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CARBON ESTIMATION AND CARBON YIELD TABLE FOR TEAK (*TECTONA GRANDIS*) AT CAUVERY DELTA ZONE OF TAMIL NADU

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Teak plantations are generally managed for timber production and presently there is an increasing interest in understanding the carbon stocks of Teak plantation. A study was developed on carbon yield table for Teak in Cauvery delta zone of Tamil Nadu, India and field data was taken from 15 sample plots of 30 m × 30 m size in different age classes, for instance 4–5 years, 7–8 years, 12–13 years, 15–16 years, 18–19 years, 23–24 years, 40–41 years and 46–47 years, respectively. Tree height and diameter of 2 meter segments from ground level to top height were measured and the average merchantable volume of 1.246 m^3 and carbon content of 373.80 kg were recorded in the age class of 46–47 years. The carbon model constructed for *Tectona grandis* using multiple linear regression was Y = -113.001+2.8616(Age)-3.6946(Total height)+1245.813(Diameter). The carbon yield table was constructed using the age class, top height class and diameter class. The overall observation of the study concluded that, the best fit carbon yield models were developed for *T. grandis* with 91 per cent accuracy by comparing actual carbon stock and predicted carbon stock.

Keywords: Biometric data, carbon model, carbon sequestration, height, tree cultivation, teak, timber, yield model

INTRODUCTION

Globally, 420 million hectares of forests were lost since 1990 and most of the losses are in tropical countries as per the latest Forest Assessment Report 2020 of the Food and Agriculture Organisation of the United Nations (FAO 2020). Even though the New York Declaration on Forests (NYDF) in 2014 reported that 350 million hectares of forest should be restored by 2030, the loss of natural forest land in the tropics continues (NYDF Assessment Report 2019) till date. Despite the fact of forest loss, global forest plantations have grown dramatically from 167.5 million hectares (4.1 % of total forest area) in 1990 to 277.9 million ha (6.9 %) in 2015 (Payn et al. 2015) and about 20% of the latter are located in the tropics. Forest plantations are likely to play a critical role in future wood supply as natural forest timber supplies continue to diminish. Forest plantation growth and production are substantially higher than natural forest growth and output. (McEwan et al. 2020).

Despite positive outcomes in terms of timber growth and productivity, forest plantations' long-term viability remains a challenge due to price fluctuations and lack of financial assistance to encourage effective management techniques (Cuong et al. 2020). While there are a variety of options for supporting and encouraging long-term forest plantation management, carbon-based incentives are critical in ensuring deforested and degraded lands are recovered in order to meet the global Sustainable Development Goals (SDGs) that must be met in the coming years.

Recently, studies on the concern of forest plantations primarily focused on either timber production, paper production, or carbon stocks in natural forests (Usuga et al. 2010). There has been little research on the value of forest plantings for long-term timber production and climate change mitigation through appropriate exploitation of harvested wood products could be the basis for recognising the importance of carbon storage in harvested wood products. Since, the adoption of the Paris Climate Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) and the SDGs in 2015, the quantity of carbon stored in harvested wood products has regained attention in research; however, the research aspects still focused on national level discussion and assessment (Johnston & Radeloff 2019, Sato & Nojiri 2019).

Teak (*Tectona grandis*) is a tropical tree endemic to tropical forest of India, Indonesia, Malaysia, Myanmar, Northern Thailand and Northwestern Laos. Due to its durability and valuable timber, several countries in the tropics have begun to reforest their deforested lands with Teak (Kimambo et al. 2020, Veridiano et al. 2020). Aside from managing teak plantation for timber production, there has been a growing interest in understanding teak plantation carbon reserves (Chanan & Iriany 2014, Pelletier et al. 2020).

Yield table is a tabulation related to the prediction of growth/volume in reference to the given age, site/crop quality and sometimes other indices such as density, carbon, etc. (Alder 1980, Vanclay 1992, Vanclay 1994). Thus, a yield table is usually followed for the even-aged forest plantation rather than uneven-aged plantations. Yield table is measured by prediction of yield determination of site quality, estimation of growing stock at present/future, determination of increment of Current Annual increment and Mean Annual Increment, determination of rotation of maximum volume production and carbon stock of trees (Skovsgaard & Vanclay 2008). In order to predict the carbon content of trees at different age classes, height classes and diameter classes, a carbon yield table is essentially prepared and it will be used for long term based on the site-specific condition (Vanclay et al. 1995, Skovsgaard 2004).

