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CARBON SEQUESTRATION AND PRODUCTION OF *Eucalyptus camaldulensis* PLANTATIONS ON MARGINAL SANDY AGRICULTURAL LANDS

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Among different available options of storing and sequestering the atmospheric carbon, the use of perennial woody vegetation is an efficient, cheaper and environmental friendly strategy. Understanding the growth habit of trees under hostile environmental conditions and their capacity to sequester CO_2 is of great interest for forestry scientists. The main objectives of the study were to analyze the growth habit of *Eucalyptus camaldulensis* on sandy marginal lands, assess the tree carbon stocks on sandy soils and to examine the potential of study area to play a role in environmental improvement while reducing the atmospheric CO_2. The study was carried out in Noorpur Thal region of Punjab. A survey of the study area was carried out through a pre-tested questionnaire and measurements of trees were taken *in situ* to calculate the biomass and carbon stocks. It was found that 19.47% of the Noorpur Thal region was covered by Eucalyptus plantations while this area can be potentially covered up to 55%. The growth habit and biomass production of *Eucalyptus camaldulensis* trees was excellent when grown on marginal sandy soils with proper irrigation. The total carbon stocks present were about 1.80 Mega ton and the CO_2 sequestration rate was observed about 6.58 Mega ton year^{-1}. However, at 55% potential, this area can sequester the 18.59 Mega ton of C worth about US$ 1459.315 million. This study might be extended to quantify the CO_2 sequestration potential if further 6.5 million hectares saline and waterlogged marginal lands are afforested in Pakistan with *Eucalyptus camaldulensis* plantations.
Keywords; Climate change, carbon dioxide flux, carbon sequestration, afforestation, carbon stocks.

INTRODUCTION

Continuous net positive CO_2 fluxes towards atmosphere due to fossil fuel burning, deforestation, land use change and other anthropogenic actions are directly resulting in climate change and global warming (Dixon *et al*., 1994; Falkowski *et al*., 2000). If the situation persists during next 100 years, the temperature of earth would increase about 2 °C and climate change phenomenon would result in the extinction of 20-30 % plants and animals with negative impacts on biodiversity (Franco *et al*., 2006; Solomon *et al*., 2007; Mcmahon *et al*., 2011). To avoid the predicted drastic scenario, this global issue was addressed by international community in the forms of international conferences and promotion of adaptation strategies: Kyoto Protocol and United Nations Framework Convention on Climate Change. The findings of these adaptive strategies and current understanding of the global carbon cycle indicate that, among other options, managing forests and agricultural lands is the credible option to increase sequestration of CO_2 as well as other greenhouse gases (GHG) (Niu and Duiker, 2006; Nabuurs *et al*., 2008; Lin *et al*., 2012). Moreover, under Kyoto Protocol Article 3, carbon sequestered through afforestation (land use change of agricultural lands) can be used as carbon credit by industrialized countries to meet their commitments of GHG emission's reduction (Niu and Duiker, 2006).

During photosynthesis, trees absorb the atmospheric CO_2 and fix it. They act as carbon sink by storing the carbon as their biomass. However, net long term CO_2 storing dynamics of trees change with age, disease and death (Nowak *et al*., 2013). Over the past decade, numerous studies assessed the carbon sequestration capacity of various woody plants and quantified their contribution towards the global carbon cycle (Niu and Duiker, 2006; Juwarkar *et al*., 2011; Kumar and Nair, 2011; Biswas *et al*., 2014; Maggiotto *et al*., 2014). Afforestation and other forestry activities are now well recognized as a part of strategies to mitigate GHG (Mckenney *et al*., 2004; Bellassen and Luyssaert, 2014; Biswas *et al*., 2014; Maggiotto *et al*., 2014). Afforestation of agricultural lands is a cost effective and environment friendly strategy for carbon sequestration (Mckenney *et al*., 2004; Richards and Stokes, 2004; Niu and Duiker, 2006) that has the great potential (Masera *et al*., 2003; Jindal *et al*., 2008; Juwarkar *et al*., 2011). Though some studies raised their objections on establishing new tree plantations with the objective of carbon sequestration because of the possibility of carbon leakage after forest fire or its use as fuelwood

(Yemshanov *et al*., 2012) but this limitation can be removed by focusing on such methods that could increase the C storage in harvested wood products (Nepal *et al.,* 2012).

