Biomass Production and Carbon Sequestration by *Pongamia pinnata* (Linn) Pierre in Tropical Environment

Priyanka Bohre[1], O. P. Chaubey[1] and P. K. Singhal[2]

[1]*State Forest Research Institute, Jabalpur – 482008, M.P. India*
[2]*Rani Durgawati University, Jabalpur- 482001, M.P. India*

pribohre@gmail.com, chaubey.dr@gmail.com, pksinghalrdvv@gmail.com

Abstract

The significance of role of biomass of tree species in carbon sequestration has long been recognized. In the present paper, attempts have been made to work out biomass accumulation and carbon sequestration by Pongamia pinnata (Linn) Pierre raised on coal mine overburden of Northern Coal Field Limited, Singrauli (India), adopting non harvest technique. The age of plantation varied from 2 to 18 years. The correlation between basal area vs volume, dbh vs volume and basal area vs total biomass was found to be significant. In terms of vertical and horizontal growth, Pongamia pinnata proved as an efficient species. The net biomass production and carbon sequestration of Pongamia pinnata showed increasing trend with the age of plantations.

Keywords: Carbon sequestration, biomass accumulation, non harvest technique, allometric equation, plantation forests

1. Introduction

In the current scenario of climate change (Manua Loa observatory 2013) and Reducing Emissions from Deforestation and Forest Degradation (REDD) and REDD plus (ISFR 2011; Ravindranath *et al.*, 2012), eco-restoration on degraded ecosystems is the need of the hour. National Afforestation Programme (NAP) and National Mission for Green India (GIM) are being implemented in the country. It is estimated that addition or improvement of forest and tree cover by implementing the various forestry related programmes will add 2 million tonnes of carbon incrementally every year, and post 2020, the forest and tree cover will be adding at least 20 million tonnes of carbon every year (Sud *et al.*, 2012; GIM Report 2012). The National Afforestation Programme (NAP) aims to restore degraded forests.

Because of importance of carbon pools in tropical forests and in the plantation systems, many organizations around the world carried out studies related to forest biomass and carbon storage in recent decades. Many workers studied biomass production of tropical forests and different species by actual harvest at a predetermined age and allometric equations relating biomass with one or more tree dimensions (Kira et al. 1964; Ogawa *et al.*, 1965; Hozumi *et al.*, 1969; Odum and Pigeon 1970; Jordan 1971; Whitemore 1975; Edwards and Grubbs 1977; Enright 1979; Tanner 1980; Negi *et al.*, 1984; Prasad and Mishra 1984; Prasad *et al.*, 1984; Rai 1984; Sharma and Srivastava 1984; Chaturvedi 1984). The results might be quite

different, if the age of assessments had changed. Generation of allometric equations that involve felling of trees is impracticable in the current scenario of climate change. Thus, it is required to adopt non harvest techniques and acceptable level of accuracy. The present paper deals with the suitability of *Pongamia pinnata* for biomass accumulation and carbon sequestration in the degraded ecosystem of coal mine.

2. Materials and Methods

Singrauli (24° 46' 60''- 24° 78' 33''N, 82° 49' 59''- 82° 83' 30''E, 275 -500m AMSL) was granted District Status on 24th May 2008, with its headquarter at Waidhan. Vegetation during pre-mining period was very dense and covered with Northern tropical dry sal forests (5 B/C) and Northern tropical dry mixed deciduous forests (5 B/C 2). Due to mining, the large forest areas were clear felled and laid barren. The present study covered artificial plantations raised in eight open cast project (OCP) sites viz; Jayant, Dudhichua, Amlohri, Jhingurdah, Nigahi, Bina, Kakari and Khadia of Northern Coal field Limited (NCL) Singrauli, India (Figure 1).

For the estimation of biomass, non harvest technique was adopted. The growth data was collected for total height and girth at breast height (gbh) over bark. Besides, the length of tree after gbh had been divided into different segments of one meter each up to the tip of the tree. The girth at over bark of each segment was measured at the center of the segments throughout the height of the tree for minimizing the tapering effect. The girth was measured without felling trees with the help of climbers. Girth was converted to diameter by dividing π, *i.e.*, 3.14. Volume was calculated for each imaginary segment using cylindrical cross sectional areas, multiplied by height of each segment ($\pi r^2 h$). Total volume of the bole was worked out by adding the volumes of different imaginary segments starting from gbh to top of a height and the volume of the base segment (*i.e.*, below gbh). The dbh, total height and total volumes were fed in SPSS software using computer. On the basis of the maximum coefficient of determination (R^2) and the minimum standard error, the best fit model was computed for the species. Multiple regression equations were tried to establish the correlation between the dbh and height, between dbh and volume, and the biomass and dbh.

