Brazilian Journal of Biology®

ISSN 1519-6984 (Print)
ISSN 1678-4375 (Online)

Original Article

Yield, carbon stock, and price dynamics of agroforestry tree species in district Mardan, Khyber Pakhtunkhwa, Pakistan

Rendimento, estoque de carbono e dinâmica de preços das espécies de árvore agroflorestal no distrito de Mardan, Khyber Pakhtunkhwa, Paquistão

N. Usman[a], M. Hussain[a*], S. Akram[b], M. Majeed[c], S. Shah[d], F. Rehman[e], A. Yousaf[f], S. Shaukat[f], S. W. A. Shah[f], R. S. Mishr[g], S. Shrestha[g], A. Saddiqa[h], S. A. Roomi[i], and A. Ali[j]

[a]University of Haripur, Department of Forestry and Wildlife Management, Haripur, Pakistan
[b]University of Northern British Columbia, Faculty of Environment, Department of Ecosystem Science and Management, Prince George, Canada
[c]Technische Universität Dresden, Institute of International Forestry and Forest Products, Faculty of Environmental Sciences, Dresden, Germany
[d]The University of Agriculture, Department of Agronomy, Peshawar, Pakistan
[e]COMSATS University Islamabad, Department of Economics, Lahore, Punjab, Pakistan
[f]University of Tuscia, Department for Innovation in Biological, Agri-food and Forestry Systems, Viterbo, Italy
[g]University of Padova, Department of Land, Environment, Agriculture and Forestry, Legnaro, Italy
[h]University of Bangor, School of Natural Sciences, Bangor City, United Kingdom
[i]National Yang Ming Chiao Tung University, Institute of Environmental and Occupational Health Sciences, Taipei, Taiwan
[j]Karakoram International University, Department of Forestry, Range and Wildlife Management, Gilgit-Baltistan, Pakistan

Abstract

A socio-economic study was conducted in district Mardan of the Khyber Pakhtunkhwa (KP) province of Pakistan to get a comprehensive knowledge of the agroforestry tree species grown on the farmlands, their yield, and carbon stock. For yield and carbon stock estimation, data were collected from 59 sample plots by measuring the diameter, height, volume, and biomass of selected agroforestry tree species through D-tape and Haga altimeter. A total of 59 sample plots were inventoried using 2.5 percent sampling intensity. Each sample plot has an area of 0.5 ha, where each tree with a Diameter at Breast Height (DBH) ≥ 5 cm was inventoried. The calculated amount of volume of each tree species was then converted to biomass by multiplying it by the density of wood and the Biomass Expansion Factor (BEF). Total yield and C stock for the selected agroforestry tree species were 11535.2 metric tons and 2102.2 metric tons, respectively. *Populus euroamericana* is classified as the main tree with 28% growing stock prior to *Morus alba* by 21%, while Melia *azedarach, Eucalyptus camaldulensis, Dalbergia* sissoo, *Acacia nilotica*, *Salix tetrasperma,* and *Bombax ceiba* consist of 15%, 12%, 8%, 6%,7% and 3% growing stock respectively. Among the species found in different sampling plots the yield of *Populus euroamericana* was found to be 4747.5 metric tons and it was followed by the species *Morus alba* found at 2027.3 metric tons. Similarly, the volume for *Melia azedarach, Eucalyptus camaldulensis*, *Dalbergia sissoo*, *Salix spp*, *Boombox ceiba*, and *Acacia nilotica was 1532.2 tons,1503 ton,745.7,203.5ton, 555.4ton and 220.5ton,* respectively. The carbon stock for *Populus euroamericana* was calculated as 777.8 ton/ha, while for *Eucalyptus camaldulensis*, *Melia azedarach*, *Morus alba*, *Dalbergia sissoo*, *Acacia nilotica*, *Salix species,* and *Bombax ceiba* it was calculated as 312.3ton/ha, 272.1ton/ha, 363ton/ha, 245.1ton/ha, 51.4ton/ha, 27.3ton/ha and 53.2ton/ha, respectively. The questionnaire survey conducted for price dynamics showed that the majority of respondents purchase timber from the market for construction. But they use farm trees with low-quality city construction. They dislike using local timber in the conventional building as timber from farm trees is liable to insect attack. Rs. 50,000-100000, (33.33%) of daily sales was concluded from 50% of the trader while (16.7%) of the traders have their sales between Rs.150,000-200,000. Therefore, it is concluded by the authors that both provincial and federal government should promote agroforestry in Pakistan through different incentives because it has the potential to cope with dilemma of deforestation of natural forests and improve the livelihood of local peoples. It is strongly recommended that special projects just like the Ten Billion Tree Afforestation Project (T-BTTP) should be launched for agroforestry plantation and promotion in the country to sustain the ecological harmony and uplift the socio-economic condition of the peoples of Pakistan.

Keywords: agroforestry, yield, carbon stock, price, Mardan, Pakistan.

Resumo

Um estudo socioeconômico foi realizado no distrito de Mardan, da província de Khyber Pakhtunkhwa (KP), Paquistão, para obter maior conhecimento das espécies de árvores agroflorestais cultivadas em terras agrícolas, seu rendimento