Afforestation of marginal lands not only provide the economic returns to farmers but also contribute a lot to environmental services such as reduction in soil erosion, sand dunes stabilization, micro-climate moderation and carbon sequestration (Nunes *et al*., 2011; Sauer *et al*., 2012; Djanibekov *et al*., 2013). Many previous studies have analyzed the beneficial effects of afforestation of marginal agricultural lands in terms of socio-economic uplift and increment in soil fertility (Djanibekov *et al*., 2013; Djanibekov and Khamzina, 2014; Nawaz *et al*., 2013). However, there are few studies that have assessed the carbon sequestration status and potential of marginal lands (Parks and Hardie, 1995; Markewitz *et al*., 2002; Niu and Duiker, 2006; Qin *et al*., 2011). Keeping in view the forest status in Pakistan (only 2.2% forest cover) and sustainability in wood supply, there is urgent need of tree planting on agricultural lands (Khan *et al*., 2007; Nawaz *et* al., 2014). Marginal lands can be efficiently utilized for this purpose.

Noorpur Thal area is rainfed sandy area with water table at 0-20 ft at some places while below 100 ft at other places (TMA, 2008). Usually, gram cultivation is carried out in this region but recently, after the commencement of several national and international agroforestry projects, the farmers are extensively planting *Eucalyptus camaldulensis* in the areas where water table is higher (0-20 ft) due to better profitability in short time period (3-5 years). The income obtained from tree plantation, is 12 times more than gram cultivation (personal views of farmers). The assessment of carbon storage status and potential by these eucalyptus plantations are crucial to quantify the environmental services provided by trees and the management of carbon resources in relation to environment. These natural sites serve as experimental areas to study the status and potential of marginal lands for C storage and their findings can be employed to improve the understanding of selecting the tree species for afforestation of marginal lands among other available options. This is the first study in Pakistan on the carbon sequestration in agroforestry systems. Hypothesis was developed either afforestation of marginal lands can play a vital role in carbon sequestration or not. The main objectives of the study were to assess the tree carbon stocks and CO_2 sequestration potential of marginal lands in Noorpur Thal region, Punjab. The development of allometric equations for *Eucalyptus camaldulensis* trees in the sandy soils of Noorpur Thal was also the secondary objective of this study.

MATERIALS AND METHODS

***Study site*:** Noorpur Thal is a Tehsil of District Khushab and is located at 31°98' N and 71°91' E (Fig. 1). The climatic conditions are very severe because winter is extremely cold (minimum daily temperature below 0°C) and summer season

