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Assessment of Biomass, Carbon stock and Carbon Sequestration Potential of Two Major Land Uses of Mizoram, India

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ABSTRACT

Assessment of biomass, carbon stock and carbon sequestration potential have never been carried out in major land uses of Mizoram. We aimed at comparing the carbon sequestration potential of two major land uses (Shifting agriculture and homegardens) involving 32 sites drawn from different size and age groups so as to understand their role in carbon sink and mitigation process. Biomass in homegardens (HGs) ranged from 116.8 to 278.5 Mg ha^{-1} and 60.0 to 95.2 Mg ha^{-1} in shifting cultivation fallows (SCFs) while the biomass carbon in HGs and SCFs ranged from 59.0 to 140.0 Mg C ha^{-1} and 31.6 to 49.1 Mg C ha^{-1}, respectively. Among the homegardens, the older HGs stored higher biomass than the younger ones while reverse was true for the SCFs. Carbon stock in HGs (291.0 ± 15.4 Mg C ha^{-1}) was higher than in the SCFs (164.1 ± 8.6 Mg C ha^{-1}). Carbon stocks of soil organic carbon (SOC) and living biomass components were significantly ($p<0.05$) higher in HGs than SCFs, while carbon stock of non-living biomass in SCFs was higher than that of HGs. In both HGs and SCFs, a positive increment of living biomass C was observed while the non-living biomass C decreased. Small HGs significantly ($p<0.05$) sequester more carbon than the medium and large sized homegardens. The rate of CO_2 mitigation potential in HGs and SCFs exhibited range of 4.86 to 22.89 and 2.67 to 12.29 Mg ha^{-1} yr^{-1}, respectively.

Key Words: Shifting Agriculture; Homegardens; Carbon Pools; Mitigation Potential; Mizoram

INTRODUCTION

It is generally accepted that green house gases (GHGs) have increased substantially since the beginning of the industrial revolution, and during the middle of the 20th century. Land conversions to agriculture and poor land management practices have been the major contributors to this sharp increase in GHGs (IPCC 2000). However, the need for systematic assessment and improved accuracy of carbon pool has gained importance during recent years. The role of tree based systems in the global carbon balance is widely recognized and determination of carbon sequestration potential through biomass estimation has been the most widely followed and appropriate approach for mitigating elevated concentrations of atmospheric CO_2 (Brown et al. 1989, Brown 1997, Chambers et al. 2001). The quantity of biomass determines the potential amount of C (carbon) that can be added to atmosphere or sequestered on the land when forests are managed for meeting emission targets (Brown et al. 1999). The aboveground biomass is an essential aspect of the studies of carbon stocks and carbon storage potential and also in the carbon balance in the atmosphere.

The concept of carbon sequestration emerged in the 1980s as a response of scientists to the steady increase in the level of carbon dioxide (CO_2) in the atmosphere since 1958. Flint and Richard (1994) were the pioneers in the carbon stock estimation in the south and south-east Asia. Worldwide numerous ecological studies have been conducted to assess carbon stocks based on carbon density of vegetation and soil (Olson et al. 1983, Saugier and Roy 2001). About four times the amount of carbon present in our atmosphere is stored in terrestrial ecosystems, of which about one third is stored above ground and two thirds are stored belowground (Watson et al. 1998, IPCC 2007, Nair et al. 2009).The carbon stock has been assessed in different ways by different researchers (Kishwan et al. 2009) and there is a clear and wide difference in the estimates made by different scientists and ecologists. Kirby and Potvin (2007) also examined evidence for a functional relationship between tree-species diversity and C storage in each land-use type, and also explored how the use of particular tree species by community members could affect C storage.

Carbon (C) sequestration techniques involving CO_2 concentration reduction with socio-economic and environmental gains through well designed and managed agroforestry systems (AFS) having perennial vegetation (trees) can be effective CO_2 sinks sequestering C in above and below ground compartment (Nair et al. 2010). The quantity and quality of residue supplied by above ground compartment in AFS enhance soil organic carbon (SOC) concentration (Oelbermann et al. 2004). The greater soil volume explored by tree roots would enhance belowground organic matter depositions (Howlett et al. 2011). In addition, C stored in the form of biomass could remain in soils or as wood products for a long duration. Reliable and stringent estimates of C sequestration are essential for development of management programmes related to climate change (Watson et al. 2000).

It was reported that thirteen million hectares of forest are deforested annually (FAO 2004), contributing to about 25% of human induced greenhouse gas emissions (IPCC 2007) thus posing deleterious impact on climate, biodiversity loss, soil erosion, and local livelihoods. In the context of climate change and biodiversity loss, the equilibrium between sustainable farming activities and sustainable forest management has yet to be identified. Necessarily, there are trade offs to consider between the conversion of land to economic activities such as agriculture, and the conservation of ecosystem and the services they provide to society (Henry et al. 2009). C sequestration and associated emission reductions from homegarden agroforestry systems and shifting cultivation fallows could be accounted for, thereby generating carbon credits as additional sources of revenue. Thus it became necessary to carry out studies to understand and estimate the biomass, carbon stock stored and carbon sequestration potential of homegardens and shifting cultivation fallows in Aizawl district of Mizoram. The objectives of this study were to quantify the potential of C sequestration by different compartments and also, to identify how C sequestration potential varies with chronosequence of age in HGs and SCFs.

STUDY AREA AND LAND USE TYPES

The study was conducted in four villages, viz. Durtlang, Sairang, Selesih and Tanhril in Aizawl district of Mizoram. The villages were chosen based on the availability of two major land uses - homegardens (HGs) and shifting cultivation fallows (SCFs) practiced in the area. On the basis of age, HGs are further stratified as Young HG (<20 years; n=12) and Old HG (>20 years; n=12). Further, these stratified HGs are grouped according to total landholding size gradient as Small HG (<0.25 ha); Medium HG (0.25- 0.5 ha); and Large HG (>0.5 ha). Similarly, the SCFs are stratified on the basis of the fallow age as Young SCF (< 5 years; n=4) and Old SCF (>5 years, n=4). All together 32 (24 HGs+8 SCFs) land use systems were selected in such a way that at least one category, either from HGs or SCFs are represented from each of the study villages. The area of each sampled HG and SCF were measured using a tape along the boundary and permanent study plots were laid within and marked with paint for reference. Geographical co-ordinates at the centre of these plots were taken using a hand held GPS.

METHODS

Biomass Inventory

Permanent plots were established randomly in differently aged HGs and SCFs. In the homegardens, a homogeneous area of 40 m x 40 m was selected as permanent plot and four sample plots (quadrats) of 0.01 ha (10 m x 10 m) were placed in the site for sampling trees. While in the case of shifting cultivation fallows, a homogeneous area of 100 m x 100 m was selected as permanent plot and four sample plots (quadrats) of 0.04 ha (20 m x 20 m) were placed in the site for sampling trees. All trees exceeding 30 cm girth over bark at breast height (1.37 m) were uniquely identified and tagged, and were measured for girth using a metal tape and height by pole method during November-December 2013 and

November-December 2015. All coarse deadwood biomass (>10 cm diameter), either felled or standing, occurring inside the tree quadrats were also recorded and the degradation status was categorized as freshly cut, moderately decomposed, highly decomposed and burnt (Ngo et al. 2013). Shrubs and bamboo were sampled by laying two 5m x 5m quadrats in each of the tree quadrats. Collar diameter of the shrubs and DBH of the bamboo culms encountered were measured. For litter and undergrowth (i.e. seedlings, saplings, shrubs and herbaceous plants) a destructive sampling approach was followed wherever possible by laying four 1 m x 1 m plots randomly in each of the tree quadrats, and all litter and undergrowth (herbs) samples were collected and measured.