Studies of carbon stock estimation, carbon yield table and prediction for the Teak trees planted in the farmer's plantation are very minimal. Moreover, these tree species are the source of wood-based industries of the country and is important to assess the productivity of tree species grown in farm settings. Carbon yield modeling and carbon yield table are suitable tools to assess and predict the yield and carbon of farm plantations and are accessible to the tree cultivators. This study emphasises the need for carbon yield table and carbon modeling for farm-grown trees and Tamil Nadu Forest Department plantations in Cauvery delta zone of Tamil Nadu.

MATERIALS AND METHODS

The study was carried out in Cauvery delta zone (Tanjaore, Tiruvarur and Nagapattinam) of Tamil Nadu for the preparation of carbon model and carbon yield table in *Tectona grandis*. The field data was taken from 15 quadrat sample plots of 30 m 30 m size in different age classes, which are 4–5 years, 7–8 years, 12–13 years, 15–16 years, 18–19 years, 23–24 years, 40–41 years and 46–47 years, respectively. They were grown by farmers and Tamil Nadu Forest Department both as block plantations and canal bank plantations. The biometric measurement namely tree height and diameter of 2-meter segments from the ground level to the top height were measured using laser distance meter. The measurement of diameter at the different height helps in neglecting the form factor used in preparation of carbon yield table.

Volume estimation

The collected data from the field was segregated into diameter and height classes. The volume of every 2-meter section was estimated using the formula given by Chaturvedi and Khanna (1982) and expressed in cubic meter (m^3).

$$V = \pi r^2 h$$

where, V = volume, r = radius, h = top height.

The calculated actual volume for every 2-meter segment from ground level to the top height was averaged and computed. This method reduced the error in volume estimation using form factor as it took into account the tapering in the standing tree.

$$V = V_1 + V_2 + V_3 + \ldots$$

where, V = total tree volume, V_1, V_2, V_3 = volume at every 2-meter section.

Carbon estimation

Tectona grandis wood samples of various age classes were collected separately, and later air and oven dried. Carbon concentration was estimated based on the ash percent as measured by Moore and Chapman (1986) by using oven dried biomass samples which were pulverised in a wiley mill. The carbon percent of *T. grandis* trees was calculated using the formula given by Dey (2005) and Dhruw et al. (2009).

$$\text{Carbon \%} = 100 \% - (\text{Ash \%} + \text{Molecular weight of } O_2 \text{ (53.3 \%) in } C_6H_{12}O_6)$$

The carbon stock in *Tectona grandis* was computed by using

Carbon (MT) = Biomass (MT) x Carbon percent

Carbon yield model for *Tectona grandis* using Multiple Linear Regression method

The Linear Multiple Regression method is used to model the relationship between the dependent and independent variable (Whittaker & Woodwell 1968). In this study, the age, tree height and diameter of the tree were defined as the independent variables and while tree carbon content was defined as dependent variable. The general equation developed through the Linear multiple regressions is

$$Y = a + b_1x_1 + b_2x_2 + b_3x_3$$

where, Y = carbon stock (kg), a = intercept, b_1 = age of the tree in years, b_2 = total height of tree, b_3 = diameter, x_1, x_2, x_3 = coefficients of b_1, b_2, b_3.

Carbon yield table construction

Age class, tree height class and diameter class intervals were fixed based on the growth performance and commercial duration i.e., up to which age the tree was retained by the farmers. Carbon content of the individual tree was estimated by substituting the age, height and diameter of the tree. The carbon stock was grouped and tabulated against the different age classes, tree height classes and diameter classes for the carbon yield table construction.

Validation of carbon yield model

The developed carbon yield model was validated using the residual plot analysis technique (Alder 1980). A set of biometric data, observed from the study area were selected for the validation. Actual carbon content of the selected biometric data was computed using the above methodology. The developed carbon model was used to compute the predicted carbon stock. The actual carbon stock and predicted carbon stock of the same data were regressed to validate the model. The smaller the residual sum of square values obtained, the closer the developed model was to the original data.

RESULTS AND DISCUSSION

Biomass and biomass carbon are the amount of organic matter stored in trees. The distribution of biomass in wood shows how much photosynthesis materials the tree has stored by the trees in its life time (Ketterings et al. 2001, Budiadi et al. 2017). The formation of a carbon yield table by observing the biometric attributes and volume calculation of wood is helpful in predicting the future carbon storage by trees.

