

# Carbon Sequestration and Crop Productivity in Eucalyptus-Wheat Agroforestry System

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## ABSTRACT

Allometric relationships between Girth at Breast Height (GBH), height, age and carbon content in eucalyptus trees were established using 100 trees of age varying from 0.5 to 24 years, height from 1.20 to 21.10m and GBH from 6.10 to 74.92cm. Regression equation with GBH i.e.  $y = 2.224x - 35.80$ ,  $r^2 = 0.89$  ( $p < 0.01$ ) was found to be the most practical and precise for determining the carbon content in eucalyptus trees. The equation was applied in Eucalyptus-Triticum aestivum (wheat) agroforestry system established at farmer's field in Jabalpur, M.P. (India). Determination of carbon stock potential of eucalyptus trees in wheat-based agroforestry and its relationship with the productivity of the crop revealed that carbon content in eucalyptus trees increased when cultivated with wheat in agroforestry system. Although, this upsurge gradually declined with age of the trees with maximum (32.64%) in 1.5 years to 0.38% in 4.5 years old trees. Simultaneously, economic yield and crop biomass of wheat crop also declined with increase in age of eucalyptus trees. The results suggest that wheat can be cultivated with eucalyptus trees during initial two years of plantation to enhance carbon stock in trees without affecting crop productivity.

Key Words: *Eucalyptus urograndis*, Allometric Equation, Agroforestry System, Carbon Sequestration, Above Ground Biomass.

## INTRODUCTION

A major role of agroforestry is emerging in the domain of environmental services to mitigate the effect of climate change through microclimate moderation in the short run and contribute to carbon sequestration in the long run (Anon. 2014). Agroforestry has the potential for reducing forest degradation by supplying timber and fuel-wood, that would otherwise be extracted from adjacent forests, thereby reducing deforestation and contributing to the goals of REDD+ and Nationally Appropriate Mitigation Actions (NAMAs) (Minang, 2013). Below ground biomass of tree species under agroforestry systems is equivalent to that of primary forests although far greater than any of the crops and grass systems. The carbon sequestration potential of agroforestry systems in India is estimated between 0.25 – 19.14 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for tree component which is 30 percent more than its crop component (Sirvi et al. 2016).

Eucalyptus due to its assured market, highly lucrative returns and supportive government policies is

the most preferred tree species comprising over 71.6 per cent of the agroforestry plantations in India (Prasad et al. 2010, Dhillon et al. 2018). A good number of paper mills are located in Madhya Pradesh at Nepa Nagar, Amlai, Vidisha, Rewa, Ratlam, Shahdol etc. The state has 18 mills which account for 6.62 per cent of the total installed capacity of India. There is tremendous scope of eucalyptus-wheat agroforestry in the state of Madhya Pradesh which is world famous for its high-protein Sharbati wheat variety and others like Durum on one hand and has established paper mill industries having demand for quality eucalyptus on the other.

Reliable estimation of total biomass for standing trees and development of precise methods to quantify carbon stocked by tree species in agroforestry is inevitable considering their role in climate change mitigation. Species-specific models increase precision of AGB estimates due to significant differences in architecture and wood density of the trees (Ketterings et al. 2001). Various authors like Mandal et al. (2013), Poultouchidou et al. (2013), Chave et al. (2005),

Tamrakar (2000) and others have proposed biomass equation for other species of eucalyptus in different regions around the world. Also, there it has been argued to develop site specific equations for accurate estimation of above ground biomass for eucalyptus trees (Missanjo 2015).

Keeping in view the increasing scope of eucalyptus plantation in agroforestry and by state forest departments, the present study was specifically conducted with the following objectives: -

1. Development of biomass functions for eucalyptus trees in agroforestry systems in India.
2. Determining productivity of eucalyptus-wheat agroforestry system compared to their individual stands.

The results of the study will contribute to assess the ecological and economical impacts of eucalyptus-wheat based agroforestry systems for maximizing carbon sequestration and understanding their role in mitigating negative impacts of climate change.

## STUDY AREA

Plantation of *Eucalyptus urograndis* (a hybrid of *Eucalyptus grandis* and *Eucalyptus urophylla*) was raised at farmer's field in Majitha village (23°11'05.6" N, 79°47'23.5" E) of Jabalpur district, M.P. (India) (Figure 1) The plantation site has loam to sandy loam soil and humid subtropical climate. Summer starts by late March

and lasts up to June followed by the monsoon showers. The winter season begins by late November and lasts till early March. The average minimum and maximum annual temperature ranges between 32.6-18.9°C while area receives precipitation of 1279.5mm.

## METHODS

### Raising of Plantations and Establishment of Agroforestry Systems

A total of 6000 eucalyptus trees ha<sup>-1</sup> of different age (1.5, 2.0, 2.5 and 4.5 years) were planted in block design with spacing of 1m x 1m. Also, spacing of 3m was maintained after every two rows to carry out agricultural operations with ease.