For estimation of tree aboveground biomass, the generic allometric model developed by Chave et al. (2014) was used as,

$$AGB = 0.0673 \times (\rho D^2 H)^{0.976}$$

where, AGB =Aboveground biomass of trees/palms in kg, D = diameter at breast height in cm, H = height of the tree/palm in m, ρ = specific wood density (g cm^{-3}) from World Agroforestry Centre's wood density database (WAC 2014).

Banana tree biomass was estimated following allometric models developed by Armecin and Coseco (2012) as,

$$AGB_b = 5.1164/(1+1343.02\ e^{-0.1550\ D})$$

where, AGB_b =Aboveground biomass banana in kg, D = diameter at breast height in cm,

Shrub biomass was estimated following allometric models developed by Ali et al. (2015) as,

$$\ln(AGB_s) = -3.50 + 1.65\times\ln(D) + 0.842\times\ln(H)$$

where, AGB_s=Aboveground biomass of shrubs in kg, D= Collar diameter in cm, H = Total height in m.

Bamboo biomass is estimated by harvesting bamboo culms samples of different diameter classes. Different component parts of bamboo: leaf, branch, culm and root/rhizome were oven dried till constant weight and biomass was estimated by multiplying with the densities of each diameter class. Likewise, the aboveground biomass of herbs was estimated by harvest method following Misra (1968).

The belowground biomass component were estimated by models developed by Cairns et al. (1997):

$$BGB = \exp[-1.0587 + 0.8836 \times \ln(AGB)]$$

where, BGB and AGB are belowground and aboveground biomass in Mg ha^{-1}.

For standing deadwood, diameter was measured at one end (D_1) as DBH or above the root buttress as appropriate, and height was measured. Diameter at the upper end ($D_{upper} = D_2$) was estimated using the taper function (Chambers et al. 2001). Major branches with over 10 cm diameter are recorded in a similar way. In practice, we rarely encountered standing dead trees with big branches as they fall off quite quickly and so branches were generally measured on the ground. For fallen woody debris, we measured the length and diameter at both ends (D_1, D_2) using a tape measure. Volume of each piece of Coarse Wood Debris was calculated using the 'frustrum of a cone' formula and summed within plots and later expressed in per unit area. Wood density values of the four wood degradation status (i.e., freshly cut, mode-rately decomposed, highly decomposed and burnt) were considered as 0.48 g cm^{-3}, 0.35 g cm^{-3}, 0.25 g cm^{-3} and 0.19 g cm^{-3} respectively (Delaney et al. 1998). All biomass measurements were converted to a per hectare basis (Mg ha^{-1}). Litter floor biomass was estimated from the litter collected from ramdomly laid four 1m x 1m quadrats, and oven dried weight is recorded.

Estimation of Biomass Carbon Stock

In the present study, biomass was calculated as the sum of both above ground and below ground components. AGB comprised of living (trees, shrubs, herbs) and non-living (deadwood and litter). Carbon stock of biomass was estimated as the product of biomass with its carbon content concentration. To convert the above ground biomass of trees, shrubs and deadwood components to carbon, 50 % of the dry mass was assumed to be carbon (Brown 1997, IPCC 2007). The carbon content in herbs and litter components were estimated following ash content method (Negi et al. 2003). For determining ash content, 3 g of oven dried sample was placed in silica crucible and burnt in an electronic muffle furnace at 550 °C for four hours. The ash content left after burning was weighed and carbon content was calculated as:

$$\text{Carbon content (\%)} = 100 - \{\text{Ash (\%)} + 53.28\}$$

Soil Organic Carbon Stock Inventory

Soil samples were collected from the established permanent plots at seasonal intervals (3 seasons: spring, rainy and winter) during 2015 for the analysis of physico-chemical characteristics. In each plot, three sampling points were selected randomly and from each point, soils were collected at four depths: 0-20, 20-50, 50-80, and 80-100 cm. The three subsamples at each plot and depth class were composited to get one composite sample for each depth class per plot. Thus, there were a total of 384 samples (32 plots x 4 depths x 3 seasons) from the four villages which were air-dried, ground, passed through 2 mm sieve and stored in air-tight plastic bags. All the analyses were done by taking three replicates from each depth at a given site. Soil Bulk density was determined by corer method (Brady and Weil 2008). Soil organic carbon concentration of soil samples was examined by Walkley-Black rapid titration method (Walkley and Black 1934). Soil Organic Carbon Stock (Mg C ha^{-1}) was computed by multiplying the SOC concentration in a sample (g C kg^{-1}), with the corresponding depth and bulk density (Mg m^{-3}) and adjusting for the soil volume occupied by coarse fragments (IPCC 2003) as:

$$SOC = \sum_{horizon=1}^{horizon=n} SOC_{horizon} = \sum_{horizon=1}^{horizon=n} \left([SOC] \bullet BulkDensity \bullet Depth \bullet (1 - frag) \bullet 10 \right)_{horizon}$$

where,
SOC = representative soil organic carbon content for the forest type and soil of interest, Mg C ha^{-1}
$SOC_{horizon}$ = soil organic carbon content for a constituent soil horizon, Mg C ha^{-1}
[SOC] = concentration of soil organic carbon in a given soil mass obtained from lab analyses, g C (kg soil)$^{-1}$
Bulk Density = soil mass per sample volume, Mg soil m^{-3})
Depth = horizon depth or thickness of soil layer, m
frag = % volume of coarse fragments/100, dimensionless

Total Carbon and Stock Carbon Sequestration Potential

The total carbon stock in the plot is the sum of biomass carbon and soil organic carbon. Carbon sequestration was estimated by deducting biomass carbon stock values of previous year from proceeding year. C sequestration estimates were converted into CO_2 equivalents for which, carbon stock is multiplied with a factor of 3.6663, which has the basis of atomic weight ratio of CO_2 to C (Rajput et al. 2015).

Data Analysis

Data collected in the study were entered and arranged for analysis using Microsoft Excel 2007 version. Analysis of variance (ANOVA) and LSD post-hoc test were performed to test for significant differences among variables. Figures were prepared using MS EXCEL and SPSS version 17.

RESULTS

Biomass and Carbon Stock

The total biomass and biomass carbon stock were higher in homegardens as compared to shifting cultivation fallows as presented in Figure 1. Total biomass in homegardens ranged from 116.8 to 278.5 Mg ha^{-1} and 60.0 to 95.2 Mg ha^{-1} in shifting cultivation fallows. Biomass carbon in homegardens and shifting cultivation fallows also ranged from 59.0 to 140.0 Mg C ha^{-1} and 31.6 to 49.1 Mg C ha^{-1} respectively. Distribution of biomass in different pools of HGs and SCFs are presented in Figure 2. Living biomass (both aboveground and belowground) and floor litter biomass were significantly ($p<0.05$) higher in HGs than SCFs. However, the presence of more deadwood biomass in SCFs than HGs is reported from the study.