*e-mail: majid@uoh.edu.pk
Received: April 1, 2022 – Accepted: May 16, 2022

e estoque de carbono. Para a estimativa de produção e estoque de carbono, foram coletados os dados de 59 parcelas amostrais, medindo-se o diâmetro, a altura, o volume e a biomassa de espécies de árvores agroflorestais selecionadas por meio de fita D e altímetro Haga. Um total de 59 parcelas amostrais foi inventariado usando 2,5% de intensidade de amostragem. Cada parcela amostral possui uma área de 0,5 ha, em que cada árvore com Diâmetro à Altura do Peito (DAP) ≥ 5 cm foi inventariada. A quantidade calculada de volume de cada espécie de árvore foi então convertida em biomassa, multiplicando-a pela densidade da madeira e pelo Fator de Expansão da Biomassa (BEF). A produção total e o estoque de C para as espécies de árvores agroflorestais selecionadas foram 11.535,2 toneladas métricas e 2.102,2 toneladas métricas, respectivamente. *Populus euroamericana* foi classificada como a principal árvore com 28% de crescimento de estoque, seguida de *Morus alba* com 21%, enquanto *Melia azedarach*, *Eucalyptus camaldulensis*, *Dalbergia sissoo*, *Acacia nilotica*, *Salix tetrasperma* e *Bombax ceiba* apresentaram 15%, 12%, 8%, 6%, 7% e 3% de crescimento do estoque, respectivamente. Entre as espécies encontradas em diferentes parcelas de amostragem, o rendimento de *Populus euroamericana* foi de 4.747,5 toneladas, seguida pela espécie *Morus alba*, com rendimento de 2.027,3 toneladas. Da mesma forma, o volume de *Melia azedarach*, *Eucalyptus camaldulensis*, *Dalbergia sissoo*, *Salix* spp, *Bombax ceiba* e *Acacia nilotica* foi de 1.532,2 toneladas, 1.503 toneladas, 745,7 toneladas, 555,4 toneladas e 220,5 toneladas, respectivamente. O estoque de carbono para *Populus euroamericana* foi calculado como 777,8 ton/ha, enquanto para *Eucalyptus camaldulensis*, *Melia azedarach*, *Morus alba*, *Dalbergia sissoo*, *Acacia nilotica*, *Salix species* e *Bombax ceiba* foi calculado como 312,3 ton/ha, 272,1 ton/ha, 363 ton/ha, 245,1 ton/ha, 51,4 ton/ha, 27,3 ton/ha e 53,2 ton/ha, respectivamente. A pesquisa por questionário, realizada para a dinâmica de preços, mostrou que os entrevistados, em sua maioria, compram madeira do mercado para construção, mas usam árvores de fazenda em construções urbanas de baixa qualidade. Eles não gostam de utilizar a madeira local na construção convencional, pois ela é suscetível ao ataque de insetos. Em relação às vendas diárias, 50% dos comerciantes vendem entre Rs. 50.000-100.000, enquanto 16,7% têm suas vendas entre Rs.150.000-200.000. Portanto, conclui-se que tanto o governo provincial quanto o governo federal devem promover, por meio de diferentes incentivos, a agrossilvicultura no Paquistão, por ter o potencial de lidar com o dilema do desmatamento de florestas naturais e melhorar a subsistência das populações locais. É fortemente recomendado que projetos especiais, como o Projeto de Reflorestamento de Dez Bilhões de Árvores (T-BTTP), sejam lançados para plantio agroflorestal e promoção no país para sustentar a harmonia ecológica e elevar a condição socioeconômica dos povos do Paquistão.

Palavras-chave: agrofloresta, rendimento, estoque de carbono, preço, Mardan, Paquistão.

1. Introduction

Agroforestry provides a sole opportunity to combine the double objectives of climate change adaptation and mitigation. It is an attractive alternative for sequestering carbon on agroforestry lands since it can sequester chief amounts of carbon still as leaving the bulk of the land in the production. Agroforestry provides a sole opportunity to combine the double objectives of climate change adaptation and mitigation. It is an attractive alternative for sequestering carbon on agroforestry lands since it can sequester chief amounts of carbon still as leaving the bulk of the land in the production. Deforestation and forest degradation contribute to increasing carbon dioxide concentration in the atmosphere. CO_2 acts as a major greenhouse gas. Globally, forest area has decreased from 31.6% in 1990 to 30.6% in 2015. Terrestrial vegetations play an important role within the global carbon cycle and hence the earth system, as it sequesters atmospheric carbon dioxide and is thus able to mitigate global warming (Denman et al., 2007; Bonan, 2008). Carbon sequestration and vegetation cover and the success of such conservation efforts are not easily quantifiable, and the spatial footprint of projects is not always commensurable with contemporary satellite and modeling-based monitoring methods. Adaptation and mitigation strategies to climate change should be anchored in knowledge of how ecosystems respond to climatic and anthropogenic disturbances (Tong et al., 2018; Bradford, 1990). Carbon sequestration is basically the progression of transforming carbon in the air (carbon dioxide or CO_2) stored in the soil carbon. Forests have also an important role on climate changes discussion once adequate land use and forest areas are mechanisms to mitigate climate change by reducing greenhouse emissions by kidnapping carbon (Sotta et al., 2006). The introduction of *Populous euroamericana*, *Eucalyptus camaldulensis*, and *Melia azedarach* is of great importance having improved the pastoral background in district Mardan KP. The multiuse sorts of *Populous euroamericana*, *Eucalyptus camaldulensis*, and *Melia azedarach* have made it tremendously prevalent trees in the study area KP. The multiuse sorts of *Populous euroamericana*, *Eucalyptus camaldulensis* and *Melia azedarach*. Therefore, the demand for poplar, eucalyptus, as well as bakain timber is high to stand many wood-based manufacturing initiatives in district Mardan, KP, Pakistan. Agroforestry is a system of land use management where trees or shrubs are cultivated around or between plants or pastures. It combines farming and forestry techniques to produce a more varied, productive, lucrative, safe, and sustainable land-use system (Atangana et al., 2014). Agroforestry is a common name for land-use schemes consisting of forests on the same unit of land coupled with plants and/or livestock. Agroforestry has the following main features. 1). Assembly of different outputs with source base security. 2). Places emphasis on various native trees and shrubs being used. 3). Particularly appropriate for fragile settings and low-input situations. 4). It is more complicated in terms of structure and function than monoculture. It is a mutual name for a land-use scheme and technology that intentionally uses woody perennials in some type of spatial structure or temporal sequence on the same land-management unit as agricultural plants and/or livestock. There are both ecological and economic interactions between the different parts in an agroforestry scheme. The ability of agroforestry, forestation, regeneration and avoided deforestation activities in tropical Asia is that they can store 7.50, 2.03, 3.8–7.7, and 3.3–5.8 Ph C respectively, from 1995 up to 2050 (Brown et al., 1996). In Pakistan we are deficient in wood and agroforestry has the potential to solve these problems. Besides the problem of wood and food, agroforestry would also help in preserving the environment. It will also help the farmers and the owners of land in increasing their income by harvesting the trees after a suitable period and will also benefit the socio-economic development of an area hence will improve the livelihood of local people and farmers (García-Amado et al., 2013). Trees are also raised scattered by the farmers on their farms, these provide shade from the heat to the labor and livestock, as well as to meet their domestic needs and get monetary return at the time of harvest (Chave et al., 2005). Like agriculture, agroforestry is quite old as itself. Agroforestry is the growing of trees either in rectilinear or closed arrangements on fields beside agricultural crops. This method is usually applied and implemented in damped as well as irrigated regions. The most basic agroforestry tree species planted in these areas are Populus euroamericana (poplar), *Dalbergia sissoo* (Shisham), *Morus alba* (Mulberry) *Bombax ceiba* (Simal), *Melia azedarach* (Bakain), *Salix spp*. (Willow), and *Acacia nilotica* (Kikar) Some exotic species like *Ailanthus altisima*, *Eucalyptus spp*., and *Robinia pseudoacacia* have also been planted with the common agroforestry tree species. These agroforestry species are basically the important cause of timber, furniture, fuelwood, and fodder (Sheldrick and Auclair, 2000). In the Mardan division, agroforestry trees species like *Populus euroamericana*, *Dalbergia sissoo*, Acacia *nilotica*, *Eucalyptus spp.* showed that the wood of these trees is highly used in the manufacturing of match sticks, sports good, tables, chairs beds, and other furniture. *Populus euroamericana* is considered as a common man species, it is because it has many useful uses. Due to quick and rapid growth, small cycle and great importance this agroforestry tree species is of great demand. So, because of all these important qualities this and other agroforestry tree species are taught as poor man's timber (Nizami et al., 2009). Farmers have raised linear plantations in the form of windbreaks around their farms from wind erosion, reducing evapotranspiration losses of soil moisture, improving soil fertility, besides fulfilling domestic needs and as a source of income (Sinclair et al., 2000). Agroforestry trees spp. are grown on the periphery of agricultural fields, water courses and roadsides. These trees spp. also serves as wind breakers. Agroforestry with poplar is a good source of employment for the rural people through which unskilled labors are engaged in raising, planting, weeding, felling, and transportation of trees and tree products The demand for current annual fuel wood is measured as 22.15-million-meter cube While the state forest produces fuelwood only 0.4 million cubic meters. Theoretically, if more land is prepared to increase the most fixed resources at the amount of twenty thousand hectares per annum, then only 2.5% forest area will be increased in the coming 100 years The objective of the study is to (i) estimate the yield of agroforest tree species in District Mardan, Khyber Pakhtunkhwa, (ii) To calculate the carbon stock and carbon dioxide (CO_2) sink by agroforest tree species in Mardan. (iii) to investigate the price dynamic of agroforest trees species.

