0.0007	0.027
<i>Populus nigra</i>	14	7.37	7	6.3	23.1	0.882	0.101	0.016	0.0007	0.025
<i>Salix alba</i>	17	8.95	8.5	7.65	28.05	1.071	0.122	0.02	0.0008	0.03
<i>Salix fragilis</i>	10	5.26	5	4.5	16.5	0.63	0.072	0.012	0.0005	0.018
<i>Ulmus villosa</i>	7	3.68	3.5	3.15	11.55	0.441	0.05	0.008	0.0003	0.013
<i>Ailanthus altissima</i>	10	5.26	5	4.5	16.5	0.63	0.072	0.012	0.0005	0.018
<i>Ailanthus excelsa</i>	6	3.16	3	2.7	9.9	0.378	0.043	0.007	0.0003	0.011
<i>Aesculus indica</i>	4	2.11	2	1.8	6.6	0.252	0.029	0.005	0.0002	0.007
<i>Robinia pseudoacacia</i>	13	6.84	6.5	5.85	21.45	0.819	0.094	0.015	0.0006	0.023
<i>Juglans regia</i>	4	2.11	2	1.8	6.6	0.252	0.029	0.005	0.0002	0.007
<i>Malus domestica</i>	8	4.21	4	3.6	13.2	0.504	0.058	0.009	0.0004	0.014
<i>Pyrus communis</i>	7	3.68	3.5	3.15	11.55	0.441	0.05	0.008	0.0003	0.013
<i>Prunus avium</i>	10	5.26	5	4.5	16.5	0.63	0.072	0.012	0.0005	0.018
<i>Prunus persica</i>	9	4.74	4.5	4.05	14.85	0.567	0.065	0.011	0.0004	0.016
<i>Prunus amygdalus</i>	3	1.58	1.5	1.35	4.95	0.189	0.022	0.004	0.0001	0.005
<i>Prunus domestica</i>	2	1.05	1	0.9	3.3	0.126	0.014	0.002	0.0001	0.004
<i>Prunus armeniaca</i>	2	1.05	1	0.9	3.3	0.126	0.014	0.002	0.0001	0.004
<i>Punica granatum</i>	1	0.53	0.5	0.45	1.65	0.063	0.007	0.001	0	0.002
<i>Diospyros kaki</i>	1	0.53	0.5	0.45	1.65	0.063	0.007	0.001	0	0.002
	143	75.26	71.5	64.35	235.95	9.009	1.03	0.167	0.007	0.256

BM, biomass (quintals/year); ADP, avoided deforestation potential (m³); CB (tC t dm), carbon content in biomass (t C per t dry matter); Tc, total carbon released; tCO₂, total carbon-dioxide emissions; tCO, total carbon-monoxide emissions; tCH₄, total methane emissions; tNO, total nitric oxide emissions; tN₂O, total nitrous oxide emissions; tNO_x, total nitrogen oxide emissions.

TABLE 2 Average agroforestry system wise biomass extraction and potential GHG emissions.

Agroforestry systems	BM (Q/yr)	ADP (m ³)	GHG emissions			Non-CO ₂ emissions				
			CB (tC t dm)	tC	tCO ₂	tCO	tCH ₄	tNO	tN ₂ O	tNO _x
Homegardens	101	53.16	50.50	45.45	166.65	6.36	0.73	0.12	0.0050	0.181
Horti-agricultural system	29	15.26	14.50	13.05	47.85	1.83	0.21	0.03	0.0014	0.052
Boundary plantation	70	36.84	35.00	31.50	115.50	4.41	0.50	0.08	0.0035	0.125
Silvi-pastoral system	94	49.47	47.00	42.30	155.10	5.92	0.68	0.11	0.0047	0.168
Horti-silvi-pastoral system	121	63.68	60.50	54.45	199.65	7.62	0.87	0.14	0.0060	0.216
Horti-silvicultural system	91	47.89	45.50	40.95	150.15	5.73	0.66	0.11	0.0045	0.163
Horti-silvi-agricultural system	88	46.32	44.00	39.60	145.20	5.54	0.63	0.10	0.0044	0.157