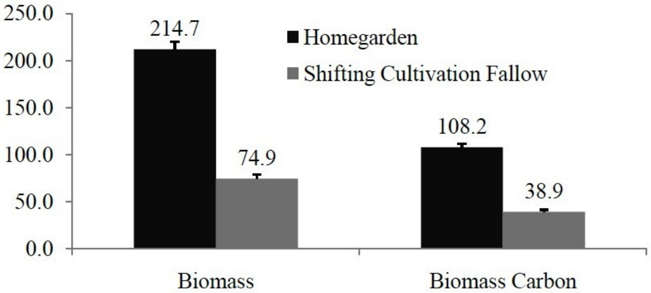

Figure 1. Total biomass (Mg ha^{-1}) and biomass carbon storage (Mg C ha^{-1}) in homegardens and shifting cultivation fallows in Mizoram

The distribution of biomass across major pools in different categories of HGs and SCFs are presented in Table 1. Higher values of biomass were reported in smaller homegardens. Living biomass (aboveground and belowground) values of Large HGs were significantly

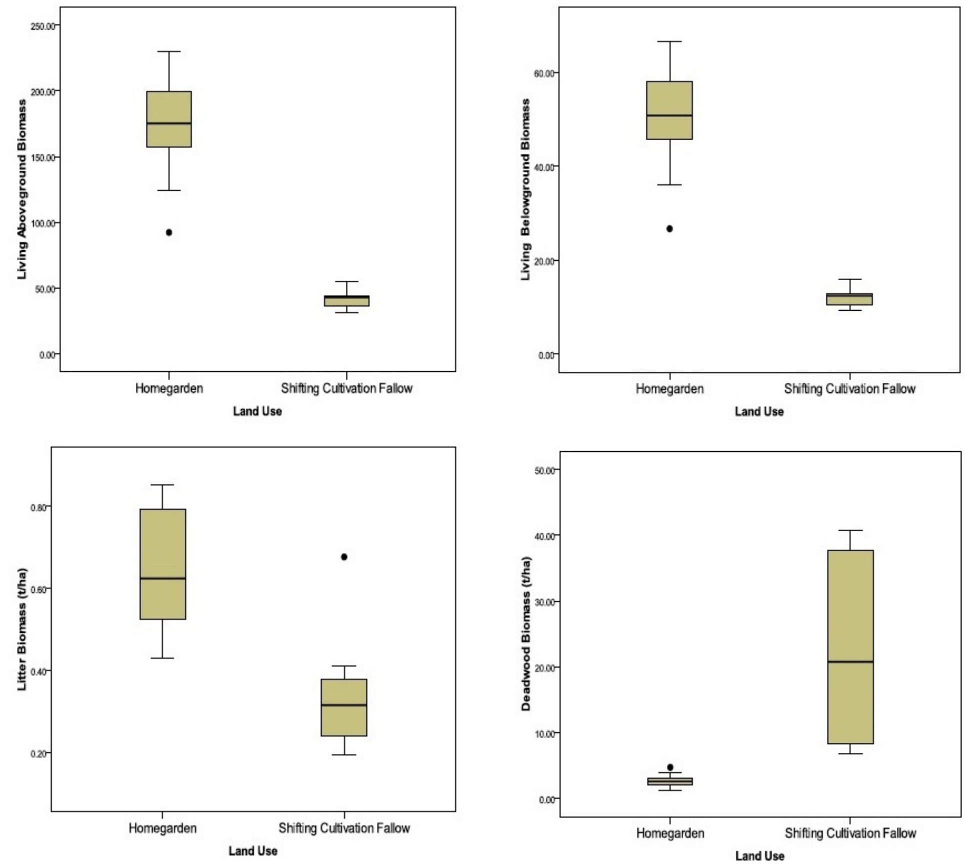

Figure 2. Boxplot representing biomass (Mg ha^{-1}) distribution in different pools in homegardens and shifting cultivation fallows in Mizoram

Table 1.Total biomass (Mg ha^{-1}) in different categories of Homegardens and Shifting Cultivation Fallows in Mizoram

Land-Use Types and Category	Living Biomass Above ground	Living Biomass Below ground	Non-living Biomass	Total Biomass
Large HG	147.5 ± 9.8	30.6 ± 1.7	3.4 ± 0.4	181.5 ± 11.6
Medium HG	180.2 ± 9.3	36.2 ± 1.6	3.2 ± 0.3	219.6 ± 10.8
Small HG	199.0 ± 6.3	39.9 ± 1.0	3.2 ± 0.2	243.0 ± 7.4
LSD ($p<0.05$)	25.2	4.4	0.9	29.8
Old HG	189.6 ± 7.7	37.9 ± 1.3	3.7 ± 0.2	231.1 ± 8.9
Young HG	162.2 ± 9.2	33.2 ± 1.7	2.9 ± 0.2	198.3 ± 10.9
LSD ($p<0.05$)	24.9	4.4	0.6	29.2
Old SCF	46.3 ± 2.9	10.6 ± 0.5	9.4 ± 1.2	66.3 ± 4.6
Young SCF	37.0 ± 2.9	8.7 ± 0.5	36.5 ± 2.5	82.2 ± 5.6
LSD ($p<0.05$)	10.1	1.8	6.8	17.8

± SEM; n= 8 large, medium & small HG; 12 old & young HG, and 4 old & young SCF

($p<0.05$) lower than the Medium and Small HGs. However, no significant differences were observed in the non-living biomass pool of differently sized HGs. Likewise, older HGs stored more biomass than the younger ones, though the difference in their values was not statistically significant. Young SCFs stored more total plant biomass than the Old SCFs. The living biomass pool is higher in older SCFs, while more non-living biomass in the form of deadwood was recorded from young SCFs. Small HGs stored more biomass carbon followed by Medium and Large HGs. Old HGs had more biomass carbon than Young HGs; whereas the Young SCFs exhibited more biomass carbon storage than the Old SCFs (Figure 3).

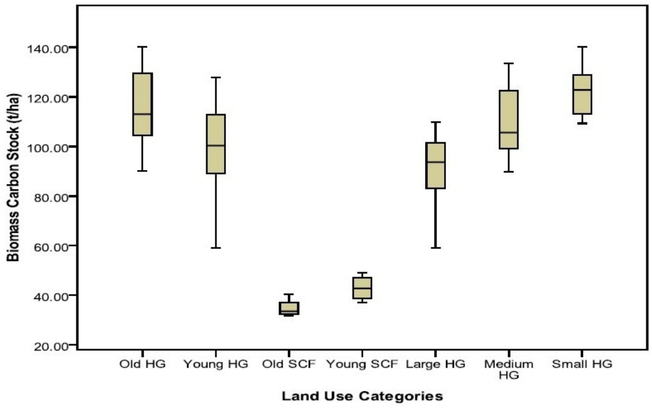

Figure 3. Boxplot of biomass carbon storage (Mg C ha^{-1}) in different categories of homegardens and shifting cultivation fallows in Mizoram

Table 2.Tree biomass and carbon (Mg ha^{-1}) of different girth class in homegardens and shifting cultivation fallows in Mizoram

GBH class (cm)	Homegardens Biomass	Carbon	%	Shifting Cultivation Fallow Biomass	Carbon	%
30-40	2.88	1.44	1.66	2.28	1.14	7.70
40-50	9.67	4.85	5.60	1.62	0.81	5.47
50-60	15.77	7.88	9.09	1.53	0.76	5.14
60-70	29.09	14.55	16.79	2.10	1.05	7.09
70-80	38.18	19.09	22.03	2.47	1.24	8.38
80-90	26.63	13.31	15.36	2.88	1.44	9.73
90-100	18.61	9.31	10.74	3.58	1.79	12.09
100-110	15.71	7.86	9.07	4.21	2.10	14.19
>110	16.73	8.37	9.66	8.92	4.46	30.14
Total	173.29	86.65	100.00	29.60	14.80	100.00

Tree biomass and biomass carbon contribution by different tree girth at breast height (GBH) classes in homegardens and shifting cultivation fallows are presented in Table 2. In HGs, maximum biomass and biomass carbon was observed in 70-80 cm GBH class contributing 19.09 Mg C ha^{-1} (22.03%) and the minimum was contributed from the lowest GBH class (30-40cm) with 1.44 Mg C ha^{-1} (1.66%). In SCFs, maximum tree biomass and biomass carbon was observed in > 110 cm GBH class contributing 4.46 Mg C ha^{-1} (30.14%) and the minimum was contributed from 50-60 cm GBH class with 0.76 Mg C ha^{-1} (5.14 %). As expected, in SCFs, tree biomass and biomass carbon were always higher in greater GBH classes. Figure 4 presents the tree biomass carbon across various categories of HGs and SCFs. Along a size gradient in homegardens, smaller HGs have more tree biomass carbon storage than the medium and large HGs. In both homegardens and shifting cultivation fallows, the older land units stored more tree biomass carbon than the younger ones.