Padugai Teak plantations (Canal bank plantations) of Tanjaore, Tiruvarur and Nagapattinam district in Cauvery delta zone of Tamil Nadu were recorded for its biometric attributes in 8 different age classes. The total height and average diameter of *T. grandis* had increased with the increase in age-class.

Volume estimation in *T. grandis*

Earlier studies in volume estimation for different tree species involved number of different variables to estimate the volume. Tree biometric attributes such as tree height, bole height, diameter at breast height, basal area, top diameter over bark were used to calculate the merchantable volume (Hahn 1984). Cao et al. (1980) compared volume ratio models and taper equation models to estimate the cubic volume prediction.

In the present study, the relationship of age and volume showed the steady increase of merchantable volume from age class of 4–5 year to the age class of 46–47 years in *T. grandis.* The volume of 0.112 m^3, 0.164 m^3, 0.197 m^3, 0.231 m^3, 0.320 m^3, 0.427 m^3, 0.712 m^3 and 1.246 m^3 were recorded in age class of 4-5 years, age class of 7–8 years, age class of 12–13 years, age class of 15–16 years, age class of 18–19 years, age class of 23–24 years, age class of 40–41 years and age class of 46–47 years, respectively were calculated by non-destructive sampling (Table 1 & Figure 1).

Mbaekwe & Mackenzie (2008) obtained similar results in the stem biomass increment in the 5 to 15 years old *T. grandis* plantations of Nigeria. They observed an increasing trend in the mean annual increment of stem biomass with the age and at the same time the results of Mbaekwe & Mackenzie (2008) also revealed that

Table 1 Carbon estimation & actual and predicated carbon stock of *Tectona grandis* in Cauvery Delta Zone of Tamil Nadu

Age	Height	Average diameter	Volume (m^3)	Weight (kg)	Actual carbon stock (kg)	Predicted carbon stock (kg)
4–5	8.86	0.121	0.112	67.20	33.60	18.54
7–8	7.52	0.156	0.164	98.40	49.20	71.50
12–13	9.96	0.158	0.197	118.20	59.10	78.52
15–16	10.49	0.165	0.231	138.60	69.30	96.73
18–19	12.72	0.178	0.320	192.00	96.00	113.27
23–24	13.53	0.200	0.427	256.20	128.10	151.99
40–41	12.38	0.268	0.712	427.20	213.60	289.60
46–47	16.27	0.312	1.246	747.60	373.80	347.22
				Total carbon stock	1022.70	1167.36
				Chi-square	1.000	
				R^2	0.911	

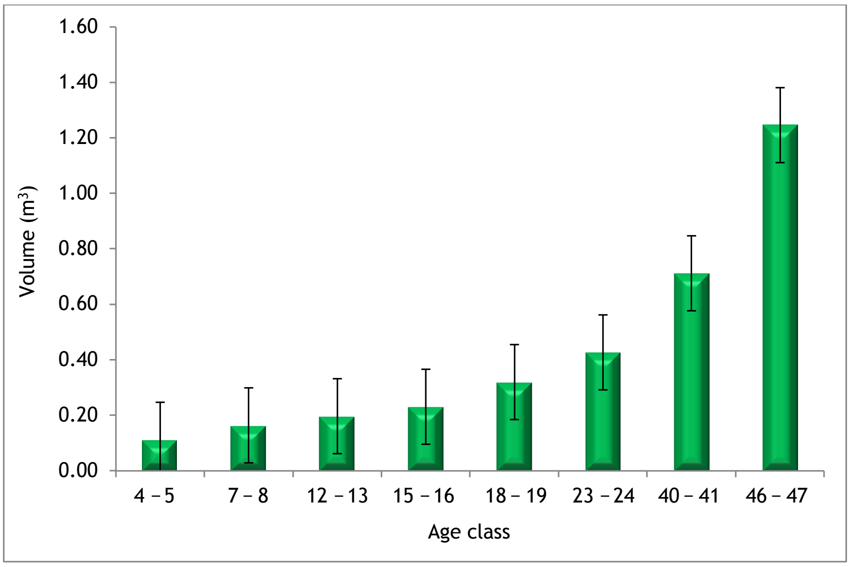

Figure 1 Effect of age class on volume production of *Tectona grandis* in Cauvery Delta Zone of Tamil Nadu

leaf biomass contribution to the total biomass decreased with the age of the plantation.