BM, biomass (quintals/year); ADP, avoided deforestation potential (m³); CB (tC t dm), carbon content in biomass (t C per t dry matter); tC, total carbon released; tCO₂, total carbon-dioxide emissions; tCO, total carbon-monoxide emissions; tCH₄, total methane emissions; tNO, total nitric oxide emissions; tN₂O, total nitrous oxide emissions; tNO_x, total nitrogen oxide emissions.

In determining how these sytems contribute to conservation of agro-biodiversity, all factors affecting its distribution within and across gardens, its evolution and resilience over time need to be understood that can captures a significant representation of the overall diversity for any given species (Brown and Marshall, 1995; Sharma et al., 2024). Fuel-wood, fodder and timber production is very important for the day-to-day requirements of the rural households, since in the Himalayan region almost ninety percent of fuelwood, fodder and timber demand is met from the agroforestry landuse (Sharma et al., 2005; Islam et al., 2022). The timber from these species is used in a number of purposes in the study area e.g. in the manufacturing of cricket bats, fruit boxes, agricultural implements, pencils, matchsticks etc. The results are in agreement with Anglaaere et al. (2011) and Bayala et al. (2011)

TABLE 3 Biomass and carbon stock status of the study area.

Tree species	AGB (t/ha)	BGB (t/ha)	TB (t/ha)	C stock (t/ha)
<i>Populus deltoides</i>	22.12	5.53	27.65	12.44
<i>Populus nigra</i>	21.03	5.26	26.29	11.83
<i>Salix alba</i>	19.93	4.98	24.92	11.21
<i>Salix fragilis</i>	19.19	4.80	23.99	10.79
<i>Ulmus wallichiana</i>	22.01	5.50	27.51	12.38
<i>Ailanthus altissima</i>	19.71	4.93	24.63	11.08
<i>Ailanthus excelsa</i>	19.35	4.84	24.19	10.89
<i>Aesculus indica</i>	19.86	4.97	24.83	11.17
<i>Robinia pseudoacacia</i>	20.69	5.17	25.86	11.64
<i>Juglans regia</i>	22.31	5.58	27.89	12.55
<i>Malus domestica</i>	18.31	6.04	24.35	10.96
<i>Pyrus communis</i>	19.52	6.44	25.96	11.68
<i>Prunus avium</i>	18.93	6.25	25.18	11.33
<i>Prunus persica</i>	18.71	6.17	24.89	11.20
<i>Prunus amygdalus</i>	17.45	5.76	23.21	10.44
<i>Prunus domestica</i>	18.28	6.03	24.31	10.94
<i>Prunus armeniaca</i>	19.26	6.36	25.62	11.53
<i>Punica granatum</i>	17.64	5.82	23.46	10.56
<i>Diospyros kaki</i>	17.42	5.75	23.17	10.43

AGB, above ground biomass (tons/ha); BGB, below ground biomass (tons/ha); TB, total biomass (tons/ha); Cstock, carbon stock (tons/ha).

TABLE 4 Agroforestry system wise biomass and carbon stock status.

Agroforestry system	C stock (t/ha)	SOC (t/ha)	TC (t/ha)	CO ₂ e (Mg)	OV (US\$/Mg)
Homegardens	128.56	25.61	154.17	565.80	1414.51
Horti-agricultural systems	72.72	17.86	90.58	332.43	831.07
Boundary plantations	57.48	10.79	68.27	250.55	626.38
Silvi-pastoral systems	79.59	22.11	101.70	373.24	933.10
Horti-silvi-pastoral systems	123.51	39.192	162.70	597.12	1492.79
Horti-silvicultural systems	112.54	37.57	150.11	550.90	1377.26
Horti-silvi-agricultural systems	109.14	34.25	143.39	526.24	1315.60