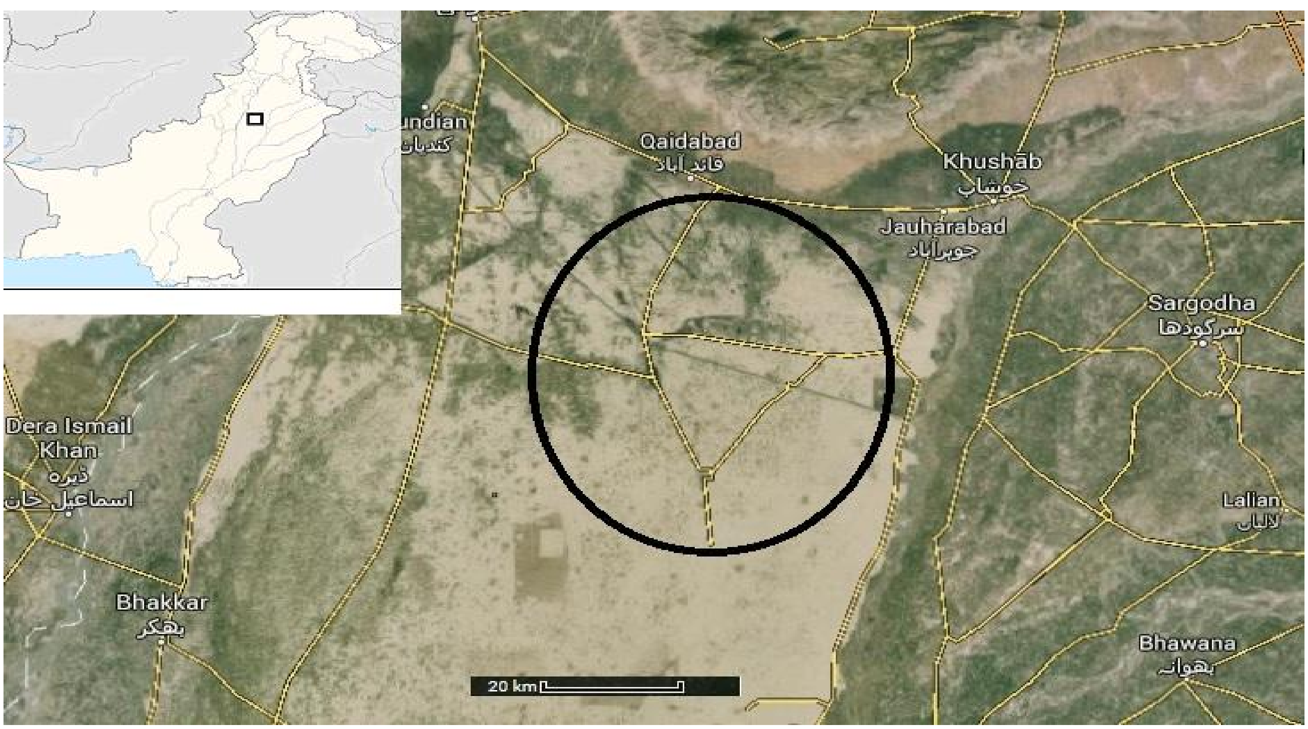

Figure 1. Location of study area (Noorpur Thal).

Table 1. Climate of study area.

Months		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Precipitation	(mm)	13.0	17.0	22.0	13.0	11.0	23.0	69.0	64.0	29.0	3.0	4.0	6.0
Avg. Temp.	°C	12.0	14.9	20.2	26.2	31.2	34.7	33.0	32.1	30.5	25.8	18.9	13.5
Min. Temp.	°C	4.0	7.3	12.7	18.4	23.1	27.4	27.6	27.0	24.2	17.6	9.9	4.8
Max. Temp.	°C	20.1	22.6	27.7	34.0	39.4	42.0	38.5	37.2	36.9	34.1	28.0	22.3

is very hot (maximum daily temperature 50°C) like any other desert. The average annual rainfall is about 274 mm. The hottest month is June and the maximum rainfall is received in July as described in Table 1.

The major area of Noorpur Thal is consisted of desert with the marginal lands. The marginal lands can be described as lands with value of production equal to its cultivation costs they are found at the edge of desert or in other isolated areas. The people of Noorpur Thal mainly grow grams because of arid conditions. They broadcast the seeds of grams before the rainy season. If there is timely and sufficient rainfall then lush green crops of gram is obtained which is about 370-500kg/ ha. Now the people of Noorpur Thal are shifting the land use in favor of *Eucalyptus camaldulensis*. About 1793 trees per hectare are planted with row to row distance of 6ft and plant to plant equal to 10ft. They irrigate with underground water to eucalyptus seedlings during the first year. Afterwards, the trees get their water from soil and also depend upon the rainfall. After 3 to 5 years, eucalyptus plantations are sold in local market. The second time plantation is developed by coppicing. So, only 5 age groups were available in the field for eucalyptus plantations ranging from 1 to 5 years.

Soil samples were taken from eucalyptus plots at a depth of 0-15 cm and 16-30 cm to determine the physico-chemical properties of soils (Dalun *et al*., 2009). Saturated soil paste was made by adding distilled water in 250 g soil sample, then pressure was applied with a filter paper and extract was obtained from saturated soil (Richard, 1954). To prevent salts's precipitation, one drop per 25 mL sodium hexametaphosphate (1%) solution was added. The soil pH was determined from saturated soil paste, electrical conductivity (EC) from soil extract, total nitrogen by Ginning and Hibbard's method (Jackson and Barak, 2005), available phosphorus (Page *et al*., 1982), a model PFP.7 Jenway flame spectro photometer was used for potassium determination, and soil organic matter was determined (Walkley and Black, 1934). A brief description of physico-chemical properties of soil is given in Table 2. Sodium and calcium were found under detection limit in our sandy soil samples.