Agroforestry systems were established by planting 1.5, 2.0, 2.5 and 4.5 years eucalyptus trees with *Triticum aestivum* (wheat) var. GW 322 as agricultural crop in a simple randomized complete block design. Eucalyptus trees of each age were planted separately into three 5m x 5m blocks with their respective control (without crop). Thus, a total of 5m x 15m area was allocated to 72 eucalyptus trees of each age (with crop) and their respective control (without crop). Also, a control without trees was also randomly established. The wheat crop was sown during last week of November and harvested during first week of April. Basal dose of chemical fertilizers viz., 80kg N, 60kg P, 40kg K and 25kg ZnSO<sub>4</sub>

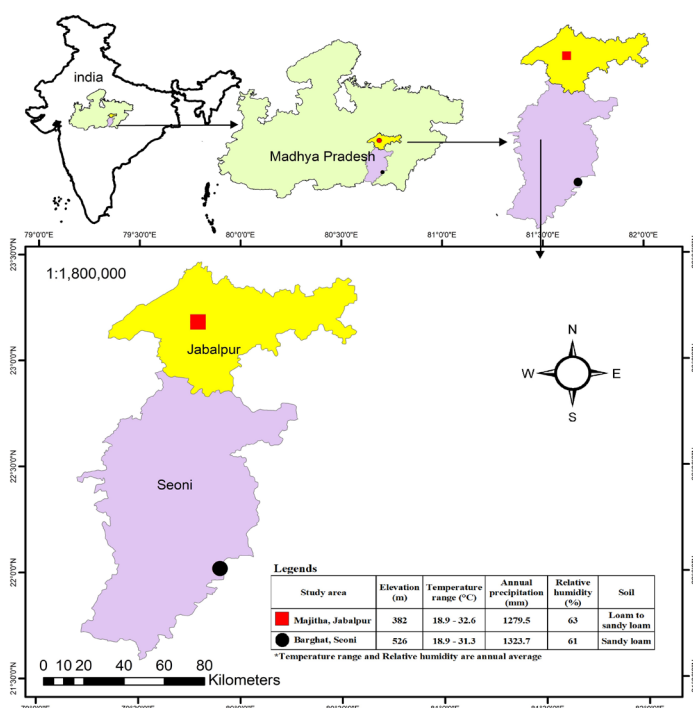


Figure 1. Map of the study area

per hectare was applied in the plots having wheat crop. Irrigation and weeding were conducted uniformly as per the demand of the crop. The control tree block and agroforestry system were adjacently located with similar soil, climate and elevation.

### Biomass and Carbon Estimation

Biomass estimates were obtained from 100 destructively sampled eucalyptus trees i.e., ten trees, each from ten different age groups (0.5, 0.75, 1.5, 4.5, 6.5, 8.5, 10.5, 12.5, 18.0 and 24.0 years). These trees were selected in time series plantations raised in Behrai forest range, Barghat forest division of Seoni district (22°01'19" N, 79°54'01" E) of Madhya Pradesh (India) having similar edaphic, climatic and other site conditions. Selected trees were cut from the base and Girth at Breast Height (GBH) and height of these trees were recorded. Thereafter, the trees were divided into four components i.e., main stem, branches, leaves, and bark and fresh weight of each was recorded followed by estimation of their oven dry weight (i.e.,  $Y_{\text{main stem}}$ ,  $Y_{\text{branches}}$ ,  $Y_{\text{leaves}}$  and  $Y_{\text{bark}}$ , respectively) at 60-80°C. The estimation of Above Ground Biomass (AGB) i.e.,  $Y_{\text{AGB}}$  from dry weight of different tree components was done as below:

$$Y_{\text{AGB}} = Y_{\text{main stem}} + Y_{\text{branches}} + Y_{\text{leaves}} + Y_{\text{bark}}$$

Below Ground Biomass (BGB) was calculated using 0.25 times AGB as per the guidelines of Intergovernmental Panel on Climate Change i.e.,

$$Y_{\text{BGB}} = 0.25 \times Y_{\text{AGB}}$$

Total Biomass in eucalyptus trees were calculated as by summing up AGB i.e., dry weight of leaves, branches and main stem and BGB:

$$\text{i.e., } Y_{\text{Total}} = Y_{\text{AGB}} + Y_{\text{BGB}}$$

$$\text{or, } Y_{\text{Total}} = 1.25 \times Y_{\text{AGB}}$$

The carbon content ( $y$ ) was considered 0.5 times the total dry biomass (AGB + BGB) of trees.

$$y = 0.5 \times Y_{\text{Total}}$$

### Development of Biometric Functions for Eucalyptus

Linear regression equations were plotted for calculated carbon content ( $y$ ) against each of the linked GBH, height and specific age of group of eucalyptus trees ( $x$ ). Also, linear regression equations were plotted for calculated carbon content ( $y$ ) in each of the four tree components against GBH:

$$y = ax - b$$

### Comparisons of Equations

The goodness of fit of models developed for GBH, height and age were evaluated by the coefficients of