Carbon stock of *T. grandis*

The carbon stock of the *T. grandis* plantation was calculated for different age classes. The carbon stock (Table 1 and Figure 2) was ranged in the order of 33.60 kg (Age class of 4–5 years) > 49.20 kg (Age class of 7–8 years) > 59.10 kg (Age class of 12–13 years) > 69.30 kg (Age class of 15–16 years) > 96.00 kg (Age class of 18–19 years) > 128.10 kg (Age class of 23–24 years) > 213.60 kg (Age class of 40–41 years) > 373.80 kg (Age class of 46–47 years). The carbon stock ratio of 40–41 years old Teak (213.60) recorded in the present study was higher than tropical dry forest (Chaturvedi et al. 2011) but closer to many other plantation species and forests such as *T. grandis* of other regions (Faruqui 1972, Sharma & Naik 1989, Karmacharya & Singh 1992), *Cryptomaria japonica* (Tadaki et al. 1965), *Populus deltoides* (Kaul et al. 1983), montane rain forest (Jordan 1971), Oak-Pine forest (Whittaker & Woodwell 1968).

Carbon yield model and carbon yield table for *T. grandis*

Regression linear method had been used to develop the carbon yield table for *T. grandis*. Bermejo et al. (2003) classified the study area into site classes to develop yield model for *T. grandis* plantations

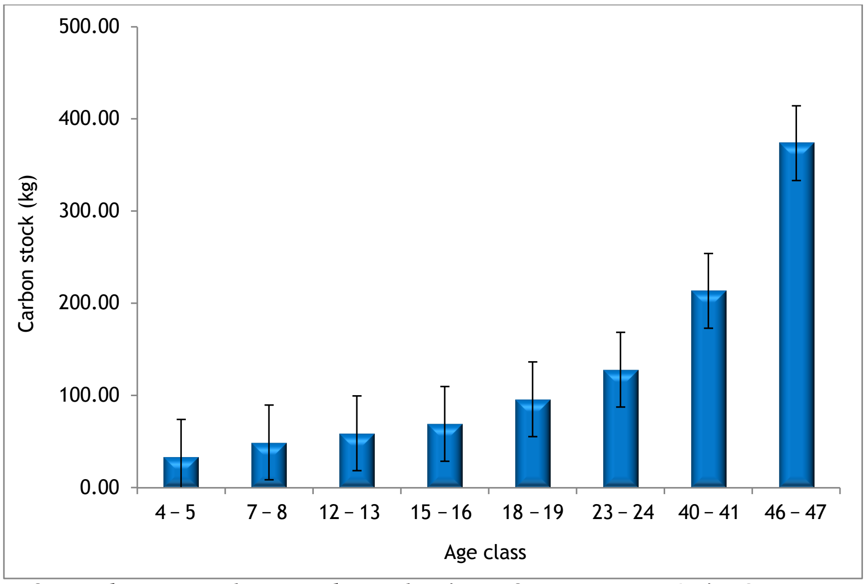

Figure 2 Effect of age class on carbon stock production of *Tectona grandis* in Cauvery Delta Zone of Tamil Nadu

in Costa Rica. Since the present study was site specific and efforts were made to develop the local carbon yield table for *T. grandis*, the whole study area was assumed to have an identical productivity. Besides, the study area selected for the *T. grandis* were incorporated under a single agro-climatic zone in respective of the tree species. The similar technique of multiple linear regression models was used by Mohammadi et al. (2011) to estimate the forest stand volume and tree density.

By using the biometric attributes, carbon yield model for *T. grandis* plantations of Cauvery delta zone was constructed using multiple linear regression,

$$Y = -113.001 + 2.8616X_1 - 3.6946X_2 + 1245.813X_3$$

Tree diameter, tree height and age of the *T. grandis* trees were selected as the independent explanatory variables to predict the dependent variable of carbon. In the recent studies on volume equation development for the important trees of Bangladesh (Miah et al. 2020, Jayaraman & Rugmini 2008) used tree diameter and bole height as the predictor variables.

The predicted carbon yield table was developed for *T. grandis* with 8 age different classes, consisted of age class of 4–5 years, 7–8 years, 12–13 years, 15–16 years, 18–19 years, 23–24 years, 40–41 years and 46–47 years. For the preparation of carbon yield table, the height class was categorised in the order of 1–5 m, 6–10 m, 11–15 m, 16–20 m and 21–25 m. While similarly, the diameter class was categorised into 0.01–0.10 m, 0.11–0.20 m, 0.21–0.30 m and 0.31–0.40 m (Table 2).