***Data collection*:** To know about the actual status of planted area and potential of tree plantation in the study area, a survey was conducted in 10 union councils of Noorpur Thal. In each union council, 2 villages were selected and 5 farmers were selected from each village to respond one page questionnaire, for seeking information about total land holding, tree planted area and potential planted area. The information obtained from 100 farmers was analyzed statistically to determine the actual planted area and potentially planted area in Noorpur Thal region. Total area of Noorpur Thal is 2,50,000 ha. Out of it, 49175.89 ha (about 19%) area was under eucalyptus plantation and about 55% area was to be desired by farmers to put under plantation.

Table 2. Soil properties under *Eucalyptus camaldulensis* based plantations.

	0-15 cm	**15-30 cm**
pH	7.9±0.1	7.8±0.1
EC (dSm^{-1})	2.2±0.1	2.19±0.2
Phosphorus (ppm)	2.5±0.3	2±0.2
Potassium (ppm)	60±6.0	61±8
Nitrogen (%)	0.008±0.003	0.0035±0.005
Organic Matter (%)	0.14±0.05	0.07±0.02
Sand (%)	97±0.5	94.5±1
Silt (%)	2.5±1.0	2.5±0.5
Clay (%)	0.5±0.25	3±1.0

From the above mentioned villages (20 villages), about 100 tree samples were selected for each (1, 2, 3, 4 and 5 years) age group. Total 500 samples of eucalyptus trees were measured for various parameters. The heights of tree were determined by Graduated pole (15 ft limit) and Hega altimeter depending upon the suitability. Their girths were measured by tailor tape at breast height. Height and girth measurements were employed to measure the tree volume at breast height by using cylindrical formula (Afzal and Akhtar, 2013). Then 5 trees per age group were harvested to calculate the true volume with the help of Samalian's formula. By this method, correction factor was obtained. Calculated volume at breast height was multiplied with this correction factor to determine the true volume of each tree as reported by Afzal and Akhtar (2013).

***Estimation of C*:** Carbon stock and CO_2 sequestration rate were determined by using the standard methods in the literature by employing the true tree volume (Niu and Duiker, 2006; Juwarkar *et al*., 2011; Kumar and Nair, 2011; Afzal and Akhtar, 2013). The below ground root mass was supposed 20% more than above ground biomass, so, it was added into above ground biomass and dry biomass was calculated by omitting 27.5% moisture (Barton and Montagu, 2006; Afzal and Akhtar, 2013). Carbon was estimated about 50% of dry biomass of the tree. To estimate the monetary value, carbon storage and carbon sequestration were multiplied with $78.5 per ton of carbon as described by Nowak *et al*. (2013).

RESULTS

The Figure 2 represents the growth trends in *Eucalyptus camaldulensis* Dehn. Foresters are always interested to know the growth habit of the tree species before providing any recommendations to farmers for their suitability in agroforestry. It can be observed that with the increment in age, there is parallel increase in primary as well as secondary growth.