2. Material and Methods

2.1. Study area

The current research was conducted in District Mardan, Khyber Pakhtunkhwa. Mardan lies between 34.1989°N latitude and 72.0231°E longitude (Figure 1). The district is famous for its agriculture industry. It is bounded on the north by Mardan district and Malakand protected area, on the east by Mardan districts, on the south by Nowshera district and on the west by District Charsadda Mardan Division is one of seven division in Pakistan's Khyber Pakhtunkhwa province. It consists of two districts Mardan and Swabi. According to the 2017 Pakistani Census, the division had a population of 3,997,667, making it the fourth-most populous division in the province, but it only spans 3,175 km^2 (1,226 sq mi) of area, which makes it the smallest division by area in the province as well. Mardan, with over 350,000 people, is the division's namesake and most populous city. The division borders Hazara Division, Malakand Division, and Peshawar Division. The local people had put their efforts and resources into building the school. Many sites have been discovered in Mardan and it looks as Mardan was the heart of the Gandhara civilization. One of the Buddhist monasteries is Mekha Sanda, which is located 17 km from Mardan on the Northeastern side of the Hills of Shahbaz Garhi. This site was surveyed and excavated by a team of Japanese archaeologists between 1959 and 1965. During courses of excavations, a good number of Gandhara art sculptures, main stupa, votive stupas, monasteries, chapels, and Monks' chambers were found. This site became a place for research and a tourist spot. The name is derived from the Pushto language. Mekha means a female buffalo and Sanda means a male buffalo. The arrangement of the stones is in such a way that it looks like buffaloes. Unfortunately, some treasure hunters illegally dug out the site in search of antiques and it has been spoiled. It is the utmost responsibility of the government to provide guards, restore this site and protect it from further destruction. So far there is no sign of it happening (Khan et al., 2011).

2.2. Selection of sampling sites for agroforest tree species

For biomass calculation fix area method was followed i.e., by using the measurements of height and diameter of the sample trees can also have calculated the volume and density as well. For the field inventory we select fixed area plot method and took some random samples in district Mardan. The size of sample plot was taken 100m×50m.

2.3. Instruments used

Instruments used were as can be seen in Figures 2-4 below.

1. Tree caliper: measures tree diameter.
2. Clinometer: used to measures the height of a tree.
3. D- tape: used to measures the distance from a tree.

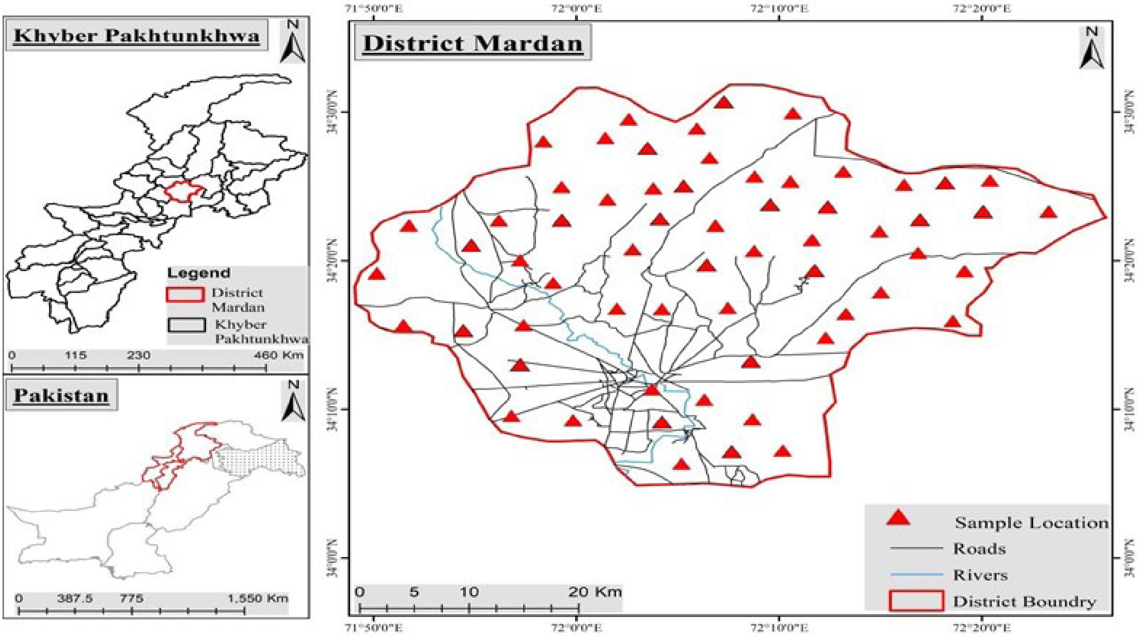

Figure 1. Location map of the study area.

Figure 2. Caliper.

Figure 4. D-tape.

Figure 3. Haga altimeter.

2.4. Sample plots and sampling intensity

In the study region, 59 sampling plots of 0.5 ha were used for this research and the trees were counted and measured within each sample plot. For yield determination and above ground biomass determination, the diameter and height of all trees in a sample plot were evaluated.

2.5. Volume calculation

Volume was calculated by using two methods i.e., by the multiplication of Height with area of the tree Volume=Area × Height. The volume table made by Pakistan Forest institute, Peshawar was considered and used to find out the volume of agroforestry trees species. As there are eight species in this study, so the volume of each species was calculated by using separate V-table. Biomass of agroforestry tree spp. was also calculated directly by using the equation (Litton and Kauffman, 2008).