Validation of constructed carbon yield models for *T. grandis*

Validation is a step in the evaluation process that determines the level of accuracy (Pretzsch et al. 2002, Yang et al. 2004). While model validation has received a lot of attention in the literature, there is not much agreement on what constitutes a good technique and furthermore, there are few examples of entire model validation. This is not surprising since there are varieties of models, model applications, and tests available such as for individual tree, stand level and size distribution models and multiple linear regression (Schneider et al. 2014, Pretzsch et al. 2002). By comparing model predictions to real data, statistical validation analyses model bias and correctness.

The residual errors are visible in graphical displays of the residuals and the distribution of observed versus anticipated values, which assists in finding undesired trends (Sharma & Oderwald 2001, Pandey & Brown 2000, Rahman & Ahmad 2000, Bokalo et al. 2013). Biometric data observed from 8 different age classes of *T. grandis* plantation was used to validate the carbon yield model. Residual mean sum of square of the yield model

Table 2 Carbon yield table for *Tectona grandis*

Age class (Years)	Height (m)																			
	1–5				6–10				11–15				16–20				21–25			
	Diameter (m)																			
	0.01–0.10	0.11–0.20	0.21–0.30	0.31–0.40	0.01–0.10	0.11–0.20	0.21–0.30	0.31–0.40	0.01–0.10	0.11–0.20	0.21–0.30	0.31–0.40	0.01–0.10	0.11–0.20	0.21–0.30	0.31–0.40	0.01–0.10	0.11–0.20	0.21–0.30	0.31–0.40
1–5	-31.77	92.82	217.40	341.98	-13.29	111.29	235.87	360.45	5.18	129.76	254.34	378.92	23.65	148.23	272.82	397.40	42.13	166.71	291.29	415.87
6–10	-17.46	107.12	231.70	356.29	01.02	125.60	250.18	374.76	19.49	144.07	268.65	393.23	37.96	162.54	287.12	411.71	56.43	181.02	305.60	430.18
11–15	-03.15	121.43	246.01	370.59	15.32	139.90	264.49	389.07	33.80	158.38	282.96	407.54	52.27	176.85	301.43	426.01	70.74	195.32	319.90	444.49
16–20	11.16	135.74	260.32	384.90	29.63	154.21	278.79	403.38	48.10	172.69	297.27	421.85	66.58	191.16	315.74	440.32	85.05	209.63	334.21	458.79
21–25	25.47	150.05	274.63	399.21	43.94	168.52	293.10	417.68	62.41	186.99	311.57	436.16	80.89	205.47	330.05	454.63	99.36	223.94	348.52	473.10
26–30	39.77	164.36	288.94	413.52	58.25	182.83	307.41	431.99	76.72	201.30	325.88	450.46	95.19	219.77	344.36	468.94	113.67	238.25	362.83	487.41
31–35	54.08	178.66	303.24	427.83	72.56	197.14	321.72	446.30	91.03	215.61	340.19	464.77	109.50	234.08	358.66	483.25	127.97	252.56	377.14	501.72
36–40	68.39	192.97	317.55	442.13	86.86	211.44	336.03	460.61	105.34	229.92	354.50	479.08	123.81	248.39	372.97	497.55	142.28	266.86	391.44	516.03
41–45	82.70	207.28	331.86	456.44	101.17	225.75	350.33	474.92	119.64	244.23	368.81	493.39	138.12	262.70	387.28	511.86	156.59	281.17	405.75	530.33
46–50	94.14	218.73	343.31	467.89	112.62	237.20	361.78	486.36	131.09	255.67	380.25	504.83	149.56	274.14	398.73	523.31	168.04	292.62	417.20	541.78

was observed to be 91 percent. Residuals obtained in this study were distributed normally (Figure 3). The P-value of the Chi-square test was 1. The average actual carbon stock recorded was 1022.70 kg and predicted carbon stock as per the carbon yield model developed was 1167.36 kg. The observation concluded that the predicted carbon stock was 9 percent deviated from the actual carbon stock obtained (Figure 4). The minimum residual sum of square was observed from the present study and the observed chi-square value confirmed the good fit of model to the data.