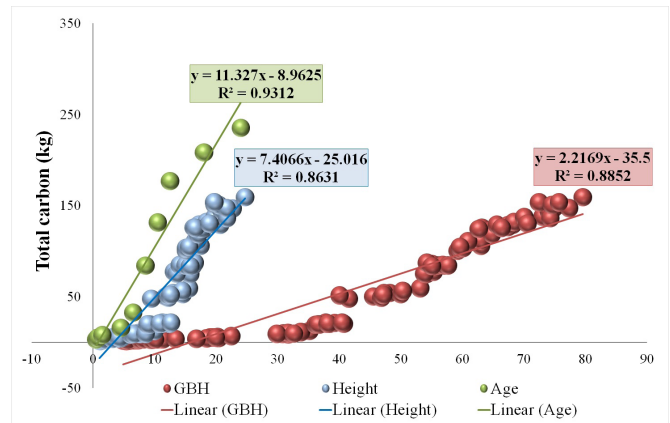


Figure 2. Relationship between GBH, height, age of trees and carbon in *Eucalyptus urograndis*

determination ( $R^2$ ) and Root Mean Square Error (RMSE) calculated as follows:

$$R^2 = \frac{N \sum xy - \sum x \sum y}{\sqrt{[N \sum x^2 - (\sum x)^2][N \sum y^2 - (\sum y)^2]}}$$

Where,  $N$  is total number of trees,  $x$  is GBH/height/age and  $y$  is the carbon content.

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(O_i - \epsilon_i)^2}{n}}$$

Where,  $O_i$  and  $\epsilon_i$  are observed and predicted carbon values of the  $n$  number of samples.

The development of equation and statistical analysis was performed by SPSS 16.0 and Microsoft Excel.

### Calculation of Carbon in Agroforestry Systems

The GBH of eucalyptus trees in agroforestry system was measured by a measuring tape in two consecutive years. Carbon content in agroforestry trees at Majitha was computed employing GBH based allometric equation developed from time series plantations of Seoni having comparable site conditions (Figure 2). The regression equations and correlation coefficients obtained for different variables of reference eucalyptus trees were statistically tested for significance at  $p < 0.05$ . Similarly, the computed carbon content in eucalyptus trees in different systems was also subjected to one-way analysis of variance. If data were found significant at  $p < 0.05$ , CD (critical difference) values were computed at  $p = 0.05$  or  $0.01$ , i.e.  $CD_{0.05}$  or  $CD_{0.01}$  for comparison of mean values obtained in different treatments.

Carbon in agricultural crop was estimated by destructive method by gently uprooting the wheat crop along with roots, washing, drying in hot air oven and weighing them till last two readings are constant.

### Calculation of harvest index of agricultural crop

Harvest index of agricultural crop was calculated by dividing economic yield with total crop biomass and then multiplying by 100.

### RESULTS

The GBH, height and total carbon of eucalyptus trees of different age groups varying from 0.5 to 24 years showed increasing trend with age of the trees. GBH ranged from 6.10 to 74.92 cm, height - 1.20 to 21.10 m and total carbon - 1.75 to 147.02 kg among the selected eucalyptus trees. Significant difference ( $p \leq 0.05$ ) was observed in GBH of the selected trees. The eucalyptus trees showed non-significant ( $p > 0.05$ ) increase in carbon content until the age of 4.5 years, after which it significant ( $p \leq 0.05$ ) difference in the carbon content (Table 1).

### Biometric Functions

Linear regression equations were developed for total carbon against GBH, height and age of trees (Figure 2) and for carbon content in different tree components against GBH (Figure 4). The goodness of fit statistics for the carbon equations against GBH, height and age of eucalyptus trees are given in Table 2 and for different components of trees against GBH in Table 3. The coefficient of determination indicated that the equations showed 88.52, 86.31 and 93.12 percent variance in total carbon content when plotted against GBH, height and

Table 1: Growth and carbon in age series plantation of *eucalyptus* hybrid

	Age of the trees (years)	Average GBH (cm)	Average height (m)	Total carbon (kg)
	0.5	6.10	1.20	1.75
	0.75	10.22	1.60	2.92
	1.5	19.65	4.00	4.86
	4.5	32.20	7.90	9.77
	6.5	38.21	10.80	20.25
	8.5	47.00	13.01	52.48
	10.5	55.51	15.05	82.00
	12.5	61.78	16.30	110.46
	18.0	67.89	18.70	130.15
	24.0	74.92	21.10	147.02
Mean	8.37	41.35	10.97	56.17
SD	7.77	24.17	7.09	56.99
SE ( $\pm$ )	-	1.0699	0.8691	3.8918
CD <sub>0.05</sub>	-	2.2477	1.8260	8.1763
CD <sub>0.01</sub>	-	3.0796	2.5018	11.2020