2.6. Aboveground tree biomass

Aboveground biomass estimation needs data on tree diameter and height. Diameters of all trees were measured in the field, but height was recorded only for randomly selected sample trees. AGTB was calculated for every sample plot by using allometric equations available in the literature. Biomass of all individuals' trees in the plot was summed and multiplied with 10 and divided by 1000 to get estimates of biomass per ha. Tree biomass was converted to carbon by multiplying with Carbon fraction which is 0.47 for all species).

2.7. Belowground biomass

Belowground biomass was calculated using root-shoot ratios available in literature (Cairns et al., 1997). Generally, belowground biomass is taken 25% of the aboveground biomass. Belowground biomass was converted to carbon by multiplying with carbon fraction 0.47.

2.8. Estimation of carbon stock

The total C stock in each land use was calculated from total biomass. The total biomass of each land use was multiplied with conversion factor of 0.5 that has been used globally (Brown and Lugo, 1982; Nizami, 2012).

2.9. Estimation of CO_2 equivalents

The carbon inventory was then transformed to CO_2 equivalent by multiplying it by 3.66, the carbon atom ratio in the CO_2 molecular weight. This determined the complete quantity of CO2 sequestered (Nizami, 2012).

2.10. Model fitting

Several allometric equations have been developed by researchers to estimate biomass of different tree species using several variables as predictors or independent variables. DBH, total height, volume, basal area are the common variables used for estimation of tree biomass (Chave et al., 2005; Mandal et al., 2013; Chave et al., 2014). However, DBH is the most commonly used independent variable for biomass estimation due to ease in measurement and being strongly correlated with tree volume and biomass. DBH alone can be used as a single biomass predictor in allometric models. When combined with other variables such as total height and density the estimates could be improved in some cases (Litton and Kauffman, 2008). The following regression models were tested in the current study (i) M=a(D^2H) ^b and M=a(pD^2H) ^b. Where M= Dry Biomass of tree in kg, D= Diameter at Breast Height, H= Total Height of tree in cm, P=Basic wood Density or specific Density, a=regression constant, b, c= Regression coefficient. The above models were used for estimation of total dry biomass separately for each species. Yield of the selected agroforestry tree species were calculated by dividing the volume of each tree spp. over the age of that tree (Yield=Volume/Age Abundance). While for price dynamic a questionnaire survey was conducted and about hundreds of the farmers were asked about the price dynamics of agroforest trees species.

3. Results

A total of trees was tallied during the field inventory. The species sampled consisted of variety of species. Poplar (*Populus euroamericana*) is the dominant species (74%) followed by Eucalyptus (8%), Bakain (5%), Mulberry (3%), Ailanthus (2%), Tagha (2%), Shisham (2%), Mango (2%), Toot (2%), contributions respectively. Majority respondents have grown poplars on their farmlands because it is the fastest growing farmland tree, a cash crop and the area are most suited for growing this specie. Much of the revenue by the farmer is earned by planting poplar, which has improved the socio-economic conditions of the people of District Mardan to a greater extent.

The mean DBH and mean height of the trees in the study areas. Where the highest mean height of the trees was noted was 20.33898 in plot no.3, the highest mean height of plot.no 3 was because it contains all the mature trees, and each tree was much exposed to sunlight. while the lowest height noted was 10.08 in plot no.11. lowest mean height of the plot was because it contains all the young age species. The highest Mean DBH obtained was 23.31373 in plot.no 32 shown in Table 1, because the trees of that plot were very untouched. And were much closed to the water channel. The lowest mean DBH noted was 9.796296 as shown in Table 1 in plot No.6, because the trees in that plot were gone through the process of pruning which let the trees grow straight instead of growing the diameter.

The aboveground biomass ton/hectare in which the highest ABGM t/h is 192.78912 in plot no.24, and the lowest above ground biomass noted was 0.3046143, the highest below ground is 24.78527 in plot number 42, while the lowest below ground biomass is 0.938493 in plot number 11. The highest total biomass is 242.9143 in plot number 24, while the lowest total biomass is 3.494647 in plot 58 as summarized in Table 2.

The highest and lowest above carbon ton/hectare are 90.61089 and 1.303559 in plot no.24 and 58 as shown in the Table 3, respectively. The highest and lowest below ground carbon ton/hectare noted were 23.55883 and 0.338925 in plot No.24 and 58 shown in the table respectively. The highest and lowest total carbon ton/hectare noted were 114.1697 TC t/h and 1.642484 TC t/h as shown in the table in plot no.24 and 58 respectively, while the highest and lowest CO2 noted in plot no.24 and 58 were 417.8612 and 6.011 492 as shown in the table respectively. The highest values were obtained because all the facilities of sunlight and water were available to them, in addition to this all the trees of plot no.24 were mature, while the trees of plot no. 58 were at the young age. And some of the trees in plot no. 58 were in grown in salt rich soil area.

Highest number of trees per hectare is 790 in plot no.12, shown in the table above, while the lowest number of trees per hectare noted in the related Table 4 above is 170 plots no 51. The highest number of the trees per hectare is because of no human activities were seen in plot no.12. Plot no.12 was much exposed to the local community of

Table 1. Mean height and mean DBH of the agroforest trees species.

Plot No	Latitude	Longitude	Mean Height	Mean DBH
1	34.2745	71.9187	16.0167	11.6667
2	34.27527	71.9189	13.2167	12.3667
3	34.27577	71.9181	20.339	16.0678
4	34.27726	71.9193	11.05	11.4
5	34.27849	71.9201	16.1259	18.6143
6	34.27655	71.9194	13.963	9.7963
7	34.27656	71.9193	12.85	10.9667
8	34.26931	71.9195	11.6949	13.8983
9	34.27634	71.9223	11.525	14.15
10	34.27464	71.9223	10.0638	9.76596
11	34.2772	71.9192	10.08	9.4
12	34.27206	71.9172	12.0667	11.5
13	34.27338	71.9178	13.678	12.1525
14	34.27662	71.9179	9.97959	8.53061
15	34.27453	71.9173	13.7833	12.8167
16	34.57492	71.917	13.7667	16.9333
17	34.57552	71.9157	14.5	19.5455
18	34.27481	71.9163	16.95	15.2167
19	34.2735	71.9159	12.8333	10.6
20	34.27342	71.9172	13.2069	11.569
21	34.97199	71.9185	13.6154	16.2885
22	34.1727	71.5534	13.8246	16.8947
23	34.173	71.5538	12.0517	14.7241
24	34.1736	71.5541	13.4006	18.6789
25	34.1758	71.5525	15.8947	22.1053
26	34.1828	71.5602	12.7241	14.5862
27	34.1821	71.5554	14.3778	17.8444
28	34.1717	71.57	13	12.766
29	34.173	71.5758	12.2105	12.9649
30	34.1532	71.5652	15.0952	23.0714
31	34.1539	71.5713	14.9623	15.283
32	34.153	71.5654	15.7059	23.3137
33	34.1531	71.5635	14.9474	17.2368
34	34.1543	71.5758	15.9464	12.1964
35	34.1556	71.5809	13.381	14.4048
36	34.1609	71.5739	15.4318	15.5227
37	34.1555	71.5814	15.3448	16.8793
38	34.1511	71.5811	13.5652	16.3261
39	34.231	71.5925	13.3514	16.4595
40	34.2337	71.592	13.9077	15.0308
41	34.2319	71.5909	13.3137	17.8431
42	34.2131	71.5835	14.6563	25.0625

Table 1. Continued...