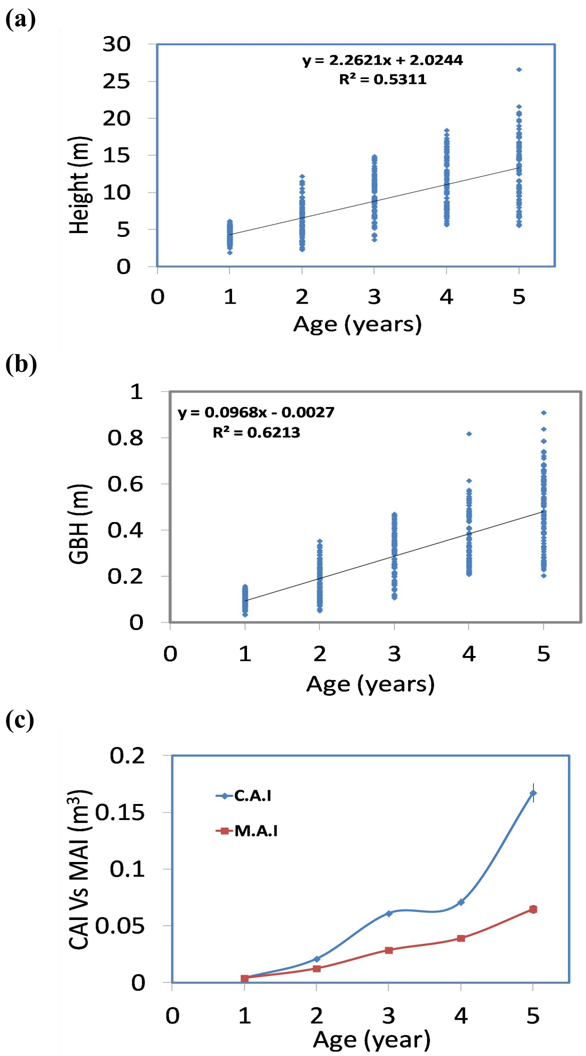

Figure 2. Increment in growth of *Eucalyptus camaldulensis* with respect to age; a. Age vs Height; b. Age vs Girth; c. Age vs volume increment.

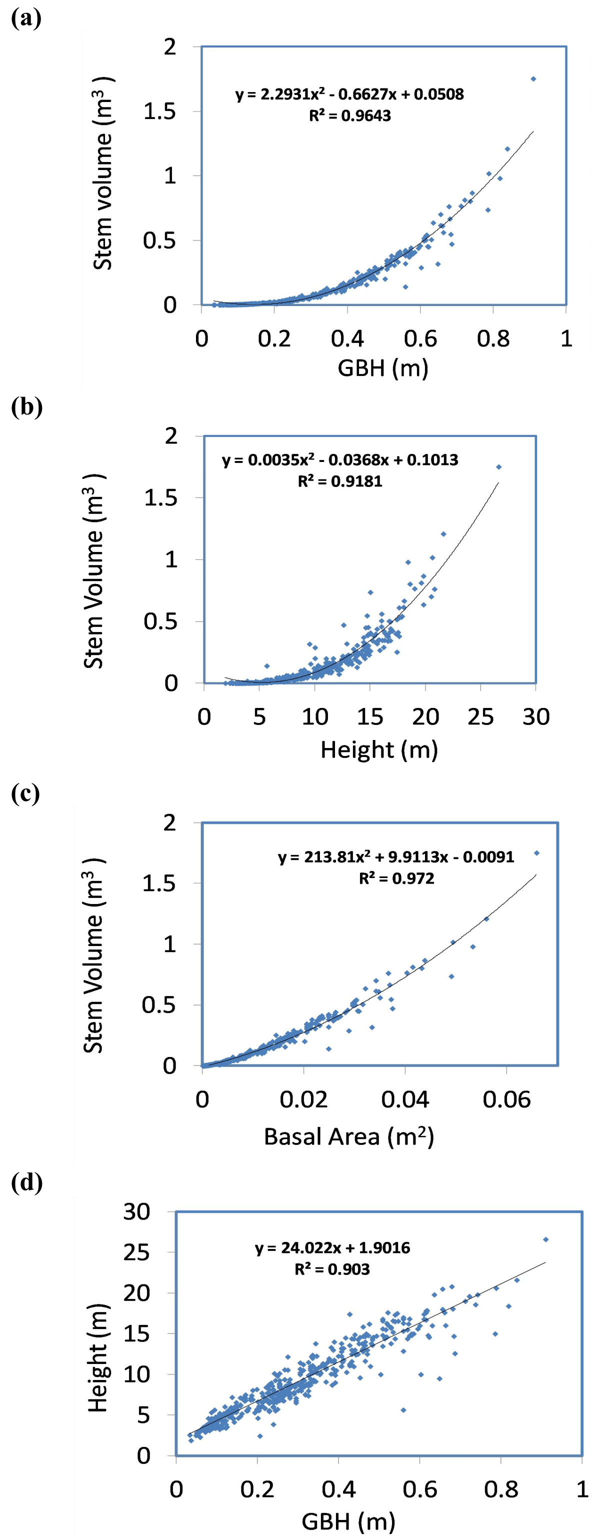

Figure 3. Inter-relation of various growth parameters of *Eucalyptus camaldulensis* tree species.