Where, SD= Standard Deviation; SE= Standard Error; CD= Critical Difference

age, respectively (Table 2). Coefficient of determination between GBH and different AGB components indicated 89.05% for main stem, 85.82% for branches, 83.40% for leaves, 82.16% for bark and 88.52% against AGB (Table 3). All the parameter estimates were significant at  $\alpha = 0.05$ . The RMSE for validation of the developed equations was the lowest in age (14.18), followed by GBH (18.37) and height (20.07) (Table 2), which was supported by the scatter plots for difference in estimated

Table 2: Goodness of fit statistics for carbon equations for eucalyptus trees in central India

Equation	Coefficient	SE	R <sup>2</sup>	RMSE	Significant F (p-value)	Significant t (p-value)
GBH: $y = 2.2169x - 35.5$	2.2169	0.081	0.8852	18.37	0.000	0.000
Height: $y = 7.4066x - 25.016$	7.4066	0.298	0.8631	20.07	0.000	0.000
Age: $y = 7.0793x - 5.6011$	7.0793	0.680	0.9312	14.18	0.000	0.000

Where, y = Total carbon; x = GBH/height/age; SE= Standard Error; R<sup>2</sup>= Coefficient of determination; RMSE= Root Mean Square Error

Table 3: Goodness of fit statistics for carbon equations for different components of eucalyptus trees in central India

Equation	Coefficients	SE	R <sup>2</sup>	Significant F (p-value)	Significant t (p-value)
Main stem $y = 0.9803x - 15.191$	0.9803	0.035	0.8905	0.000	0.000
Branches $y = 0.3161x - 5.0017$	0.3161	0.013	0.8582	0.000	0.000
Leaves $y = 0.1134x - 1.7949$	0.1134	0.005	0.8340	0.000	0.000
Bark $y = 0.2513x - 4.5819$	0.2513	0.012	0.8216	0.000	0.000
(Above Ground Biomass (AGB) $y = 1.6627x - 26.625$	1.6627	0.060	0.8852	0.000	0.000

Where, y = Carbon in the component; x = GBH; SE= Standard Error; R<sup>2</sup>= Coefficient of determination

and predicted values of the parameters (Figure 3).

The GBH based linear regression equation  $y = 2.2169x - 35.5$  was used to compute carbon in eucalyptus trees in the agroforestry system under the study due to its applicability in both plantations and natural forests where the age of trees is unknown and difficult to estimate. Negative values of carbon at initial stage of growth of eucalyptus trees corresponding to about 16 cm GBH, 3-4 m height and 0.5-1 year age of trees sets limits for use of the developed allometric equations. Such observation supports frustum structure of trees associated with resumption of secondary growth attaining woody nature.

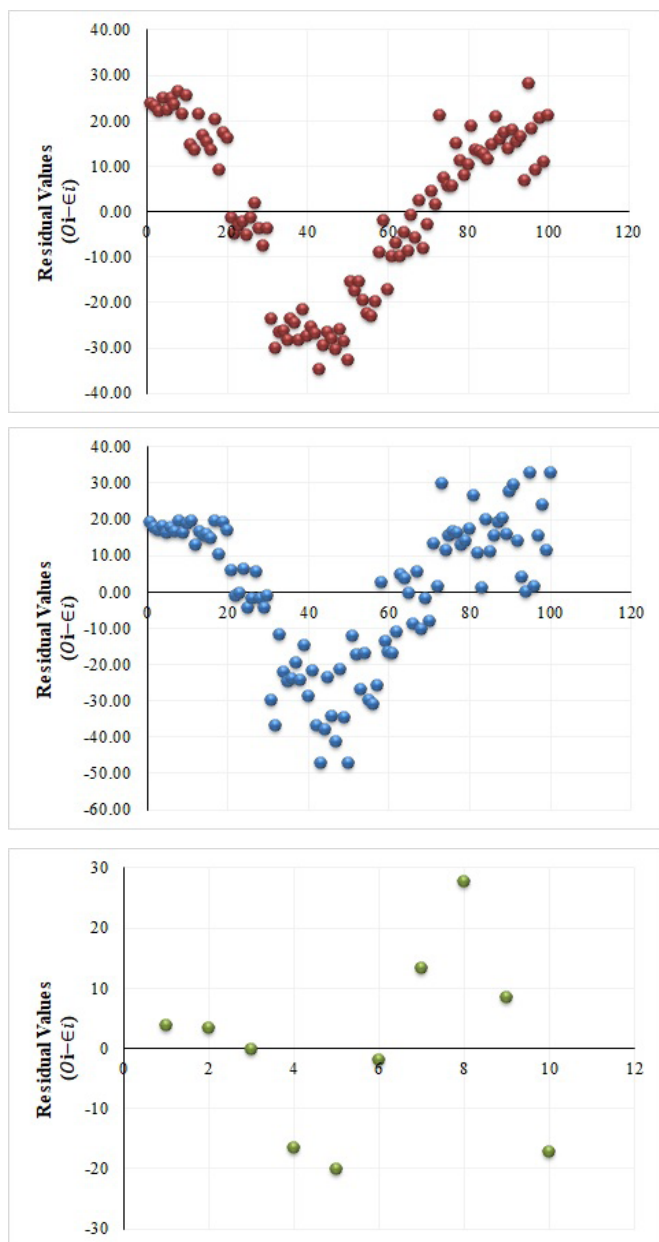


Figure 3. Residual scatter plot of carbon with a) GBH b) Height and c) Age in *Eucalyptus urograndis*