Plot No	Latitude	Longitude	Mean Height	Mean DBH
43	34.2128	71.5836	16.9149	23.9575
44	34.2124	71.5835	14.3514	16.5946
45	34.2124	71.5842	14.5094	13.3962
46	34.2117	71.5845	12.0465	12.0465
47	34.2108	71.585	12.2745	14
48	34.1402	72.0937	12.4651	12.6744
49	34.1402	72.0948	10.8421	12.3947
50	34.1355	72.0935	12.6809	13.5745
51	34.1431	72.0709	12.3846	13.3846
52	34.0658	72.0117	12.6346	14.8269
53	34.0657	72.0116	12.8444	18.8
54	34.0656	72.0115	14.6889	19.4
55	34.0704	72.0109	12.6038	13.1132
56	34.0707	72.011	12.0244	11.5366
57	34.0453	72.0138	12.5942	13.4203
58	34.0456	72.0142	12.4182	12.5818
59	34.1703	71.5552	12.623	15.2787

Table 2. Above ground biomass (AGB) ton/hectare, below ground biomass (BGM) ton/hectare and total biomass ton/ hectare.

Plot No	AGB t/h	BGB t/h	TBM t/h
1	21.286742	5.53455	26.8213
2	20.330999	5.28606	25.6171
3	47.667771	12.3936	60.0614
4	22.87761	5.94818	28.8258
5	71.322744	17.8694	86.5978
6	12.983107	3.37561	16.3587
7	14.464795	3.76085	18.2256
8	22.150886	5.7191	27.7156
9	14.604755	3.79724	18.402
10	7.1920423	1.86993	9.06197
11	7.1920423	0.93849	4.54808
12	16.457981	4.27908	20.7371
13	0.3046143	4.84041	23.4574
14	5.6400588	1.46642	7.10647
15	21.465436	5.58101	27.0465
16	38.625792	10.0427	48.6685
17	53.746291	13.974	67.7203
18	37.277792	9.69223	46.97
19	13.976441	3.63388	17.6103
20	16.500772	4.2902	20.791
21	29.964036	7.79065	37.7547

Table 2. Continued...

Plot No	AGB t/h	BGB t/h	TBM t/h
22	35.402204	9.20457	44.6068
23	24.166929	6.2834	30.4503
24	192.78912	50.1252	242.914
25	54.831443	14.2562	69.0876
26	12.191622	3.16982	15.3614
27	38.05691	9.8948	47.9517
28	15.112257	3.92919	19.0414
29	18.643232	4.84724	23.4905
30	49.213852	12.7956	62.0095
31	32.619861	8.48116	41.101
32	70.216462	18.2563	88.4727
33	25.0675	6.51755	31.5851
34	20.0524	5.21362	25.266
35	23.174462	6.02536	29.1998
36	32.498618	8.44964	40.9483
37	37.88558	9.85025	47.7358
38	27.83766	7.23779	35.0755
39	45.23048	11.7599	56.9904
40	31.99824	8.31954	40.3178
41	33.63064	8.74397	42.3746
42	95.32798	24.7853	120.113
43	70.30386	18.279	88.5829
44	22.6274	5.88313	28.5105
45	29.78083	7.74301	37.5238
46	11.70945	3.04446	14.7539
47	21.04921	5.47279	26.522
48	16.41666	4.26833	20.685
49	17.68016	4.59684	22.277
50	17.41805	4.52869	21.9467
51	13.0818	3.40127	16.4831
52	41.01308	10.6634	51.6765
53	32.27402	8.39125	40.6653
54	38.53161	10.0182	48.5498
55	17.76928	4.62001	22.3893
56	10.87444	2.82735	13.7018
57	4.037415	1.04973	5.08714
58	2.77353	0.72112	3.49465
59	4.705689	1.22348	5.92917

that area due to which a very limited number of trees were let grown. Total biomass (TBM t/h), where the highest total biomass ton per hectare was 242.9143 Ton/hectare plot no.24, the reason behind the highest total biomass was the best soil condition, more humidity, while the lowest noted total biomass ton/hectare was 3.494647 as shown in the table above. The table above also shows the total carbon ton per hectare (TC t/h) of the study area. where the highest amount of the total Carbon ton/hectare noted was 114.1697 in plot no.24, while the lowest total Carbon

Table 3. Above ground carbon (AGC) ton /hectare, below ground carbon (BGC) ton /hectare, total ground carbon ton /hectare and carbon dioxide.

Plot No	AGC t/h	BGC t/h	TC t/h	CO2
1	10.0048	2.60124	12.606	46.138
2	9.55557	2.48445	12.04	44.0665
3	22.4039	5.825	28.2289	103.318
4	10.7525	2.79564	13.5481	49.5861
5	33.5217	8.39861	41.9203	153.428
6	6.10206	1.58654	7.6886	28.1403
7	6.79845	1.7676	8.56605	31.3518
8	10.4109	2.68798	13.0989	47.942
9	6.86424	1.7847	8.64894	31.6551
10	3.38026	0.87887	4.25913	15.5884
11	1.69651	0.44109	2.1376	7.82361
12	7.73525	2.01117	9.74642	35.6719
13	8.74997	2.27499	11.025	40.3514
14	2.65083	0.68922	3.34004	12.2246
15	10.0888	2.62308	12.7118	46.5253
16	18.1541	4.72007	22.8742	83.7196
17	25.2608	6.5678	31.8286	116.493
18	17.5206	4.55535	22.0759	80.7978
19	6.56893	1.70792	8.27685	30.2933
20	7.75536	2.01639	9.77176	35.7646
21	14.0831	3.66161	17.7447	64.9456
22	16.63904	4.32615	20.9652	76.7326
23	11.35846	2.9532	14.3117	52.3807
24	90.61089	23.5588	114.17	417.861
25	25.77078	6.7004	32.4712	118.845
26	5.730062	1.48982	7.21988	26.4248
27	17.88675	4.65055	22.5373	82.4865
28	7.102761	1.84672	8.94948	32.7551
29	8.762319	2.2782	11.0405	40.4083
30	23.13051	6.01393	29.1444	106.669
31	15.33133	3.98615	19.3175	70.702
32	33.00174	8.58045	41.5822	152.191
33	11.78172	3.06325	14.845	54.3326
34	9.424628	2.4504	11.875	43.4626
35	10.892	2.83192	13.7239	50.2295
36	15.27435	3.97133	19.2457	70.4392
37	17.80622	4.62962	22.4358	82.1152
38	13.0837	3.40176	16.4855	60.3368
39	21.25833	5.52717	26.7855	98.0349
40	15.03917	3.91019	18.9494	69.3546
41	15.8064	4.10966	19.9161	72.8928
42	44.80415	11.6491	56.4532	206.619

Table 3. Continued...