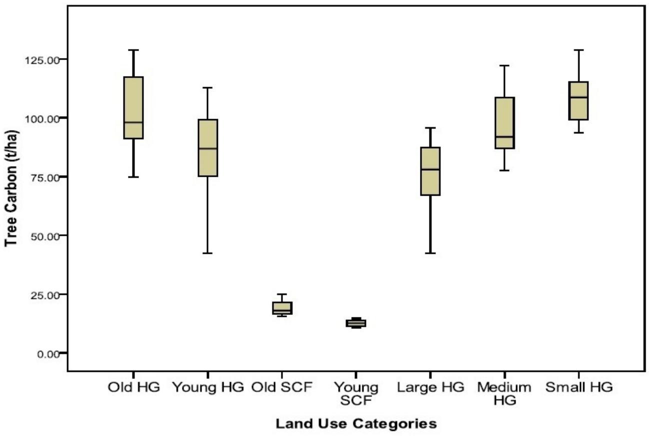

Figure 4. Boxplot of tree biomass carbon storage in different categories of homegardens and shifting cultivation fallows in Mizoram

Biomass distribution in different strata across various categories of homegardens and shifting cultivation fallows were presented in Table 3. In the HGs, small HGs have significantly higher values of bamboo biomass than he medium and large HGs. In shifting cultivation fallows, differences in deadwood biomass (standing and fallen) were significantly different with higher values in young SCFs than the old SCFs. Carbon storage values in different components contributing to biomass in homegardens and shifting cultivation fallows are also presented in Table 4. Carbon stock in trees, shrubs, herbs, banana and floor litter biomass carbon were higher in HGs than SCFs, while bamboo and deadwood biomass carbon stock were more

Table 3. Biomass (Mg ha^{-1}) of different components of homegardens (HG) and shifting cultivation fallows (SCF) in Mizoram

Land Use	Types and Category	Trees	Shrubs	Herbs	Banana	Bamboo					Litter			Deadwood		
						Leaf	Branch	Culm	Rhizome	Total	Leaf	Non Leaf	Total	Standing	Fallen	Total
HG	Large	140.2	35.6	1.08	0.49	0.04	0.05	0.43	0.14	0.65	0.19	0.55	0.74	0.21	2.48	2.69
	Medium	179.2	35.6	0.94	0.51	0.01	0.01	0.13	0.04	0.19	0.24	0.33	0.57	0.37	2.32	2.68
	Small	200.5	33.0	1.15	0.40	0.27	0.34	3.09	0.99	4.69	0.24	0.42	0.66	0.34	2.22	2.56
	LSD @5%	28.1	4.2	0.16	0.38	0.13	0.17	1.50	0.48	2.28	0.05	0.11	0.13	0.31	0.75	0.84
	Old	188.6	36.3	1.00	0.38	0.07	0.09	0.77	0.25	1.18	0.25	0.45	0.70	0.56	2.42	2.98
	Young	158.0	45.4	1.12	0.55	0.14	0.18	1.65	0.53	2.51	0.20	0.41	0.61	0.05	2.25	2.30
	LSD @ 5%	28.4	25.5	0.14	0.29	0.14	0.18	1.63	0.52	2.48	0.04	0.12	0.11	0.12	0.60	0.60
SCF	Old	35.4	17.2	0.47	0.05	0.28	0.36	3.24	1.04	4.92	0.08	0.36	0.44	5.83	3.16	9.0
	Young	23.8	16.6	0.61	0.05	0.34	0.43	3.87	1.24	5.88	0.06	0.18	0.25	28.88	7.38	36.3
	LSD@5%	9.94	12.1	0.18	0.11	0.39	0.49	4.42	1.42	6.71	0.03	0.24	0.21	5.35	1.67	6.9

LSD- Least Significant Difference

Table 4. Biomass carbon (Mg C ha^{-1}) and its percentage distribution in different components of homegardens and shifting cultivation fallows in Mizoram

Land-Use Types	Trees	Shrubs	Herbs	Bamboo	Banana	Litter	Deadwood	Total
Homegardens	86.6 ± 3.7 (80.52 %)	17.4 ± 0.4 (16.18 %)	0.40 ± 0.01 (0.37 %)	1.35 ± 0.43 (1.26 %)	0.22 ± 0.03 (0.20 %)	0.26 ± 0.02 (0.24 %)	1.32 ± 0.08 (1.23 %)	107.6 ± 3.9 (100.00 %)
Shifting Cultivation Fallows	14.8 ± 1.4 (38.07 %)	8.4 ± 1.2 (21.71 %)	0.20 ± 0.02 (0.53 %)	3.95 ± 0.93 (10.16 %)	0.02 ± 0.009 (0.05 %)	0.14 ± 0.02 (0.37 %)	11.32 ± 2.66 (29.12 %)	38.9 ± 2.2 (100.00 %)
LSD @ 5 %	13.4	2.0	0.06	1.90	0.12	0.06	3.04	14.1

± SEM; * Figures within brackets indicate the percentage of the total; LSD- Least Significant Difference

in SCFs than the HGs. It was also observed that tree biomass carbon contributed the maximum to biomass carbon storage with values of 80.52 % and 38.07 % in HGs and SCFs respectively. Deadwood biomass carbon contributed 29.12.51 % and 1.23 % to total biomass carbon in SCFs and HGs respectively.

Carbon storage in different components in homegardens and shifting cultivation fallows are presented in Figure 5. Carbon stock in homegardens (291.0±15.4 Mg C ha^{-1}) was higher than the shifting cultivation fallows (164.1±8.6 Mg C ha^{-1}). Carbon stock in SOC and living biomass components were significantly ($p<0.05$) higher in HGs than SCFs, while carbon stock of non-living biomass in SCFs was higher than that of HGs. Carbon stored in different components across various categories of homegardens and shifting cultivation fallows are given in Table 5. Figure 6 shows the total carbon stock stored in different categories of homegardens and shifting cultivation fallows. Older HGs and SCFs stored higher carbon than the younger ones. In HGs, small HGs

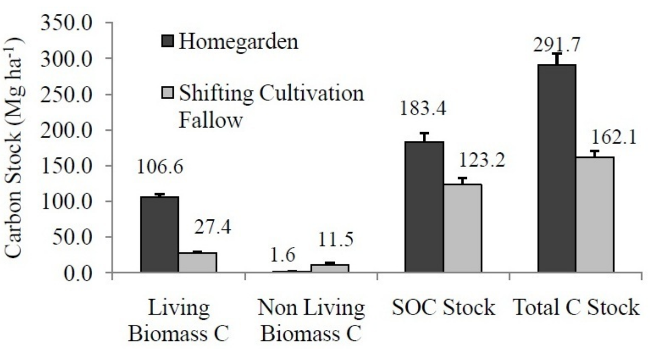

Figure 5. Carbon storage in different components of homegardens and shifting cultivation fallows in Mizoram

Table 5. Carbon Stock (Mg C ha^{-1}) in different components of Homegardens (HG) and Shifting Cultivation Fallow (SCF) in Mizoram

Land-Use Types and Category		Living Biomass Above Ground	Living Biomass Below Ground	Non living Biomass	SOC Stock (0-100 cm)
HG	Large HG	73.6 ± 4.9	15.4 ± 0.7	1.6 ± 0.2	144.6 ± 15.0
	Medium HG	90.0 ± 4.6	18.1 ± 0.8	1.6 ± 0.1	176.2 ± 16.9
	Small HG	99.7 ± 3.1	21.1 ± 0.6	1.5 ± 0.1	229.5 ± 21.4
	LSD (p<0.05)	12.7	2.2	0.8	52.9
	Old HG	94.6 ± 3.8	19.2 ± 0.7	1.8 ± 0.1	224.2 ± 15.8
	Young HG	80.9 ± 4.6	17.2 ± 1.0	1.4 ± 0.1	142.6 ± 9.2
	LSD (p<0.05)	12.4	2.5	0.3	37.8
SCF	Old SCF	23.1 ± 1.5	7.0 ± 0.2	4.7 ± 0.6	144.3 ± 11.5
	Young SCF	18.5 ± 1.5	6.2 ± 0.4	18.2 ± 1.3	102.6 ± 3.6
	LSD (p<0.05)	5.2	1.1	3.4	29.5