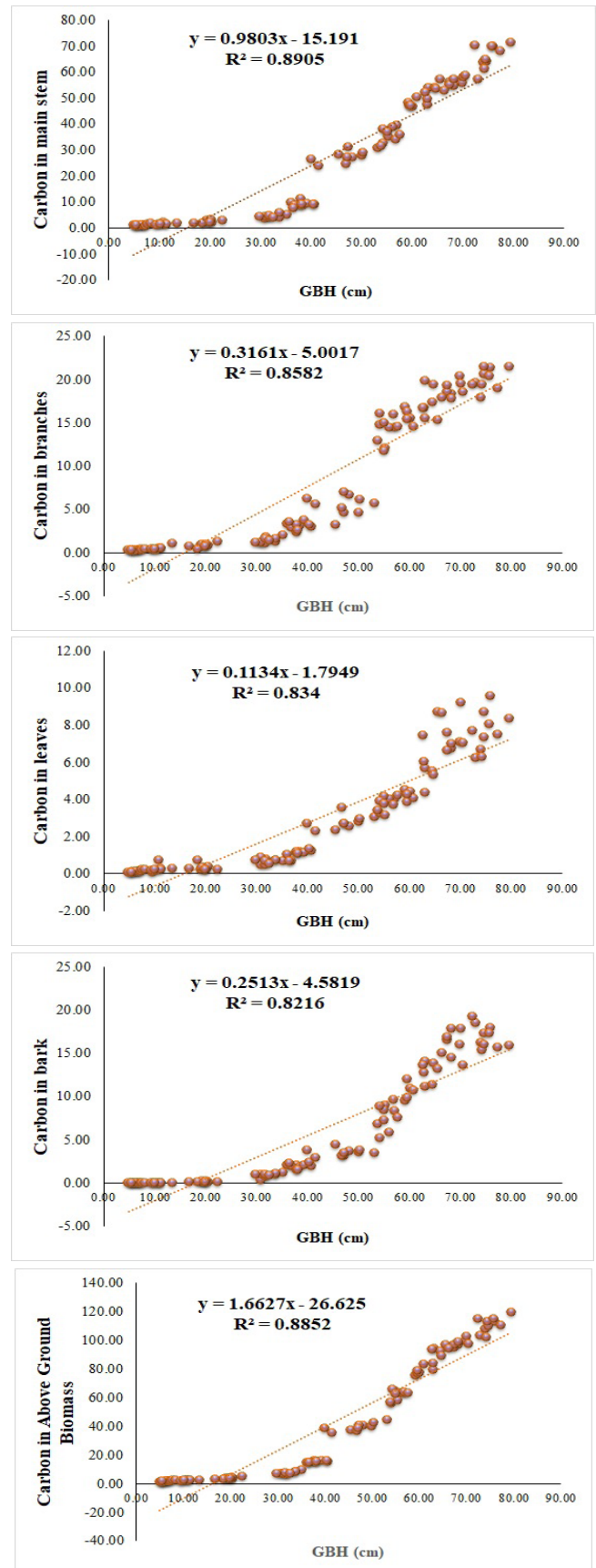


Figure 4. Relationship between GBH and carbon in various tree components a) main stem b) branches c) leaves d) bark and e) Above Ground Biomass (AGB) in *Eucalyptus urograndis*

### Productivity of Eucalyptus-Wheat Agroforestry System

Carbon content in trees of the agroforestry systems was more when compared to the monoculture trees of same age class without the agriculture crops. This increase in carbon content in agroforestry systems declined significantly ( $p \leq 0.05$ ) with age in their respective monoculture plantation counterpart without agriculture crop, ranging from 32.64% in 1.5 years old trees, 13.68% in 2 years old trees, 3.45% in 2.5 years old trees and 0.38% in 4.5 years old trees (Table 4).

The overall productivity of the wheat-eucalyptus agroforestry system was estimated by calculating economic yield and total crop biomass. Wheat yield in the control experiment (without trees) was compared with agroforestry system having different aged eucalyptus trees. Economic yield, stover mass and total crop biomass of wheat was found maximum in agriculture crop without trees and decreased significantly ( $p \leq 0.05$ ) with increase in age of the reference eucalyptus trees in the established agroforestry systems. Crop biomass reduced to 11.68% with 1.5 years, 24.22% with 2 years, 33.55% with 2.5 years and 46.20% with 4.5 years old

eucalyptus trees in comparison to control plots (without trees) (Table 5).