Plot No	AGC t/h	BGC t/h	TC t/h	CO2
43	33.04281	8.59113	41.634	152.38
44	10.63488	2.76507	13.4	49.0438
45	13.99699	3.63922	17.6362	64.5485
46	5.503443	1.4309	6.93434	25.3797
47	9.893128	2.57221	12.4653	45.6232
48	7.715831	2.00612	9.72195	35.5823
49	8.309673	2.16052	10.4702	38.3209
50	8.186484	2.12849	10.315	37.7528
51	6.148445	1.5986	7.74704	28.3542
52	19.27615	5.0118	24.288	88.8939
53	15.16879	3.94389	19.1127	69.9524
54	18.10986	4.70856	22.8184	83.5154
55	8.351561	2.17141	10.523	38.5141
56	5.110985	1.32886	6.43984	23.5698
57	1.897585	0.49337	2.39096	8.7509
58	1.303559	0.33893	1.64248	6.01149
59	2.21167	0.57504	2.78671	10.1994

Table 4. Tree/hectare, total biomass ton/hectare and total carbon ton/hectare.

Plot no	Tree/h	TBM t/h	TC t/h
1	390	26.8213	12.606
2	590	25.6171	12.04
3	590	60.0614	28.2289
4	530	28.8258	13.5481
5	390	86.5978	41.9203
6	320	16.3587	7.6886
7	390	18.2256	8.56605
8	460	27.7156	13.0989
9	790	18.402	8.64894
10	480	9.06197	4.25913
11	550	4.54808	2.1376
12	790	20.7371	9.74642
13	280	23.4574	11.025
14	650	7.10647	3.34004
15	590	27.0465	12.7118
16	500	48.6685	22.8742
17	590	67.7203	31.8286
18	280	46.97	22.0759
19	580	17.6103	8.27685
20	560	20.791	9.77176
21	370	37.7547	17.7447
22	360	44.6068	20.9652

Table 4. Continued...

Plot no	Tree/h	TBM t/h	TC t/h
23	390	30.4503	14.3117
24	270	242.914	114.17
25	340	69.0876	32.4712
26	190	15.3614	7.21988
27	190	47.9517	22.5373
28	190	19.0414	8.94948
29	390	23.4905	11.0405
30	190	62.0095	29.1444
31	330	41.101	19.3175
32	330	88.4727	41.5822
33	370	31.5851	14.845
34	190	25.266	11.875
35	200	29.1998	13.7239
36	190	40.9483	19.2457
37	190	47.7358	22.4358
38	190	35.0755	16.4855
39	190	56.9904	26.7855
40	190	40.3178	18.9494
41	210	42.3746	19.9161
42	230	120.113	56.4532
43	190	88.5829	41.634
44	230	28.5105	13.4
45	190	37.5238	17.6362
46	190	14.7539	6.93434
47	190	26.522	12.4653
48	200	20.685	9.72195
49	210	22.277	10.4702
50	190	21.9467	10.315
51	170	16.4831	7.74704
52	250	51.6765	24.288
53	280	40.6653	19.1127
54	310	48.5498	22.8184
55	230	22.3893	10.523
56	210	13.7018	6.43984
57	250	5.08714	2.39096
58	280	3.49465	1.64248
59	310	5.92917	2.78671

ton/hectare noticed in the study area was 1.642484 as shown in the table.

3.1. Price dynamics

The price dynamic was found by questionnaire survey. All the farmers and labors were asked about the trees grown on the farmlands. The data regarding shows that majority of respondent purchase timber from market for construction. But they use farm trees for low quality construction. They dislike using local timber in conventional building as timber from farm trees is liable to insect attack. The farmers who are poor and cannot afford the purchase of timber from market mainly depend on farm trees, sheds for livestock are also constructed from local timber obtained from agriculture field. The data analysis depicts those trees are generally grown as a raw material for local wood-based goods manufacturing units and distantly located industries within the province and outside. The result shows that (37.4%) of the trees are used as a timber material while (63.6.2%) of trees growing on farmlands supply raw material for industrial use. It can be concluded that wood grown on farmlands in mainly used as timber and as industrial raw material. Poplar in bulk is used as industrial wood and shuttering material for construction and Shisham, bakain and toot as timber for furniture. The respondents were asked about suitable specie for requirements. The Table (indicates that majority (77%) suggested Poplar, (10%) Shisham,8% Bakain and about 6% Toot. The majority (72.6%) sold the agroforestry tree species in standing form. Further analysis of data indicated that trees are generally sold in standing form because of better negotiation power as compared to felled one when the timber merchants exploit the farmers as material left for longer time losses its value.

3.2. Market survey and interview of wood dealers

To study marketing system preliminary data through market survey of 12 wood traders located at district Mardan, Tehsil Takht Bhai was also carried out. The purpose was to quantify wood traded, buying, and selling costs, transportation, felling and conversion costs, profit per unit and common sizes traded. The primary market data were collected through a structured questionnaire and 9 traders were interviewed at those locations. From the survey it was concluded that majority of the traders (50.0%) have their daily sale between Rs. 50,000-100000, (33.33%), while (16.7%) of the traders have their sale between Rs.150,000-200,000. Middlemen are the main purchasers of wood and the key persons in the marketing system. For the sale of wood, farmers were contacted by middlemen. Lower percentage of contacts by the middlemen represents the poor marketing of wood in the area. Majority population in the study area was found that they are selling a single tree of *Populus deltoids* above Rs. 850 having 10 inches diameter and 20 feet height. *Dalbergia sisso* above RS.1700, *Melia azedarach* Rs.450 Morus *alba* Rs600, *Eucalyptus camaldulensis*, Rs 800, *Bombax cieba* Rs 250 *Acacia nilotica* Rs 150.