± SEM; n= 8 large, medium & small HG; 12 old & young HG, and 4 old & young SCF; LSD- Least Significant Difference

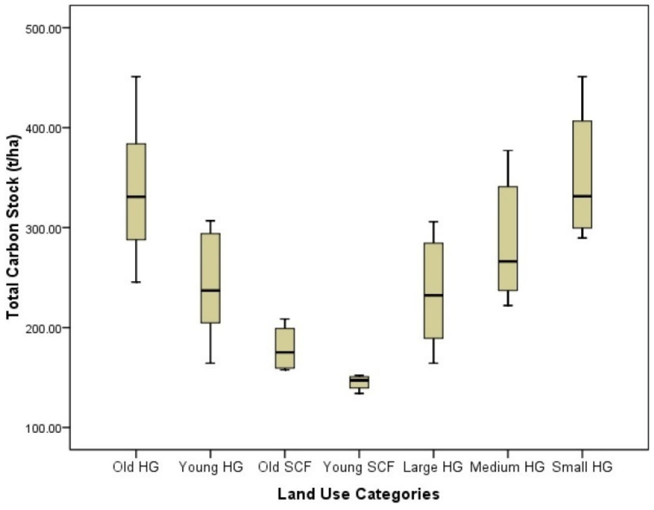

Figure 6. Boxplot of total carbon storage in different categories of homegardens and shifting cultivation fallows in Mizoram

Table 6. Relationship (Pearson's correlation coefficient) between tree biodiversity and Tree Carbon Stock in homegardens (HGs) and shifting cultivation fallows (SCFs) in Mizoram

Variables	Total Data Set (n=32)	HGs (n= 24)	SCFs (n= 8)
Basal Area (m^2 ha^{-1})	0.990**	0.964**	0.923**
Tree Density (trees ha^{-1})	0.846**	0.205^{ns}	0.925**
Simpson Dominance Index	0.022^{ns}	- 0.597^{ns}	- 0.512^{ns}
Shannon Weiner Diversity Index	0.053^{ns}	0.601**	0.574^{ns}
Pielou's Evenness Index	- 0.075^{ns}	0.375^{ns}	0.047^{ns}
Margalef's Species Richness Index	- 0.105^{ns}	0.608**	0.466^{ns}

** - $p < 0.01$; ^{ns} – $p > 0.05$ (not significant)

stored highest carbon followed by medium and large homegardens. Based on the tree diversity and tree carbon stock in homegardens and shifting cultivation fallows, relationship between these parameters is given in Table 6 and Figure 7. Tree basal area, density and Shannon Weiner Diversity Index showed a positive correlation with the tree carbon stock.

Carbon Sequestration Potential

Carbon sequestration in the homegardens and shifting cultivation fallows were estimated 3.04 ± 0.26 and 2.64 ±0.31 Mg C ha^{-1} yr^{-1} (Figure 8). The values exhibited a range of 0.31 to 5.23 and -0.31 to 2.28 Mg C ha^{-1} yr^{-1} in HGs and SCFs respectively. In both HGs and SCFs, a positive increment of living biomass C was observed while the non living biomass C decreased. The increment of tree basal area and carbon stock during the study period (2013-15) is presented in Figure 9. Among different GBH classes, maximum basal area and carbon increment was observed in 60-90 cm (0.79 m^2 ha^{-1} yr^{-1}) and 90-120 cm (0.69 m^2 ha^{-1} yr^{-1}) trees in homegardens and shifting cultivation fallows respectively. Rate of C sequestration and CO$_2$ mitigation potential of various categories of HGs and SCFs from the study are presented

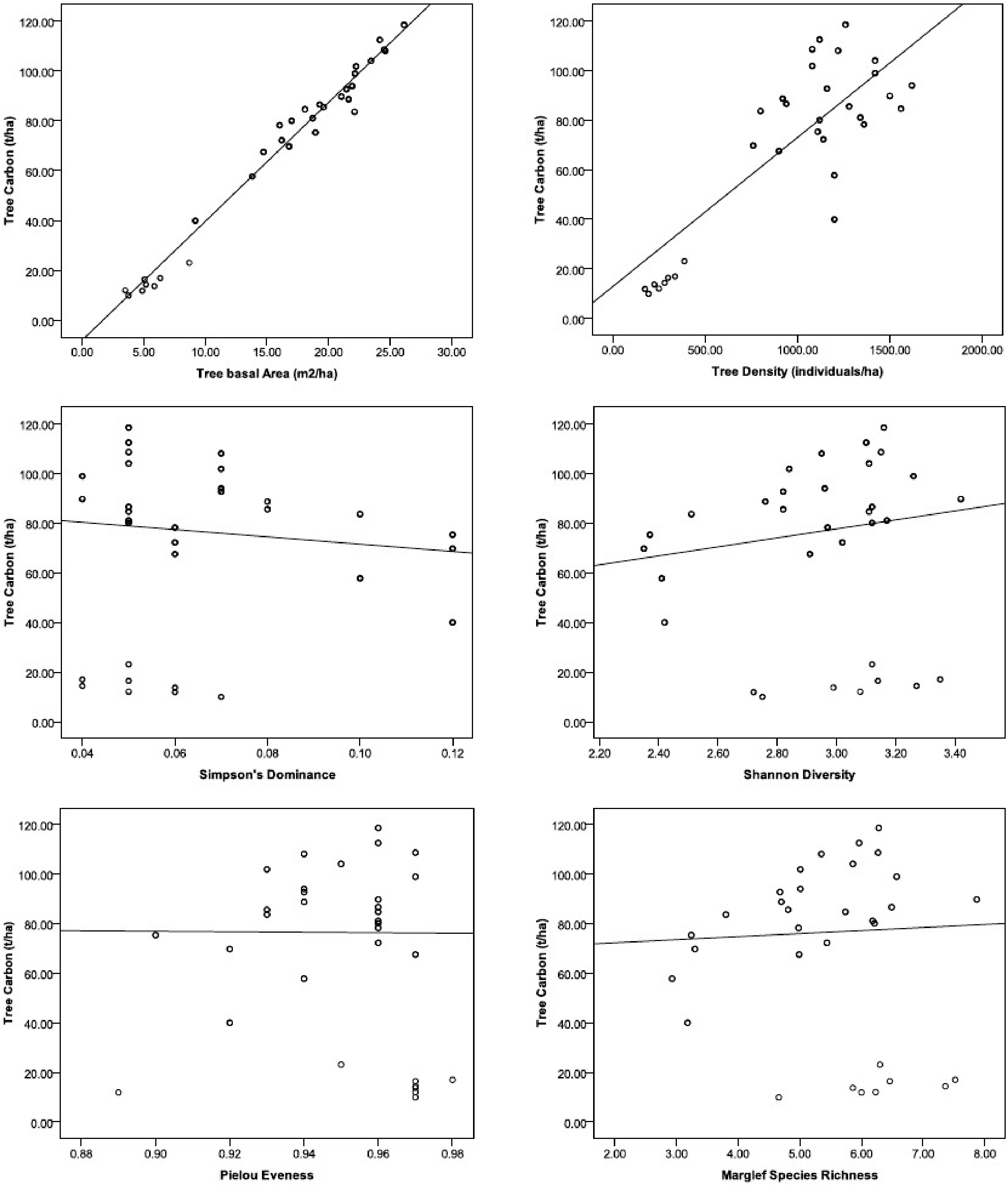

Figure 7. Relationship between tree carbon stock and tree structural diversity indices (n=32) in homegardens (HG) and shifting cultivation fallows (SCF) in Mizoram