AGB, above ground biomass (tons/ha); BGB, below ground biomass (tons/ha); TB, total biomass (tons/ha); Cstock, carbon stock (tons/ha); SOC, soil organic carbon (tons/ha); TC, total carbon stock (tons/ha); CO₂e, carbon-dioxide equivalent (Megagrams); OV, offset value (US \$/Mg).

who reported that the growing of specific tree species in these agro-ecosystems mainly depends on the utility of the tree species to meet the varied requirements of the farmers and to match the ecological conditions of the area. Agroforestry is mainly based on the natural occurrence of trees and is practiced in the areas to meet diverse needs of fuelwood, fodder, timber, etc from the same unit of land (Banyal et al., 2016). The implementation of integrated agroforestry systems decreases pressure on natural forests, providing farmers with fuelwood, fodder and timber and improvement of livelihood (Russo, 1996; Ahmad et al., 2021).

4.2 Biomass extraction status and GHG emissions

A total quantity of 143 quintals of biomass extracted from the tree component of all the agroforestry systems reveal the fact that these systems have very high potential for mitigating global climate change effects with an average avoided deforestation potential of 75.26 m³. To mitigate the adverse climate change effects, agroforestry is known to have a great potential in the short run through natural resources and microclimate moderation and by sequestering carbon in the long run (Rao et al., 2007;

Khan et al., 2024). High species diversity of agroforestry systems is likely to encourage species which have high resource-utilization characteristics as compared to less diverse systems (Tilman et al., 1997; Chappa et al., 2024), and may increase the net primary productivity, which in turn contributes to greater carbon sequestration. The total green house gas (GHG) emissions of 64.35 and 235.95 of tC and tCO₂ are emission potentials of this extracted material. The maximum CO₂ emission was recorded from *Salix alba* (28.05). An average value of 9.009, 1.030, 0.167, 0.007 and 0.256 of tCO, tCH₄, tNO, tN₂O and tNO_x respectively were recorded for non-CO₂ emissions. The average Greenhouse gas emissions recorded from the sampled area were lowest as compared to the emissions from forest (fuelwood and deforestations). This may be due to the use of advanced techniques and proper management of agroforestry systems. Our studies are in line with Aguilera et al. (2015) who also reported that in organic farms, the combined use of both techniques and management practices resulted in an average emission of 39 g CO₂e/kg, which was comparatively very less as compared to the emissions from forest. Makundi and Sathaye (2004) stated that there are a variety of agroforestry practices that have been in existence in many countries, which can be applied for GHG mitigation. Using agroforestry systems as carbon sinks, the Kyoto Protocol provides new ways of designing a suitable emissions trading system (Walsh, 1999; Nungula et al., 2025).

4.3 Agroforestry system wise biomass extraction and GHG emission

The average highest biomass extraction was recorded for Horti-silvi-pastoral systems (121 Q/yr), followed by Homegardens (101 Q/yr) and whereas, the minimum was recorded for Horti-agricultural systems (29 Q/yr). The highest avoided deforestation potential value of 63.68 Q/yr was recorded for Horti-silvi-pastoral systems, followed by Homegardens (53.16 Q/yr) (Table 2). According to Sharma et al. (2005) most of the farmers of Jabalpur district in Madhya Pradesh, India had adopted agri-silvi-horticulture system (40%) on their farm lands. By doing so, farmers were able to get fuel wood for their daily need and also fruits which they used for increasing their livelihoods. These results are in line with Murthy et al. (2013) who reported that the agroforestry design with a combination of fast and slow growing tree species (Horti-silvicultural, Horti-silvi-pastoral or Horti-silvi-agri-cultural system) is useful, as the different harvesting time of the two species provide wood that is economically useful for construction or other purposes, and fuelwood for burning purposes. Also, the finding of Pala et al. (2020) reported maximum biomass extraction of 150.01 Mg/yr from homegardens of Cooch Behar district of West Bengal, owing to less pressure for fuelwood, fodder and small timber on the nearby forests.