The average heights (m) for *E. camaldulensis* were observed 4.27, 6.26, 9.28, 11.06 and 13.18 after 1st, 2nd, 3rd, 4th and 5th years of age respectively. Similarly, after 1st, 2nd, 3rd, 4th and 5th years of age of *E. camaldulensis*, the average girths at breast height (GBH) were 0.10 m, 0.18 m, 0.30 m, 0.37 m, and 0.49 m respectively. Moreover, it was observed that *E. camaldulensis* tree species can attain the maximum heights (m) of 6.16, 11.49, 14.4, 17.8 and 26.6 (Figure 2a) while GBH (m) of 0.16, 0.35, 0.46, 0.81 and 0.91 (Figure 2b) after the age of 1st, 2nd, 3rd, 4th and 5th years respectively in the study area. It was observed that the maximum average increment in height (3.02 m) and GBH (0.12 m) was occurred after 3rd year of growth as compared to other years. The relation between age and GBH was stronger ($r^2 = 0.621$) than the relation between age and height ($r^2 = 0.531$) of *E. camaldulensis* trees.

The relation between age and average annual volume increments of trees has been represented in Figure 2c. It can be observed that current annual increment (CAI) increased and became the maximum after 5th (0.16 m^3) while minimum during first year (0.0039 m^3). Similarly, mean annual increment (MAI) was the maximum during 5th year (0.064 m^3) as compared to all other years.

The relations between primary and secondary growth are represented in Figure 3. These relations help to understand the nature of tree species. Furthermore, these relations can be utilized to develop growth models and volume tables for any species. The Figure 3 shows that there is strong relation between primary and secondary growth. The relation between stem volume (m^3) and GBH (m) is comparatively stronger ($r^2 = 0.961$) than between stem volume and height ($r^2 = 0.92$) as presented in Figure 3a and 3b. Similarly, the relations between lateral expansion and vertical expansion (Figure 3c and 3d) are very strong and r^2 value is above 0.90 for *E. camaldulensis*.

The Figure 4 represents the carbon stocks and annual carbon sequestration rate in the study area. It can be observed that maximum carbon stocks of the area are in the form of 4th year tree plantations (0.60 mega tons) and plantations of 4th year are sequestering the highest amount of CO_2 annually (2.21 mega tons). The carbon stocks in the 1st, 2nd, 3rd and 5th are 0.062, 0.13, 0.49, 0.55 mega tons respectively. Moreover, annual carbon sequestration rate by 1st, 2nd, 3rd and 5th year plantations are 0.62, 0.49, 1.78 and 2.035 respectively. Results of Figure 4 can be better understood with Table 3.

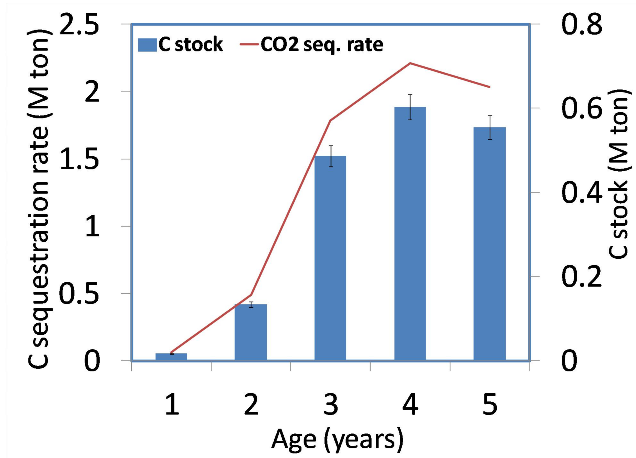

Figure 4. Carbon sequestration rate and carbon stocks of *Eucalyptus camaldulensis* based plantations in Thal area.