The stem wood biomass was worked out by multiplying volume with wood density (Reyes *et al.*, 1992) of *Pongamia pinnata*. The stem wood biomass was then "expanded" to total above ground biomass of tree including leaves, twigs, branches, bole and bark using biomass expansion factor (BEF).

Total above ground biomass = Stem wood volume X Wood density X BEF

The mean BEF value of 1.5 was used for this study as prescribed by Brown and Luge (1992). The below ground biomass was calculated by using simple default value of 25% (for hardwood species) of the total above ground biomass as recommended by IPCC (2006). Wood density information was presented in units of oven dry weight in gm^{-3} (*i.e.*, tonne m^{-3}) of green volume. Multiple regression equations were tried to establish the correlation between the biomass and dbh and / or bole biomass. The amount of carbon in a standing tree was calculated by dividing its biomass by 2 as per the guidelines of IPCC (2006), and was expressed in tonne $tree^{-1}$ and tonne ha^{-1}. Carbon content was then multiplied by 44/12 to estimate CO_2.

Nursery raised seedlings were used for this purpose. Fifteen randomly selected seedlings of each species were harvested for measuring their height and dry weight (dried at 104°C till the constant weight obtained). The average height and dbh of each species according to age were taken to estimate volume. The best fit equation was then applied to determine the

accumulation of total biomass (above- and below- ground) and carbon content. The initial value of biomass and carbon in a seedling of a species was then subtracted from its corresponding estimates to obtain realistic amount of biomass accumulation and carbon sequestration by a tree. Per tree accumulation of biomass was multiplied by the actual number of seedlings usually planted per hectare (*i.e.*, 3333) to express the values in tonne ha^{-1}. The biomass and carbon tables were prepared after making volume growth tables. The best fit regression equation was determined using SPSS software to prepare volume growth tables. The general volume equations (GVEs), i.e. regression function in volume diameter and height, were selected for each species. The nine regression equations, as used by Forest Survey of India (FSI 1996), were attempted to determine the best equation for estimating volume overbark (VOB) for this species. After getting values of constants for best fit equation, the actual volumes as well as those predicted by the equation were tabulated and computed. The biomass tables for above - and below- ground biomass were prepared separately for different diameter and height classes for *Pongamia pinnata*. The table for the total biomass of a tree was obtained by adding its values of above and below ground biomass. The projected biomass tables for above- and below- ground and total biomass were also prepared using data of volumes estimated for tree of different dbh (2 cm interval) and height (1 m interval) class. The biomass was expressed in tonne tree^{-1}.

3. Results

One hundred three trees (each having ≥ 5 cm dbh) were randomly selected from total trees to quantify their biomass and carbon. The diameter and girth at breast height varied widely from 6.36 to 34.36 cm and 20 to 108 cm mainly due to variation in the age of tree in different plantations. Total height ranged from 2 to 17.32 m. The height varied significantly within a gbh or dbh class, denoting that vertical growth of trees varied among different sites due to variation in growth factors. For example, the height of trees with dbh of 7.00 cm varied from 3 to 9 m. Such variations were observed in all age classes. The volume of trees varied positively and linearly in response to variation in its basal area (r=0.953, r^2=0.909). The variation in basal area could explain nearly 91% of the variation in volume. Therefore, basal area could be a good predictor of volume in trees. The total biomass of trees varied positively and linearly with variation in its basal area (r=953, r^2=0.909). Basal area explained a higher proportion (i.e. 91%) of variation recorded in total biomass. Though, diameter at breast height was used to estimate basal area, it could explain relatively lower amount of variation in volume (r=0.940, r^2=0.884). dbh could hardly explain 88% of variation recoded in volume of trees. The minimum and maximum volume values of trees were computed between 0.00781 m^3 and 0.40646 m^3, minimum and maximum total biomass values of trees ranged between 0.008347 tonne tree^{-1} and 0.434401 tonne tree^{-1} and the value of carbon sequestered varied from 0.004174 (minimum) to 0.2172000 tonne tree^{-1} (maximum), respectively. The linear correlation between basal area and volume, dbh and volume, and basal area and total biomass among 103 trees taken for actual measurement was found to be significant with the values of R^2 being 0.909, 0.884 and 0.909, respectively. The values of R^2 are closer to 1, which indicates that the better the line fits the data (Figure 2).