The greenhouse gas emissions were recorded maximum for Horti-silvi-pastoral systems (60.50, 54.45 and 199.65 of CB, tC and tCO₂ respectively). The non-CO₂ emissions were recorded maximum for Horti-silvi-pastoral systems (7.62, 0.87, 0.14, 0.0060 and 0.216 of tCO, tCH₄, tNO, tN₂O and tNO_x respectively). The establishment of higher number of trees in different agroforestry

land use systems can also increase the fuelwood production and avoid the extraction of wood from forests (Ndayambaje et al., 2013; Kinyili, 2022). In India, agroforestry is mainly followed by the local people for meeting their livelihood requirements and also the availability of other services like fuel wood, fodder, etc. (Pala et al., 2020). Borlaug (2007) reported in Mexico that better technology and management practices enable sufficient supply of food, fodder and fuelwood owing to less clearance of forests for agriculture and subsequently avoiding deforestation. The trees on agroforestry systems contributed considerable amount of carbon stock (Ghimire and Bolakhe, 2020), this indicates that agroforestry systems can be one of the important land use systems for reducing greenhouse gas emissions in the atmosphere, and eventually help in climate change mitigation. Agroforestry systems can contribute to reduced CO₂ emissions by avoiding burning of forest-based fuelwood and helping in avoiding deforestation (Murthy et al., 2013; Sahoo et al., 2022). Evidences are emerging that agroforestry systems are promising management practices to increase aboveground and soil carbon stocks to mitigate greenhouse gas emissions (Pandey, 2007). Carbon sequestration in aboveground biomass and greenhouse gas emission reduction associated with avoided deforestation are the major benefits expected from agroforestry systems (Kiyono et al., 2007; Khan et al., 2024).

4.4 Biomass and carbon stock status

Among the nineteen species found in the study area, the maximum total biomass (TB) was recorded for *Juglans regia* with a value of 27.89 tons/ha, followed by *Populus deltoides* (27.65 tons/ha) (Table 3). Divy and Pankaj (2008) and Shukla et al. (2012) in West Bengal found that fallow land and agricultural field sequester 5.86 and 4.73% carbon, respectively, compared to the natural forest of *Shorea robusta*. Recent study by Chauhan et al. (2015) revealed that on poplar based agri-silvicultural system, the total biomass in the system was found to be 113.6% higher than mono-cropping, where net carbon storage was 34.61 tC/ha compared to 18.74 tC/ha in mono-cropping system. It is also stated that the agri-horticulture system while sequestering carbon also provides production of agricultural crops and other economic benefits (Sahoo et al., 2022). Several studies (Sudha et al., 2007; Khan et al., 2024) reported that agroforestry is the best option for climate change mitigation as it sequesters large amounts carbon in vegetation as well as in soil.

4.5 Agroforestry system wise carbon stock for offset values

Henry et al. (2009) reported that different carbon stock in different regions is a result of differences in tree diversity, altitudinal ranges and management practices. The soil organic carbon was found maximum for Horti-silvi-pastoral systems (39.19 t/ha), followed by Horti-silvicultural systems (37.57 t/ha) and whereas, minimum was recorded for Boundary plantations (10.79 t/ha; Table 4). Our results are in line with Martens (2000) and Stefano and Jacobson (2018), who reported that the soils of agroforestry