4. Discussion

This study provides the first assessment of existing and potential carbon pools for agroforestry systems in district Mardan. Although not inherently carbon dense compared to systems such as forests or intensively managed pastures, agroforestry systems provide opportunities to increase carbon storage in agricultural fields by about 20.4 to 21.4 TC ha−1 globally (Zomer et al., 2016) through the incorporation of long-lived, deep-rooted trees (Albrecht and Kandji, 2003). While climatic conditions are homogeneous across the district we sampled, the amount of carbon sequestered varied because of the distribution of tree species, tree density, tree basal area, and tree age, emphasizing the importance of management decisions in determining carbon stocks. Lowest tree carbon noted was 1.642484 t/ha in plot no. 53 while the highest tree carbon noted was 114.169 t/ha in plot no. 24. On the other hand, lowest tree carbon was note 0.39 Mg/ha in Faisalabad and highest tree carbon noted is 8.79 Mg/ha in tehsil Lalian (Yasin et al., 2019). Total carbon obtained from the sampled plots was 1064.888 t/ha which is lower than 4,487,087 Mg for Chiniot, 9,396,682 Mg for Faisalabad, and 9,952,629 for Sargodha as the number of plots taken in Chiniot, Faisalabad and Sargodha were 80,90,80 (Yasin et al., 2019), while the plots taken in district Mardan were 59. The traditional agroforestry system involves cultivation of crops and useful plants under the natural tree canopy with varying structures, functions, socioeconomic attributes, and ecological services. In comparison, improved agroforestry involves selective management of trees with high economic value in association with high-yielding annual and perennial crops. The economics is concerned with looking at how limited resources are best used to create optimal services for rural people (Viswanath et al., 2018; Sekhar, 2007). Soil is known as an important subsystem in the agroforestry system to reduce CO2 in the atmosphere (Nair et al., 2009a). compared the trend of carbon sequestration in agroforestry and other land use systems and ranked them according to their soil carbon sequestration rate: forests > agroforests > tree plantations > arable crops. Agroforestry systems have higher soil carbon contents, as soil carbon in agroforestry largely depends on the amount and quality of biomass input by tree and non-tree components of the system. Moreover, a greater amount of organic carbon returns to the soil in the form of vegetation detritus and litter from pruning under proper agroforestry management (Stefano and Jacobson, 2018; Oelbermann et al., 2004). Total Above ground biomass obtained from sampled plots in district Mardan was 1780.4442 t/ha. According to Ali et al. (2020), the highest aboveground biomass is found in dry temperate forests as 211.5 t/ha, followed by moist temperate forests as 180.9 t/ha. On average, temperate forests have aboveground biomass of 192.6 t/ha. In subalpine and oak forest ecosystems, average aboveground biomass estimates were 72.9 t/ha and 73.6 t/ha, respectively. For subtropical pine forests, aboveground biomass was 52.7 t/ ha. Similarly, in subtropical broad-leaved evergreen forests and dry tropical thorn forests, aboveground biomass values are 9.6 t/ha and 9.5 t/ha, respectively (Ali et al., 2020). Several industries like paper and pulp, plywood, particle board, fiber board, furniture, housing and matches box and value addition industries are based on wood which is contributed from forestry or agroforestry. Owing to rapid depletion of our forests a need was felt conserve the natural forest resources by encouraging reconstituted wood products such as plywood, Hardboard, particleboard and medium Density fiber board (MDF) to meet the rising demand of wood from consumers including individuals, Railways, Defense, Furniture and Laminate manufacturers, builders etc. this led to a greater scope for agroforestry (Becker and Statz, 2003). From the questionnaire survey that we conducted it was concluded that majority of the traders (50.0%) have their daily sale between Rs. 50,000-100000, (33.33%) of the traders have their sale between Rs.100,000-150,000, while (16.7%) of the traders have their sale between Rs.150,000-200,000. Middlemen are the main purchasers of wood and the key persons in the marketing system. For the sale of wood, farmers were contacted by middlemen. Lower percentage of contacts by the middlemen represents the poor marketing of wood in the area. Majority population in the study area was found that they are selling a single tree of *Populus deltoids* above Rs. 850 having 10 inches diameter and 20 feet height. *Dalbergia sisso* above RS.1700, *Melia azedarach* Rs.450 Morus *alba* Rs600, *Eucalyptus camaldulensis*, Rs 800, *Bombax cieba* Rs 250 *Acacia nilotica* Rs 150.

5. Conclusions

Our sampling in district Mardan showed that the agroforestry system in this district stores moderate amounts of carbon in plants and soil. Based on farmer willingness to increase tree stocking the district studied has the potential to increase the carbon storage capacity. Khyber Pakhtunkhwa's farmers could help Pakistan meet her commitments to the Paris Climate accord through reasonable changes in tree planting on existing agroforestry systems. Aside carbon sequestration agroforestry could help in boosting the socio-economic purposes of the district Mardan, Khyber Pakhtunkhwa, Pakistan. Therefore, it is concluded by the authors that both provincial and federal government should promote agroforestry in Pakistan through different incentives because it has the potential to cope with dilemma of deforestation of natural forests and improve the livelihood of local peoples. It is strongly recommended that special projects just like the Ten Billion Tree Afforestation Project (Ten-BTTP) should be launched for agroforestry plantation and promotion in the country to sustain the ecological harmony and uplift the socio-economic condition of the peoples of Pakistan.

References

ALBRECHT, A. and KANDJI, S.T., 2003. Carbon sequestration in tropical agroforestry systems. *Agriculture, Ecosystems & Environment*, vol. 99, no. 1-3, pp. 15-27. http://dx.doi.org/10.1016/S0167-8809(03)00138-5.

ALI, A., ASHRAF, M.I., GULZAR, S., AKMAL, M. and AHMAD, B., 2020. Estimation of soil carbon pools in the forests of Khyber Pakhtunkhwa province, Pakistan. *Journal of Forestry Research*, vol. 31, no. 6, pp. 2313-2321. http://dx.doi.org/10.1007/s11676-019-01059-9.

ATANGANA, A., KHASA, D., CHANG, S. and DEGRANDE, A., 2014. *Tropical agroforestry*. Dordrecht: Springer. Definitions and classification of agroforestry systems, pp. 35-47. http://dx.doi.org/10.1007/978-94-007-7723-1_3.

BECKER, M. and STATZ, J., 2003. Marketing of parkland products. In: Z. TEKLEHAIMANOT, ed. *Improvement and management of agroforestry parkland systems in Sub-Saharan Africa*. Bangor: University of Wales, pp. 142-151. EU/INCO project contact IC18-CT98-0261, Final report.

GARCÍA-AMADO, L.R., PÉREZ, M.R., DAHRINGER, G., ESCUTIA, F.R., GARCÍA, S.B. and MEJÍA, E.C., 2013. From wild harvesting to agroforest cultivation: a *Chamaedorea* palm case study from Chiapas, Mexico. *Forest Policy and Economics*, vol. 28, pp. 44-51. http://dx.doi.org/10.1016/j.forpol.2012.12.004.

KHAN, M., HUSSAIN, F. and MUSHARAF, S., 2011. A fraction of freshwater algae of Kalpani stream and adjoining area of district Mardan, Pakistan. *International Journal of Biosciences*, vol. 1, no. 3, pp. 45-50.

NAIR, P.K.R., KUMAR, B.M. and NAIR, V.D., 2009a. Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science*, vol. 172, no. 1, pp. 10-23. http://dx.doi.org/10.1002/jpln.200800030.