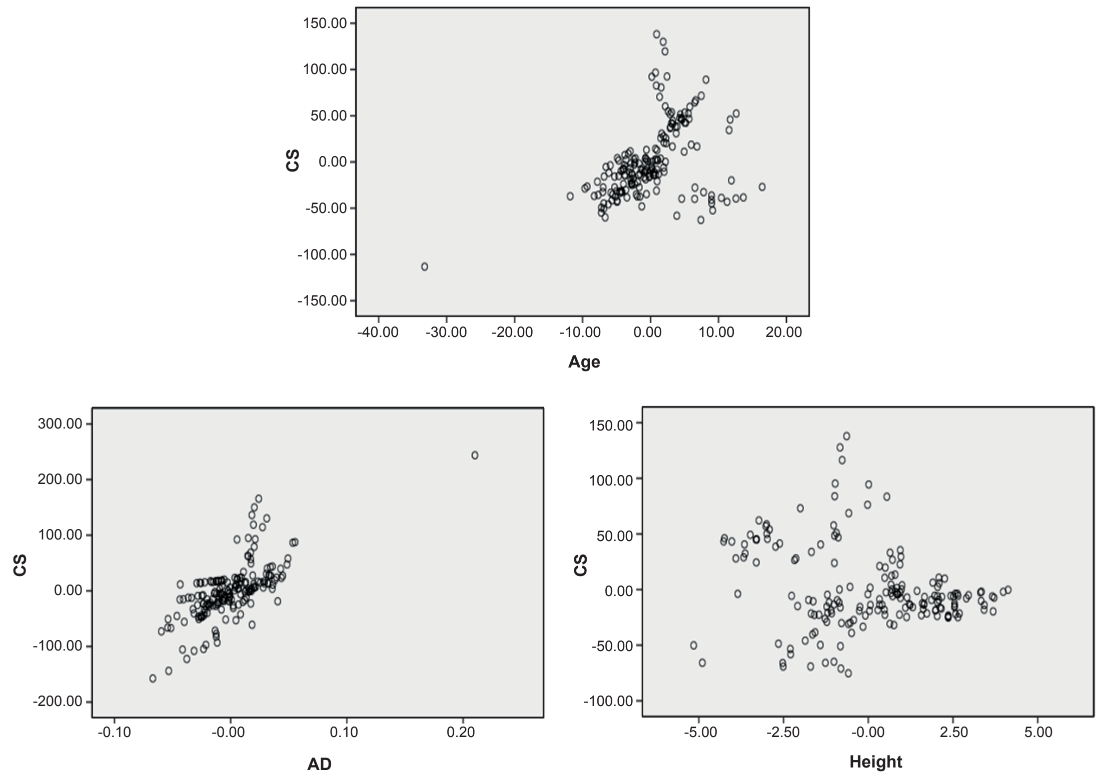

Figure 3 Graph of carbon stock and other independent variables (Age, Height and Diameter) CS = carbon stock, AD = average diameter

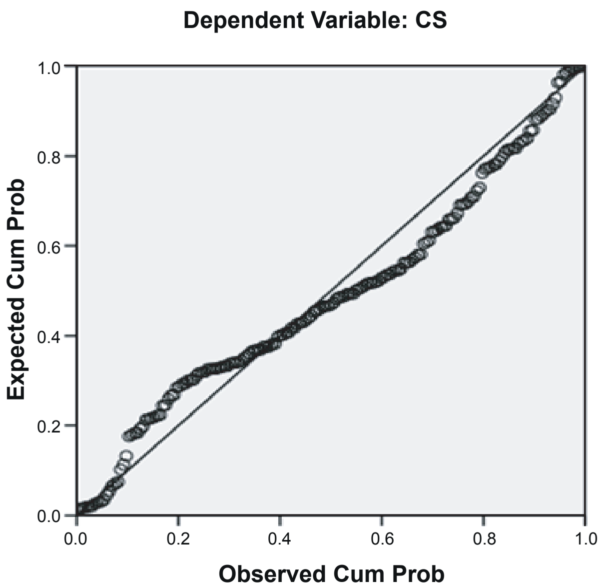

Figure 4 Graph of the actual carbon stock versus predicted carbon stock

CONCLUSION

This study concluded that a user-friendly carbon yield model and carbon yield table was prepared for *T. grandis* in respect to the site-specific location (Cauvery delta zone of Tamil Nadu). The best fit carbon yield model was developed by multiple linear regression method with 91 percent accuracy by comparing the actual carbon stock and predicted carbon stock.

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