systems having grass component were having more SOC content as compared to other agroforestry systems. Chauhan et al. (2019) reported that the quantity of SOC content differed over time with species composition, age and geometry of planting. There were noticeable differences of soil organic carbon under different tree species. Soil is also an important component of agroforestry system which reduces CO₂ in the atmosphere (Albrect and Kandji, 2003). The difference in carbon sequestration potential of these blocks may be due to the difference in soil organic carbon content, age of trees and mainly due to the structure of the agroforestry system. Our results are supported by Roshetko et al. (2007) and Hartoyo et al. (2022), who reported that different carbon contents in different agroforestry systems are due to difference in density of tree species. In our study, Homegardens were having the highest tree density as compared to other systems and were thus recorded for highest carbon stock. Goswami et al. (2014) studied agroforestry land use system prevailing on arable and non-arable land in the Kwalkhad watershed of middle Himalayan region of Himachal Pradesh, where Agri-silvi- horticultural systems (14.78 Mg/ha) and Agri-horti-silviculture systems (14.45 Mg/ha) sequestered a high amount of Carbon than silvi-pasture, pure agriculture and grassland alone. The minimum total carbon stock was recorded for Boundary plantations (68.27 t/ha). The maximum CO₂ equivalent of 597.12 Mg was recorded for Horti-silvi-pastoral systems and whereas, minimum was recorded for Boundary plantations (250.55 Mg). Pala et al. (2020) stated that the homegardens have a high potential of carbon sequestration and climate change mitigation. Agroforestry systems provide indirect benefits as carbon sequestration because they decrease the deforestation pressure on natural forests which are actually the largest sinks for carbon (Kumar et al., 2009; Atangana et al., 2013).

The highest offset value of 1492.79 US\$/Mg was recorded for Horti-silvi-pastoral systems, followed by Homegardens (1414.51 US\$/Mg) and the minimum offset value of 626.38 US\$/Mg was recorded for Boundary plantations. The average price of (US\$ 2.5/MgCO_{2e}) is taken into account as applied by Asian Offset suppliers (Pala et al., 2020) to quantify the carbon trade benefits. The maximum carbon sequestration, reduced greenhouse gas emissions and other related benefits could be expected from agroforestry systems (Kiyono et al., 2007; Torres et al., 2017). Kumar et al. (2009) identified landuse systems with high carbon storage capacity and as an alternative mitigation potential of terrestrial carbon sequestration in Nubra Valley (Trans-Himalayan Region) covered with more than 5,75,000 agroforestry plantations (Willow and Poplar). These species have been found to sequester more than 75,000 tons of carbon.

5 Conclusion and recommendation

Horti-silvi-pastoral systems and Homegardens were found to be best in biomass extraction of fuelwood, fodder and timber. In terms of carbon stock and carbon sequestration potential, Horti-silvi-pastoral systems and Homegardens were found to be best as these are more diverse in nature and accumulate both long and short rotation tree species. On an average, a single sampled household helps to sequester 4.7 Mg carbon annually in the present study. Therefore, a cluster-based approach

by bundling together villages in the entire Ganderbal district would result in approximately sequestering 213,196 Mg CO_{2e} and hence would claim US\$ 536,620 per annum. In our study, we found that the species like *Populus deltoides*, *Salix alba*, *Robinia pseudoacacia*, *Malus domestica*, *Prunus avium*, *Prunus armeniaca* and *Prunus persica* were recorded for higher extraction of fodder and fuelwood. Introduction of these species in the less diverse areas of the study area will result in the increase in biodiversity and will provide enough fodder, fuelwood and small timber which will in turn reduce the pressure on the adjoining forests. Farmers could be promoted to adopt systems like Homegardens, Horti-silvi-pastoral and Horti-silvi agricultural systems which are more diverse in nature. These systems will provide maximum benefits to them and will help in improving biodiversity. The present study for estimation of carbon stock and carbon offset values which could act as a baseline for the future implementation of CDM, REDD and REDD++ projects in J&K.

Data availability statement

The original contributions presented in the study are included in this article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/ participants OR patients/participants legal guardian/next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

IF: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. NP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. GB: Data curation, Supervision, Writing – review & editing. MR: Methodology, Project administration, Writing – review & editing. PS: Writing – review & editing. PA: Writing – review & editing. AM: Writing – review & editing. JM: Writing – review & editing. SK: Writing – review & editing. MR: Writing – review & editing. EO: Writing – review & editing. SH: Writing – review & editing.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2025.1707961/full#supplementary-material>

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