It can be observed in Table 3 that planted area is the maximum under 2nd and 3rd year of plantation but minimum under 5th year plantations. In spite of smaller covered area by 4th year of plantations as compared to plantations of other age groups, , they are providing more services to stock C and sequester CO_2 as compared to other age group plantations. Total carbon stocks of the study area were calculated as 1.80 mega tons with annual sequestration rates of 6.58 mega tons. From the results obtained from questionnaire based survey of the area, it was found that the study area is 19.47% covered with plantations but it can be covered up to 55% with *Eucalyptus camaldulensis* plantations. So, this area has the potential of annually sequestering 18.59 mega tons of CO_2 worth of US$ 1459.315 million.

DISCUSSION

Table 3. Actual status and potential of carbon sequestration by Eucalyptus based plantations on marginal lands in Noorpur Thal region.

Age (Years)	Planted area (%)	C stocks (Mega tons)	Annual CO_2 sequestration (Mega tons)	Potential planted area (%)	Potential CO_2 sequestration (Mega tons)
1	3.70 ± 0.05	1.80 ± 0.05	6.58 ± 0.21	55 ± 5	18.59 ± 1.69
2	5.66 ± 0.13				
3	5.06 ± 0.16				
4	3.50 ± 0.09				
5	1.55 ± 0.10				
	19.47 ± 0.53				

*C stocks, sequestration rates are given as sum of all age classes for whole studied area

Mean heights for *E. camaldulensis* in this study were found similar to previous findings at about same tree density but mean GBH was slightly smaller as compared to reported in previous studies (Thoranisorn *et al*., 1991; Saint-Andre *et al*., 2005; Barton and Montagu, 2006) that can be attributed to prevailing set of climatic and edaphic conditions in the study area. So, the growth rate of *E. camaldulensis* tree species was not modified on sandy soils.

Rotation age of the tree is determined at the point where Current Annual Increment (C.A.I.) line intercepts the Mean Annual Increment (M.A.I.) line in the graph. However, no interception and continuous increase in C.A.I. and M.A.I in our study means trees are harvested before their rotation age, which is resulting in profit reduction for farmers. However, the farmers of this area are poor and they are always more interested in small quick incomes than larger delayed incomes. The higher values of C.A.I. and M.A.I. show that *E. camaldulensis* is fast growing tree species and responded very well to the given set of climatic and edaphic conditions in the study area.

Higher values of r^2 for regression relations between lateral and vertical growth show that *E. camaldulensis* species in the study area exhibited the smooth growth in both directions. The reason of excellent growth of *E. camaldulensis* in the study area can also be due to planting of proper tree density per hectare (1793 trees ha^{-1}). It has been reported that tree density above 2500 trees ha^{-1} results in more tree mortality. Moreover, the survival rate of trees is above 80%, if tree density of *E. camaldulensis* falls between 1100 to 2500 trees ha^{-1} (Thoranisorn *et al*., 1991).

Age is an important factor on which C stock and C sequestration rate are dependent. One year age trees sequestered little amount of carbon and with the increase of age the C stock and sequestration rate from 2^{nd} to 4^{th} year trees is increased. However, after 4^{th} year, tree C stock and C sequestration rate decreased because trees are often sold before reaching 5^{th} year of age, so, there is very less planted area under 5^{th} year of plantations. In addition, area under 4^{th} year plantations is more and they have larger biomass, so, they are sequestering more CO_2 as compared to all other age group plantations. In literature, it is widely reported that carbon stocks and carbon sequestration rate were increased with tree age (Luyssaert *et al*., 2008).

***Conclusion*:** The growth of Eucalyptus plantations on marginal sandy soils of Noorpur Thal region (in the presence of plenty of underground water) is excellent. These plantations are annually sequestering huge amount of atmospheric CO_2. This area has still huge potential for tripling the eucalyptus covered area and in annual carbon sequestration. There are several marginal lands of Pakistan with similar or harsher conditions than Noorpur Thal, which have the potential not only to serve as timber mines for this forest deficient country but also provide valuable environmental services in term of atmospheric CO_2 removal. *Eucalyptus camaldulensis* is one of the best options for water available marginal areas because it is fast growing tree species with well-established market value. In other marginal areas, native woody vegetation can, no doubt, substitute the *E. camaldulensis* species for both of the above mentioned services. However, grand initiatives are required at government level to farmer level to convert this wood deficient country into wood sufficient country.

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