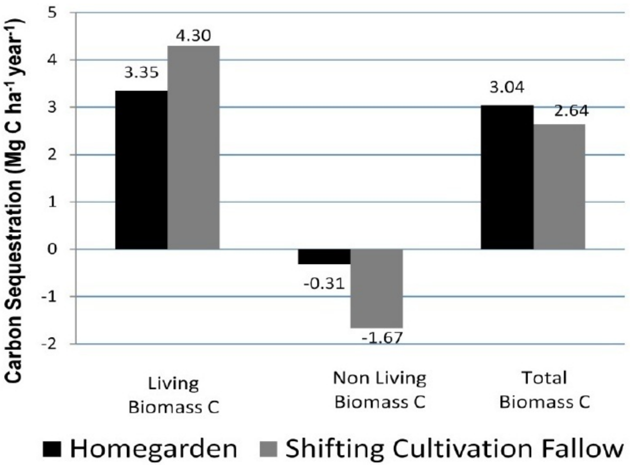

Figure 8. Carbon sequestration rate (Mg C ha^{-1} yr^{-1}) in different pools of homegardens and shifting cultivation fallows in Mizoram

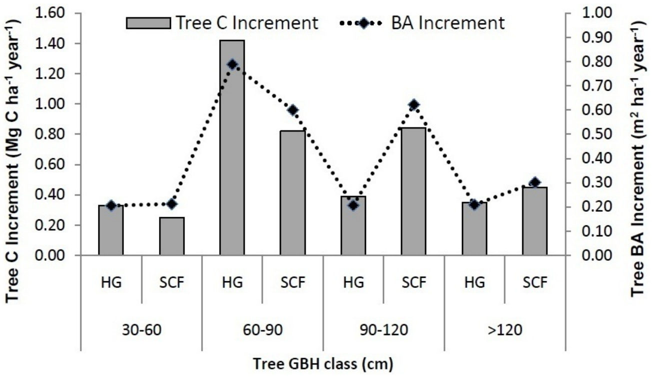

Figure 9. Basal area (m^2 ha^{-1} yr^{-1}) and Carbon Increment (Mg C ha^{-1} yr^{-1}) of trees in different GBH class of homegardens (HG) and shifting cultivation fallows (SCF) in Mizoram

Table 7. C sequestration (Mg C ha^{-1} yr^{-1}) and CO_2 mitigation potential (Mg ha^{-1} yr^{-1}) in various categories of homegardens (HG) and shifting cultivation fallows (SCF) in Mizoram

Land-Use Types and Category		Rate of C Sequestration			CO_2 mitigation potential
		Living biomass C	Non-living biomass C	Total Biomass C	
	Large HG	2.86 ± 0.4	- 0.32 ± 0.2	2.54 ± 0.3	9.31 ± 1.3
HG	Medium HG	2.83 ± 0.2	- 0.37 ± 0.2	2.46 ± 0.3	9.02 ± 1.1
	Small HG	4.35 ± 0.4	- 0.23 ± 0.4	4.11 ± 0.4	15.08 ± 1.6
	LSD (p<0.05)	1.2	0.86	0.8	4.04
	Old HG	3.18 ± 0.4	- 0.42 ± 0.1	2.76 ± 0.4	10.12 ± 1.5
	Young HG	3.52 ± 0.3	- 0.20 ± 0.1	3.32 ± 0.3	12.16 ± 1.2
	LSD (p<0.05)	1.00	0.35	1.07	3.91
	Old SCF	3.92 ± 0.6	- 1.42 ± 0.1	2.50 ± 0.6	9.17 ± 2.2
SCF	Young SCF	4.69 ± 0.6	- 1.91 ± 0.4	2.77 ± 0.3	10.17 ± 1.0
	LSD (p<0.05)	2.05	0.89	1.59	5.84

± SEM; n= 8 large, medium & small HG; 12 old & young HG, and 4 old & young SCF

in Table 7. Small HGs significantly ($p<0.05$) sequester more carbon than the medium and large sized homegardens. During the study period, non living biomass components decreased in both homegardens and shifting cultivation fallows. Amongst the HGs, CO2 mitigation potential was found highest in small HGs (15.05±1.6 Mg ha^{-1} yr^{-1}) followed by large and medium HGs. In both HGs and SCFs, younger systems showed higher sequestration and miti-gation potential, though not statistically significant at $p<0.05$. The rate of CO_2 mitigation potential in HGs and SCFs exhibited range of 4.86-22.89 and 2.67-12.29 Mg ha^{-1} yr^{-1} respectively. Younger HGs and SCFs showed greater potential to mitigate CO_2 than the older ones.

DISCUSSION

The allometric models and sampling approach used may introduce errors in the estimates of carbon, and thus both may have substantial influences on the results of groundbased biomass estimates (Brown 1997, Ketterings et al. 2001, Chave et al. 2005). Locally developed and calibrated allometeric models have the potential to minimize this uncertainty in biomass carbon accounting (Chave et al. 2005). In our study, we used the most recent allometric model developed by Chave et al. (2014) for estimating living woody biomass in tropical forests. The model developed by Chave et al. (2014) is reported to underestimate the aboveground living biomass by 20% when observed biomass exceeded 30 Mg for individual stems, although this trend disappears when a stem's biomass is between 10-30 Mg (Chave et al. 2014). The average biomass carbon stock of homegarden in Aizawl district of Mizoram is found to be 107.6 Mg C ha^{-1} which ranged from 61.0Mg C ha^{-1} (Young and large HG) to 141.6 Mg C ha^{-1} (Old and Small HG). As has already been expressed that small homegarden had higher amount of biomass carbon (122.3 Mg C ha^{-1}) than medium (109.7 Mg C ha^{-1}) and large (90.6 Mg C ha^{-1}) homegardens respectively. On an average, old HGs stored more biomass carbon (115.6 Mg C ha^{-1}) than the young HGs (99.5 Mg C ha^{-1}). The average biomass carbon stocks presently reported are higher than Javanese homegarden (58.6 Mg C ha^{-1}) as well as mature (>35-yr old) agroforestry systems (101 Mg C ha^{-1}) in Indonesia (Jensen 1993, Roshetko et al. 2002). The variability among the homegardens in this respect may be because of differences in plant composition, site characteristics, management practices, and holding sizes in different physiographic zones. Size of the homegardens was a major factor affecting carbon stock per unit area and in the present study C stock gradually decreased in the order of small > medium > large homegarden. Similar result was reported by Saha et al. (2009) in the homegarden of Thrissur, Kerala, India.

In the present study, results showed that shifting cultivation fallows are significant sinks for biomass carbon. On an average, 34.8and 42.9 Mg C ha^{-1} biomass carbon was reported from old and young SCFs respectively in Aizawl district of Mizoram. The coarse deadwood biomass in young SCF is more than the old SCF, and it constitutes a major part of the biomass carbon. This is largely due to the long disturbance (and use) history and the large remaining amount of deadwood on sites after being used for shifting cultivation (Eaton and Lawrence 2009). However, Orihuela-Belmonte et al. (2013) have found that in Mexico coarse deadwood biomass carbon is higher in older fallow areas and also significantly different across sites of different fallow age. A relatively greater contribution of older fallow areas over young fallow areas was observed in terms of carbon storage in trees indicating the age dependence of forest biomass or C stocks (Peichl and Arain 2006, Taylor et al. 2007). It is however clear from our study that living tree biomass is the most vulnerable carbon pool in tropical secondary forests. A similar observation is also made by Kotto-Same et al. (1998). Our results indicate that tree basal area and density have significant and positive relationship with carbon stock in the HGs and SCFs in Aizawl, Mizoram which is in conformity with the findings of Murali et al. (2005), Mani and Parthasarathy (2007), Kumar and Nair (2011) and Borah et al. (2013). Shannon Weiner diversity of trees showed positive relation with carbon stock as reported by several authors (Vila et al. 2007). Caspersen and Pacala (2001) found a positive relationship between carbon storage and tree species diversity. However, other studies have produced contrasting results reporting negative relationships (Firn et al. 2007, Jacob et al. 2010), which might have occurred due to the complexity of ecosystem structure and function (Wang et al. 2011). Nevertheless, the findings from this study supports and states that carbon stock increased with increasing tree species diversity in homegardens and shifting cultivation fallows in Aizawl district of Mizoram.