### DISCUSSION

Timber trees exhibits regular taper from base to first branch/ fork, in branches and further at different levels. It maintains frustum like structure whose volume {i.e.  $V = \pi h/3(R^2 + Rr + r^2)$ } is mathematical function of radius (maximum R; minimum r) or height (h) (Socha and Kulej 2007). Tree biomass, a function of wood density and volume is quantified by either destructive method or allometric equations, which relate dry biomass and hence carbon to measurable variables like GBH, height and wood density (Brown et al. 1989). Wood density varies with species (Sterck et al. 2001, Swaine and Whitmore 1988), tree age (Fujimoto et al. 2006), life-history strategy (King et al. 2005) and environmental factors such as topography and slope aspect (Hultine et al. 2005). But it is by and large, same for different individuals of a species implying that the biomass depends majorly upon volume of trees, thereby on GBH and height.

Table 4: Effect of wheat crop on carbon stock in eucalyptus trees

Age of trees (Years)	With or without crop	GBH (cm)	Total carbon/tree* (kg)	Total carbon ( t ha <sup>-1</sup> )**	Increase in carbon stock (%)
1.5	With	18.78	5.97	35.80	32.64
	Without	18.12	4.50	26.99	
2.0	With	22.83	14.97	89.84	13.68
	Without	22.02	13.17	79.03	
2.5	With	26.90	24.03	144.15	3.45
	Without	26.54	23.22	139.35	
4.5	With	34.67	41.31	247.84	0.38
	Without	34.60	41.15	246.90	
	SE ( $\pm$ )	0.1969			
	CD <sub>0.05</sub>	0.4222			
	CD <sub>0.01</sub>	0.5860			

Where, SE= Standard Error; CD= Critical Difference

\* Total carbon/ tree area based on AGB and BGB

\*\* Total carbon/ ha is based on 6000 trees/ ha

Table 5: Crop biomass and harvest index under different aged eucalyptus trees

Age of trees (years)	Economic yield (t ha <sup>-1</sup> )	Stover mass (t ha <sup>-1</sup> )	Crop biomass (t ha <sup>-1</sup> )	Harvest index	Decrease in crop biomass (%)
Control (without trees)	4.82	8.51	13.33	36.16	--
1.5	4.15	7.62	11.77	35.26	11.68
2.0	3.77	6.23	10.10	37.33	24.22
2.5	3.42	5.44	8.86	38.60	33.55
4.5	2.75	4.42	7.17	38.35	46.20
SE ( $\pm$ )	0.2269	0.2534			
CD <sub>0.05</sub>	0.5233	0.5843			
CD <sub>0.01</sub>	0.7614	0.8501			

Where, SE= Standard Error; CD= Critical Difference

The present study depicts significant correlations between carbon content of trees with GBH and height (Figure 2). The values of coefficients of determination in our study for carbon content against GBH, height and age vary from 0.93-0.88. Precise measurement of height or determination of age in a stand is time consuming and rather difficult (Larjavaara and Muller-Landau 2013, Chave et al. 2004; Nelson et al. 1999). Moreover, trees of same age may attain different growth due to genetic diversity in forestry species deterring use of age as a reliable parameter for computing AGB. Hence, most allometric models for biomass, in tropical forests are based solely on Girth at Breast Height (GBH) (Chambers et al. 2001, Ryan et al. 2004, Chave et al. 2004) as in this case is to estimate carbon directly. Brown et al. (1989) advocated use of GBH and height for quantifying AGB while Williams and Schreuder (2000) suggested not using height for such computation. Basuki et al. (2009) also favors GBH based allometric equations for Dipterocarp forests as 95% confidence interval of such models is closer to the observed values. Gupta et al. (2006) have established DBH based non-linear functions for estimating AGB of *Eucalyptus tereticornis* in central India, but biomass functions for this species in agroforestry systems in India is less explored.

The present study uses GBH to compute carbon in eucalyptus trees in agroforestry systems with *Triticum aestivum* agricultural crop (Table 4). Carbon stock increased in eucalyptus trees when cultivated with short term agricultural crop, which could be due to ample supply of water and nutrients made available to agricultural crop, regular soil working and increase in organic carbon in the soil from continuous addition of agricultural residues (Dhyani et al. 2009). Increase in carbon content declined with age of the trees with maximum increase (32.64%) in 1.5 years old to 0.38% in 4.5 years old trees. The decline in above ground production can be regarded to decline in photosynthetic capacity with increasing age or due to hydraulic limitation (Ryan et al. 2004).

Economic yield and crop biomass of wheat decreased with increase in eucalyptus tree age, which is due to increasing dominance of the trees as they mature (Ong et al. 2004) and compete with crops for light, water and nutrients (Ong and Huxley 1996). Tree roots extend to considerably greater distances and depths in comparison to crop roots (Stone and Kalisz 1991). However, a significant decrease in root biomass, number and length with increasing soil depth is found in trees. Although tree roots use higher volume of soil than crop plants, this volume includes the surface soil layers

where crop roots are located, and thus there are chances for competition in the use of below ground resources (Schroth 1999).