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 & Environment*, vol. 104, no. 3, pp. 359-377. http://dx.doi.org/10.1016/j.agee.2004.04.001.

SEKHAR, N.U., 2007. Traditional versus improved agroforestry systems in Vietnam: a comparison. *Land Degradation & Development*, vol. 18, no. 1, pp. 89-97. http://dx.doi.org/10.1002/ldr.758.

STEFANO, A. and JACOBSON, M.G., 2018. Soil carbon sequestration in agroforestry systems: a meta-analysis. *Agroforestry Systems*, vol. 92, pp. 285-299.

TONG, X., BRANDT, M., YUE, Y., HORION, S., WANG, K., KEERSMAECKER, W., TIAN, F., SCHURGERS, G., XIAO, X., LUO, Y., CHEN, C., MYNENI, R., SHI, Z., CHEN, H. and FENSHOLT, R., 2018. Increased vegetation growth and carbon stock in China karst via ecological engineering. *Nature Sustainability*, vol. 1, no. 1, pp. 44-50. http://dx.doi.org/10.1038/s41893-017-0004-x.

VISWANATH, S., LUBINA, P.A., SUBBANNA, S. and SANDHYA, M.C., 2018. Traditional agroforestry systems and practices: a review. *Advanced Agricultural Research & Technology Journal*, vol. 2, no. 1, pp. 18-29.

YASIN, G., NAWAZ, M.F., MARTIN, T.A., NIAZI, N.K., GUL, S. and YOUSAF, M.T.B., 2019. Evaluation of agroforestry carbon storage status and potential in irrigated plains of Pakistan. *Forests*, vol. 10, no. 8, p. 640. http://dx.doi.org/10.3390/f10080640.

ZOMER, R.J., NEUFELDT, H., XU, J., AHRENDS, A., BOSSIO, D., TRABUCCO, A., VAN NOORDWIJK, M. and WANG, M., 2016. Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, vol. 6, no. 1, p. 29987. http://dx.doi.org/10.1038/srep29987. PMid:27435095.

DENMAN, S., CHANDRAN, V. and SRIDHARAN, S., 2007. An adaptive optical flow technique for person tracking systems. *Pattern Recognition Letters*, vol. 28, no. 10, pp. 1232-1239. http://dx.doi.org/10.1016/j.patrec.2007.02.008.

BONAN, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, vol. 320, no. 5882, pp. 1444-1449.

BROWN, S., SATHAYE, J., CANNELL, M. and KAUPPI, P.E. 1996. Mitigation of carbon emissions to the atmosphere by forest management. The Commonwealth Forestry Review, pp.80-91.

CHAVE, J., ANDALO, C., BROWN, S., CAIRNS, M.A., CHAMBERS, J.Q., EAMUS, D., FÖLSTER, H., FROMARD, F., HIGUCHI, N., KIRA, T., LESCURE, J.P., NELSON, B.W., OGAWA, H., PUIG, H., RIÉRA, B. and YAMAKURA, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, vol. 145, no. 1, pp. 87-99. http://dx.doi.org/10.1007/s00442-005-0100-x. PMid:15971085.

NIZAMI, S.M., MIRZA, S.N., LIVESLEY, S., ARNDT, S., FOX, J.C., KHAN, I.A. and MAHMOOD, T., 2009. Estimating carbon stocks in sub-tropical pine (Pinus roxburghii) forests of Pakistan. *Pakistan Journal of Agricultural Sciences*, vol. 46, no. 4, pp. 266-270.

SINCLAIR, F., EASON, B. and HOOKER, J. 2000. Understanding and management of interactions. In: Hislop M. and Claridge J. (eds), Agroforestry in the UK. Forestry Commission Bulletin 122. Forestry Commission, Edinburgh, pp. 17-28.

NIZAMI, S.M., 2012. The inventory of the carbon stocks in sub-tropical forests of Pakistan for reporting under Kyoto Protocol. *Journal of Forestry Research*, vol. 23, no. 3, pp. 377-384. http://dx.doi.org/10.1007/s11676-012-0273-1.

MANDAL, R.A., YADAV, B.K.V., YADAV, K.K., DUTTA, I.C. and HAQUE, S.M., 2013. Development of allometric equation for biomass estimation of eucalyptus camaldulensis: a study from Sagarnath Forest, Nepal. *Int J Biodiv Ecosyst*, vol. 1, pp. 1-7.

LITTON, C.M. and KAUFFMAN, J.B., 2008. Allometric models for predicting aboveground biomass in two widespread woody plants in Hawaii. *Biotropica*, vol. 40, no. 3, pp. 313-332. http://dx.doi.org/10.1111/j.1744-7429.2007.00383.x.

BRADFORD, L.E., 1990. *Agroforestry in Afghanistan/prepared by Lester Ezar Bradford*. Kabul: Afghan Digital Libraries.

SOTTA, E.D., VELDKAMP, E., GUIMARAES, B.R., PAIXAO, R.K., RUIVO, M.L.P. and ALMEIDA, S.S., 2006. Landscape and climatic controls on spatial and temporal variation in soil CO2 efflux in an Eastern Amazonian Rainforest, Caxiuana, Brazil. *Forest Ecology and Management*, vol. 237, no. 1-3, pp. 57-64. http://dx.doi.org/10.1016/j.foreco.2006.09.027.

SHELDRICK, R. and AUCLAIR, D., 2000. Origins of agroforestry and recent history in the UK. In A.M. HISLOP and J.N. CLARIDGE, eds. *Agroforestry in the UK*. Edinburgh: Forestry Commission, pp. 7-16.

CAIRNS, M.A., BROWN, S., HELMER, E.H. and BAUMGARDNER, G.A., 1997. Root biomass allocation in the world's upland forests. *Oecologia*, vol. 111, no. 1, pp. 1-11. http://dx.doi.org/10.1007/s004420050201. PMid:28307494.

BROWN, S. and LUGO, A.E., 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. *Biotropica*, vol. 14, no. 3, pp. 161-187. http://dx.doi.org/10.2307/2388024.

CHAVE, J., RÉJOU-MÉCHAIN, M., BÚRQUEZ, A., CHIDUMAYO, E., COLGAN, M.S., DELITTI, W.B., DUQUE, A., EID, T., FEARNSIDE, P.M., GOODMAN, R.C., HENRY, M., MARTÍNEZ-YRÍZAR, A., MUGASHA, W.A., MULLER-LANDAU, H.C., MENCUCCINI, M., NELSON, B.W., NGOMANDA, A., NOGUEIRA, E.M., ORTIZ-MALAVASSI, E., PÉLISSIER, R., PLOTON, P., RYAN, C.M., SALDARRIAGA, J.G. and VIEILLEDENT, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, vol. 20, no. 10, pp. 3177-3190. http://dx.doi.org/10.1111/gcb.12629. PMid:24817483.