In the present study, homegardens and shifting cultivation fallows sequester 3.02 and 2.64 Mg C ha^{-1} yr^{-1} respectively. Jarecki and Lal (2003) reported above-ground biomass C sequestration potential range of 0.98-6.7 Mg C ha^{-1} yr^{-1} in the agroforestry systems and 2-4 Mg C ha^{-1} yr^{-1} for tree plantations in degraded tropical areas. Biomass C sequestration in this study is comparable to C sequestration in different tree based systems of Central Himalayan Tarai region with estimation range of 0.56-4.34 Mg C $ha^{-1}yr^{-1}$ (Kanime et al. 2013). Watson et al. (2000) estimated C sequestration rate for agroforestry systems of 0.72 Mg C ha^{-1} yr^{-1}. The variability in the C stock of different land use systems depends on several factors including age, the structure and the way the system is managed (Albrecht and Kandji 2003). CO_2 mitigation potential of HGs and SCFs from the present study is comparable to estimates of different land use systems along an altitudinal gradient in north-western Himalayas with maximum value of 7.81 Mg ha^{-1} yr^{-1} in the orchard + cereal based land use system (Rajput et al. 2015).

CONCLUSION

The present study reveals that homegardens store more biomass carbon than shifting cultivation fallows in Aizawl district of Mizoram. There were differences in biomass with respect to size and age variation in the homegardens. Small land holding size homegardens tend to store more carbon than the medium and large homegardens. Also, older homegardens exhibit more biomass carbon storage than young homegardens. The homegardens resemble young secondary forests in structure and biomass accumulation, and may be considered as a human-made forest kept in a permanent early successional state with considerable productive potential. The results from shifting cultivation fallows also proved themselves as important carbon sinks in tropical ecosystems. Allowing development of such secondary re-growth has clear potential for carbon storage in the aboveground forest biomass. Biomass carbon distribution differs across sites with different fallow ages, and larger amount of carbon is stored in living woody biomass in older fallow areas indicating the dynamic nature of the landscape and succession development towards undisturbed forests. In young SCF, large amounts of carbon are stored in coarse deadwood material which ultimately provided inputs to the soil for biomass accumulation in living trees. These regenerating secondary forests (SCFs) have the potential to mitigate the impacts tropical deforestation and degradation and to contribute to global carbon sequestration.

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REFERENCES

Albrecht, A. and Kandji, S.T. 2003. Carbon sequestration in tropical agroforestry systems. Agriculture, Ecosystems and Environment 99: 15-27.

Ali, A.; Xu, M.S.; Zhao, Y.T.; Zhang, Q.Q.; Zhou, L.L.; Yang, X.D. and Yan, E.R. 2015.Allometric biomass equations for shrub and small tree species in subtropical China. Silva Fennica 49: 1-10.

Armecin, R.B. and Coseco, W.C. 2012. Abaca (Musa textilis Nee) allometry for above-ground biomass and fiber production. Biomass and Bioenergy 46: 181-189.

Borah. N.; Nath, A.J. and Das, A.K. 2013. Aboveground biomass and carbon stocks of tree species in tropical forests of Cachar District, Assam, Northeast India. International Journal of Ecology and Environmental Sciences 39: 97-106.

Brady, N.C. and Weil, R.R. 2008. The Nature and Properties of Soils, 14th edition. Pearson Education, New Jersey. 980 pages.

Brown, S. 1997. Estimating Biomass and Biomass Change of Tropical Forests: A Primer. FAO forestry paper 134, Food and Agriculture Organization, Rome. 55 pages.

Brown, S.; Gillespie, A. and Lugo, A. 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science 35: 881-902.

Brown, S. L.; Schroeder. P. and Kem.J.S. 1999. Spatial distribution of biomass in forests of the eastern USA. Forest Ecology and Management 123: 81-90.

Capersen, J.P. and Pacala, S.W. 2001. Successional diversity and forest ecosystem function. Ecological Research 16: 895-903.

Chambers, J.Q.; dos Santos, J.; Ribeiro, R.F. and Higuchi, N. 2001. Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest. Forest Ecology and Management 152: 73-84.

Chave, J.; Andalo, C.; Brown, S.; Cairns, M.A.; Chambers, J.Q.; Eamus, D.; Folster, H.; Fromard, F.; Higuchi, N.; Kira, T.; Lescure, J.P.; Nelson, B.W.; Ogawa, H.; Puig, H.; Riera, B. and Yamakura, T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145: 87-99.

Chave, J.; Rejou-Mechain, M.; Burquez, A.; Chidumayo, E. and Colgan, M.S. 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Global Change Biology 20**:** 3177-3190.

Delaney, M.; Brown, S.; Lugo, A.E.; Torres-Lezama, A. and Quintero, N.B. 1998. The quantity and turnover of dead wood in permanent forest plots in six life zones of Venezuela. Biotropica 30: 2-11.

Eaton, J.M. and Lawrence, D. 2009. Loss of carbon sequestration potential after several decades of shifting cultivation in the Southern Yucatan. Forest Ecology and Management 258: 949-958.

FAO (Food and Agriculture Organization of the United Nations). 2004. Carbon Sequestration in Dryland Soils. World Soil Resources Report No.102. Rome, Italy. 129 pages.

Firn, J.; Erskine, P.D. and Lamb, D. 2007. Woody species diversity influences rates of soil carbon and nitrogen availability in tropical plantations. Oecologia 154: 521-533.

Flint, P.E. and Richards, J.F. 1994. Historic land use and carbon estimates for South and Southeast Asia 1880-1980. ORNL/CDIAC- 61, NDP-046, Oak Ridge National Laboratory, Tennessee, USA. 326 pages.

Henry, M.; Tittonell, P.; Manlay, R. J.; Bernoux, M.; Albrecht, A. and Vanlauwe, B.2009. Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. Agriculture, Ecosystems and Environment 129: 238-252.

Howlett, D.S.; Mosquera-Losada, M.R.; Nair, P.K.R.; Nair, V.D. and Rigueiro-Rodriguez, A.2011.Soil C storage in silvopastoral systems and a treeless pasture in northwestern Spain. Journal of Environmental Quality 40: 784-790.

IPCC (International Panel on Climate Change) 2000. Land Use, Land-Use Change, and Forestry. Special Report. Summary for Policy Makers. IPCC, Geneva, Switzerland. 20 pages.

IPCC (International Panel on Climate Change) 2003. LUCF sector good practice guidance. Pages 3.1-3.312, In: Penman, J.; Gytarsky, M.; Hiraishi, T.; Krug, T.; Kruger, D.; Pipatti, R.; Buen-dia, L.; Miwa, K.; Ngara, T.; Tanabe, T.; Wagner, F. (Editors), IPCC Good practice guidance for LULUCF. IPCC National Greenhouse Gas Inventories Programme, and Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan.

IPCC (International Panel on Climate Change). 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Appendix 1: Glossary. Parry. M.L.; Canziani, O.F.; Palutikof. J.P.; van der Linden. P.J. and Hanson. C.E. (Editors). Cambridge University Press, Cambridge. 976 pages.

Jacob, M.; Leuschner, C. and Thomas, F.M. 2010. Productivity of temperate broad leaved forest stands differing in tree species diversity. Annals of Forest Science 67: 503p1-503p9.