## CONCLUSION

Land scarcity has largely contributed to the destruction of forests in the developing countries, hence there is great need for drafting policies to encourage raising tree plantations outside the forests. Trees Outside Forests (TOF) include trees in agroforestry systems, alongside fields, roads, within urban areas and parks. Agroforestry imparts ameliorating and mitigating effects on harsh and erratic climatic conditions and poor soils, raising soil fertility build-up and enhances symbiotic activities helping crop growth. With the increasing role of TOF in mitigating negative impacts of climate change, it becomes necessary to develop precise techniques to quantify carbon in tree components of agroforestry systems. Owing to the emphasis for TOF, scope and commercial demand of eucalyptus in paper and pulp industries, our study concludes with development of GBH based allometric equation and its use in precise computation of carbon stock in eucalyptus trees planted with wheat agriculture crop. Carbon stock increased in eucalyptus trees when cultivated with short term agricultural crop but this increase in carbon content significantly decreased with age of trees.

## ACKNOWLEDGEMENTS

The authors are grateful to Indian Council of Forestry Research & Education, Dehradun, India for financial assistance. Thanks are also due to Director, Tropical Forest Research Institute, Jabalpur for providing necessary facilities to carry out this work. We are also thankful to the research staff and research scholars of Forest Ecology and Climate Change Division for help provided during the course of study.

**Author contributions:** Dr. Avinash Jain planned and designed the study. He also contributed in data collection and finalization of the manuscript. Nidhi Mehta drafted the manuscript, compiled data and conducted statistical analysis.

**Conflict of interest:** Authors do not have any conflict of interest with respect to the publication of this manuscript.

## REFERENCES

Anonymous 2014. National Agroforestry Policy-2014. Department of Agriculture and Cooperation GOI. Retrieved from: <http://>