Jarecki, M.K. and Lal,R.. 2003. Crop management for soil carbon sequestration. Critical Reviews in Plant Sciences 22:471-502.

Kanime, N.; Kaushal, R.; Tewari, S.K.; Raverkar, K.P.; Chaturvedi, S. and Chaturvedi, O.P. 2013. Biomass production and carbon sequestration in different tree-based systems of Central Himalayan Tarai region. Forests, Trees and Livelihoods 22: 38-50.

Ketterings, Q.M.; Coe, R.; van Noordwijk, M.; Ambagau, Y. and Palm, C.A. 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. Forest Ecology and Management, 146: 199-209.

Kirby. K. R. and Porviu, C. 2007. Variation in carbon storage among tree species: Implications for the management of a small-scale carbon sink project. Forest Ecology and Management 246: 208 -221.

Kishwan.J, Pandey, R. and Dadhwal, V.K. 2009. India's Forest and Tree Cover: Contribution as a Carbon Sink. Indian Council of Forestry Research and Education Technical Paper. ICFRE, Dehradun. 12 pages.

Kotto-Same, J.; Woomer, P.L.; Appolinaire, M and Louis, Z. 1998. Carbon dynamics in slash-and- burn agriculture and land use alternatives of the humid forest zone in Cameroon. Agriculture, Ecosystems and Environment 65: 245-256.

Kumar, B.M. and Nair, P.K.R. (Editors). 2011. Carbon Sequestration Potential of Agroforestry Systems. Springer, Dordrecht, Netherlands. 377 pages.

Mani. S. and Parthasarathy, N. 2007.Above-ground biomass estimation in ten tropical dry evergreen forest sites of peninsular India. Biomass and Bioenergy 31: 284-290.

Misra, R. 1968. Ecology Workbook. Oxford and IBH Publishing, New Delhi. 242 pages.

Murali, K.S.; Bhat. D.M. and Ravmdranath, N.H. 2005. Biomass estimation equation for tropical deciduous and evergreen forests. International Journal of Agricultural Resources, Governance and Ecology 4: 81 -92.

Nair, P.K.R.; Nair, V.D.; Kumar, B.M. and Showalter, J.M. 2010. Carbon sequestration in agroforestry systems. Advances in Agronomy 108: 237-307.

Nair. P.K.R.; Kumar, B.M. and Nair, V.D. 2009. Agroforestry as a strategy for carbon sequestration. Journal of Plant Nutrition and Soil Science 172: 10-23.

Negi, J.D.S, Manhas, R.K. and Chauhan, P.S. 2003.Carbon allocation in different components of some tree species of India: a new approach for carbon estimation. Current Science 85: 1528-1531.

Ngo, K.M.; Turner, B.L.; Muller-Landau, H.C.; Davies, S.J.; Larjavaara, M.; Nik Hassan, N.F. and Lum, S. 2013. Carbon stocks in primary and secondary tropical forests in Singapore. Forest Ecology and Management 296: 81-89.

Oelbermann, M.; Voroney, R.P. and Gordon, A.M. 2004. Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. Agriculture, Ecosystems and Environment 104: 359-377.

Olson, J.S.; Watts, J.A. and Allison, L.J. 1983. Carbon in live vegetation of major world ecosystems. ORNL 58-62, Oak Ridge National Laboratory, Oak Ridge, TN, USA. 152 pages.

Orihuela-Belmonte, D.E.; Jong, B.H.J.; Mendoza-Vega, J.; Wal, J.V.; Paz-Pellat, F.; Soto-Pinto, L. and Flamenco-Sandoval, A. 2013. Carbon stocks and accumulation rates in tropical secondary forest at the scale of community, landscape and forest type. Agriculture, Ecosystems & Environment 171: 72-84.

Peichl, M. and Arain, M.A. 2006.Above and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. Agricultural and Forest Meteorology 140: 51-63.

Rajput, B. S.; Bhardwaj D.R. and Pala, N.A. 2015. Carbon dioxide mitigation potential and carbon density of different land use systems along an altitudinal gradient in north-western Himalayas. Agroforestry Systems doi: 10.1007/s10457-015-9788-8.

Roshetko, M.; Delaney, M.; Hairiah, K. and Purnomosidhi, P. 2002. Carbon stocks in Indonesian homegarden systems: Can smallholder systems be targeted for increased carbon storage? American Journal of Alternative Agriculture 17: 125-137.

Saha, S.; Nair, P.K.R.; Nair, V.D. and Kumar, B.M. 2009.Soil carbon stock in relation to plant diversity of home gardens in Kerala, India. Agroforestry Systems 76: 53-65.

Saugier. B. and Roy, J. 2001. Estimations of global terrestrial productivity; converging towards a single number? Pages 543-557. In: Roy, J.; Saugier, B. and Mooney, H.A. (Editors). Global Terrestrial Productivity: Past, Present and Future. Academic Press, New York.

Taylor, A.R.; Wang, J.R.; Chen, H.Y.H. 2007. Carbon storage in a chrosequence of red spruce (Piceaerubens) forest in central Nova Scotia, Canada. Canadian Journal of Forest Research 37: 2260-2269.

Vila, M.; Vayreda, J.; Comas, L.; Ibanez, J.J.; Mata, T. and Obon, B. 2007. Species richness and wood production: A positive association in Mediterranean forests. Ecology Letters 10: 241-250.

WAC (World Agroforestry Centre) 2014. Wood density data base. http://www.worldagroforestry.org/output/wood-density-database.

Walkley, A. and Black, I.A. 1934. An examination of degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37: 29-37.

Wang, W.; Lei, X.; Ma Zhihai, Kneeshaw, D.D. and Peng, C. 2011. Positive Relationship between Aboveground Carbon Stocks and Structural Diversity in Spruce-Dominated Forest Stands in New Brunswick, Canada. Forest Science 57: 506-515.

Watson, R.T.; Noble, I.R.; Bolin,B.; Ravindranath, N.H.;Verardo, D.J. and Dokken, D.J. 2000. IPCC Special Report on Landuse, Land Use Change, and Forestry. http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=0

Watson. R.T.. Dixon. J.A.; Hamburg, S.P.; Janetos. A.C. and Moss. R.H. 1998. Protecting Our Planet Securing Our Future - Linkages Among Global Environmental Issues and Human Needs. United Nations Environment Programme, U.S. National Aeronautics and Space Administration, and The World Bank, Washington, DC. 95 pages.

Yelenik, S.G.; Stock, W.D. and Richardson, D.M. 2004. Ecosystem level impacts of invasive Acacia salignain the South African Fynbos. Restoration Ecology 12: 44-51.

Young, A. 1997.Agroforestry for Soil Management, Effect of Trees on Soils. CAB International, Wallingford, UK 214 pages.

Ziegler, A.D.; Bruun, T.B.; Guardiola-Claramonte, M.; Giambelluca, T.W.; Lawrence, D. and Lam, N.T. 2009. Environmental consequences of the demise in swidden cultivation in Montane Mainland Southeast Asia: hydrology and geomorphology. Human Ecology 37: 361-373.

Ziegler, A.D.; Fox, J. M.; Webb, E.L.; Padoch, C.; Leisz, S.J.; Cramb, R.A.; Mertz, O.; Bruun, T.B. and Vien, T.D. 2011. Recognizing contemporary roles of swidden agriculture in transforming landscapes of Southeast Asia. Conservation Biology 25: 846-848.

Ziegler, A.D.; Phelps, J.; Yuen, J.Q.; Webb, E.L.; Lawrence, D.; Fox, J.M.; Bruun, T.B.; Leisz, S.J.; Ryan, C.M.; Padoch, C. and Koh, L.P. 2012. Carbon outcomes of major land-cover transitions in SE Asia: great uncertainties and REDD+ policy implications. Global Change Biology 18: 3087-3099.

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