- [agritech.tnau.ac.in/ta/forestry/pdf/National%20Agroforestry%20Policy%202014.pdf](http://agritech.tnau.ac.in/ta/forestry/pdf/National%20Agroforestry%20Policy%202014.pdf). 29 pages.
- Basuki, T.M.; Van Laake, P. E.; Skidmore, A.K. and Hussin, Y.A. 2009. Allometric equations for estimating the above ground biomass in tropical lowland Dipterocarp forests. *Forest Ecology and Management* 257: 1684-1694.
- Brown, S.; Gillespie, A.J.R. and Lugo, A.E. 1989. Biomass estimation methods for tropical forest with applications to forest inventory data. *Forest Science* 35(4): 881-902.
- Chambers, J.Q.; Santos, J.; Ribeiro R.J.; and Higuchi, N. 2001. Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest. *Forest Ecology and Management* 152 (1-3): 73-84.
- Chave, J.; Andalo, C.; Brown, S.; Cairns, M.A.; Chambers, J.Q.; Eamus, D.; Foelster, H.; Fromard, F.; Higuchi, N.; Kira, T.; Lescure, J.; Nelson, B.; Ogawa, H.; Puig, H.; Riéra, B. and Yamakura, T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145: 87-99.
- Chave, J.; Condit, R.; Aguilar, S.; Hernandez, A.; Lao, S. and Perez, R. 2004. Error propagation and scaling for tropical forest biomass estimates. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 359(1443): 409-420.
- Dhillon, R.; Chavan, S.; Bangarwa, K.; Bharadwaj, K.; Kumari, S. and Sirohi, C. 2018. Eucalyptus-based agroforestry system under semi-arid condition in north-western India: An economic Analysis. *Indian Journal of Ecology* 45: 470-474.
- Dhyani, S.K.; Newaj, R. and Sharma, A.R. 2009. Agroforestry: its relation with agronomy, challenges and opportunities. *Indian Journal of Agronomy* 54(3): 249-266.
- Fujimoto, T.; Kita, K.; Uchiyama, K.; Kuromaru, M.; Akutsu, H. and Oda, K. 2006. Age trends in the genetic parameters of wood density and the relationship with growth rates in hybrid larch (*Larixgmelinii* var. *japonica* x *L. kaempferi*) F1. *Journal of Forestry Research* 11(3): 157-163.
- Gupta, A.; Rai, P. and Handa, A. K. 2006. Allometry for estimating above ground biomass of *Eucalyptus tereticornis* under energy and boundary plantations in central India. *Annals of arid zone* 45(2): 175-182.
- Hultine, K. R.; Koepke, D. F.; Pockman, W. T.; Fravolini, A.; Sperry, J.S. and Williams, D.G. 2005. Influence of soil texture on hydraulic properties and water relations of a dominant warm-desert phreatophyte. *Tree Physiology* 26(3): 313-323.
- Ketterings, Q.M.; Coe, R.; Noordwijk, M. V.; Ambagau, Y. and Palm, C.A. 2001. Reducing uncertainty in the use of allometric biomass equation for predicting above-ground tree biomass in mixed secondary forests. *Forest Ecology and Management* 146(1): 199-220.
- King, D.A.; Davis, S.J.; Supardi, M.N.N. and Tan, S. 2005. Tree growth is related to light interception and wood density in two mixed dipterocarp forests of Malaysia. *Functional Ecology* 19(3):445-453.
- Larjavaara, M. and Muller-Landau, H.C. 2013. Measuring tree height: a quantitative comparison of two common field methods in a moist tropical forest. *Methods in Ecology and Evolution* 4(9): 1-9.
- Mandal, R.; Kumar, B.; Yadav, B.V.; Yadav, K.; Ishwar, C.; Dutta, Shamsul, M. and Haque. 2013. Development of allometric equation for biomass estimation of *Eucalyptus camaldulensis*: A study from Sagarnath forest, Nepal. *International Journal of Biodiversity and Ecosystems* 1: 1-7.
- Minang, P.; Bernard, F.; Van Noordwijk, M.; and Kahurani, E. 2013. Agroforestry in REDD+: Opportunities and Challenges. ASB Policy Brief 26. ASB Partnership for the Tropical Forest Margins, Nairobi, Kenya 4 pages.
- Missanjo, E.; Kamanga-Thole, G. and Bonongwe, D. 2015. Allometric equations for estimation of above ground biomass of *Eucalyptus camaldulensis* in Malawi. *Journal of Basic and Applied Research International* 2: 41-47.
- Nelson, B.W.; Mesquita, R.; Pereira, J. G.; De-Souza, S.A. and Batista, G. and Couto, L.B. 1999. Allometric regressions for improved estimate of secondary forest biomass in the central Amazon. *Forest Ecology and Management* 117: 149-167.
- Ong, C.K. and Huxley, P. 1996. *Tree-Crop Interactions: A Physiological Approach*. CAB International and ICRAF, Wallingford. 389 pages.
- Ong, C. K.; Kho, R.M.; Radersma, S. 2004. Ecological interactions in multispecies agroecosystems: concepts and rules. pages 1-15, In: Noordwijk, M.V.; Cadisch, J. and Ong, C.K. (Editors) *Below-ground Interactions in Tropical Agroecosystems: Concepts and Models with Multiple Plant Components*. CABI, Wallingford.
- Poultouchidou, A.; Monnier, V. and Birigazzi, L. 2013. Inventory of allometric equations for estimation of above-ground tree biomass and volume in the Pacific. UN-REDD Programme, MRV report 17, Rome, Italy. 13 pages.
- Prasad, J.S.; Korwar, G.R.; Rao, K.V.; Mandal, U.K.; Rao, C.A. R.; Rao, G.R.; Ramakrishna, Y.S.; Venkateswarlu, B.; Rao, S.N.; Kulkarni, H.D. and Rao, M.R. 2010. Tree row spacing affected agronomic and economic performance of Eucalyptus-based agroforestry in Andhra Pradesh, Southern India. *Agroforestry Systems* 78: 253-267
- Ryan, M.G.; Binkley, D.; Fownes, J.H.; Giardina, C.P. and Senock, R.S. 2004. An experimental test of the causes of forest growth decline with stand age. *Ecological Monographs* 74(3): 393-414.
- Schroth, G. 1999. A review of belowground interactions in agroforestry, focusing on mechanisms and management options. *Agroforestry Systems* 43: 5-34.
- Sirvi, A.; Dhyani, S. and Dev, I. 2016. Potential of agroforestry systems in carbon sequestration in India. *Indian Journal of Agricultural Sciences* 86: 1103-1112.
- Socha, J. and Kulej, M. 2007. Variation of the tree form factor and taper in European larch of Polish provenances tested under conditions of the BeskidSadecki mountain range (southern Poland). *Journal of Forest Science* 53(12): 538-547.
- Sterck, F.J.; Bongers, F. and Newbery, D.M. 2001. Tree architecture in a Bornean lowland rain forest: intraspecific and interspecific patterns. *Plant Ecology* 153(1-2): 279-292.
- Stone, E.L. and Kalisz, P. J. 1991. On the maximum extent of tree roots. *Forest Ecology and Management* 46: 59-102.
- Swaine, M.D.; Whitmore, T.C. 1988. On the definition of ecological species groups in tropical rain forests. *Vegetatio* 75(1-2): 81-86.
- Tamrakar, P.R. 2000. Biomass and volume tables with species description for community forest management. Ministry of Forests and Soil Conservation, Government of Nepal, Kathmandu, Nepal. 37 pages.
- Tiepolo, G.; Calmon, M.; Ferretti, A.R. 2002. Measuring and monitoring carbon stocks at the Guaraqueçaba climate action project, Parana, Brazil. pages 98-115, In: Lin, K. and Lin, J. (Editors) *International Symposium on Forest Carbon Sequestration and Monitoring*. Extension Series, Taiwan Forestry Research Institute, Taipei, Taiwan.
- Williams, M.S.; Schreuder, H.T. 2000. Guidelines for choosing volume equations in the presence of measurement error in height. *Canadian Journal of Forest Research* 30: 306-310.

Received: 02 July, 2020

Accepted: 24 September, 2020