Trees measured for estimation of biomass accumulation and carbon sequestration were taken from 2, 4, 5, 6, 8, 9, 10, 13, 14, 15 and 18 years old plantations. The seedlings used for plantations had the average height of 0.55 m. The average dbh in different year's plantations

showed increasing trend with the advancement of age. In different aged plantations of 2, 4, 5, 6, 8, 9, 10, 13, 14, 15 and 18 years, the average dbh were 2.5 cm, 3.6 cm, 5.5 cm, 6.7 cm, 8.8 cm, 10.2 cm, 11.5 cm, 15.0 cm, 16.9 cm, 19.7 cm and 27.8 cm and average height were 2.50m, 3.10 m, 4.65 m, 4.80 m, 5.10 m, 6.10 m, 6.50 m, 8.10 m, 8.35m, 9.20 m and 12.15 m, respectively. The values of above ground and below ground biomass, and total biomass and carbon content were given for different years old plantations determined by using best fit equation used for individual trees of different dbh and height (Table 1). On critical examination of the data, the biomass accumulation from the seedling stage to sapling and tree stage in plantations of 2, 4, 5, 6, 8, 9, 10, 13, 14, 15 and 18 years was found to be 3.90, 4.43, 26.88, 43.58, 73.88, 106.47, 135.81, 247.32, 310.61, 434.43 and 936.42 tonne ha^{-1}, respectively, showing the increasing trend of biomass accumulation (Table 2).

Multiple regression equations were tried to find out best fit equation. On the basis of maximum correlation coefficient (R^2) and minimum standard error, the best model was computed to be VOB = -0.007 + 0.002D + 2.638 x $10^{-5}D^2H$ - 3.863 x $10^{-10}(D^2H)^2$, Where, VOB = Volume over bark in CMT, D= Diameter at breast height in cm, H= Total tree height in m. The general volume table was prepared by using the best fit regression equations on the actual growth data. Variables all entering or removing variables, reveals the independent variables namely D, D^2H and $(D^2H)^2$ are part of the equation and V is the dependent variable. The model summary of the output of the volume of *Pongamia pinnata* trees is a function of the multiple correlation coefficient (R= 0.970, R^2=0.940, SE= 0.0235515041) had its D, D^2H and $(D^2H)^2$. The ANOVA confirmed that regression of V on D, D^2H and $(D^2H)^2$ was highly significant (Fp < 0.001). This denotes that one variability in volume of *Pongamia pinnata* trees is directly regulated by independent variables such as D, D^2H and $(D^2H)^2$. The coefficients of the output give us the values that we need in order to write the regression equation. The correlation between actual and computed volume for 103 trees, was found to be highly significant at 0.01 levels (97% confidence level).

Since the accuracy of the volume table has been tested statistically, thus it can be safely used to predict the volume of single trees of different dimensions, in efficient and scientific forest management. The general volume table was used for preparing the above ground biomass using the formula: wood density (g cm^{-3} = tonne m^{-3}) x volume of tree (m^3). Biomass table showed the increasing trend between biomass and growth (height and dbh) parameters. The total minimum and maximum biomass was found to be 0.0021 and 0.5571 tonne $tree^{-1}$, respectively. The minimum and maximum values of carbon content were 0.0010 tonne and 0.2786 tonne $tree^{-1}$, respectively. The minimum and maximum values of CO_2 absorbed from the atmosphere were 0.0038 and 1.0214 tonne $tree^{-1}$, respectively (Table 3).

Table 1. Biomass and carbon content in *Pongamia pinnata* according to age of the plantations (values are mean ± standard deviation)

S. N.	Plantation year	Age (years)	Av. dbh (cm)	Av. Height (m)	Above ground biomass (Tonne ha^{-1})	Below ground biomass (Tonne ha^{-1})	Total biomass (Tonne ha^{-1})	Carbon content (Tonne ha^{-1})	CO$_2$ (Tonne ha^{-1})
Seedling used for planting	1/2 (6 month)	-	0.55	0.009	0.003	0.012	0.006	0.022
1	2007-08	2	2.5 ±0.40	2.50 ±0.57	3.12 ±0.81	0.78 ±0.20	3.92 ±1.01	1.95 ±0.50	7.17 ±1.86
2	2002-03	4	3.6 ±0.62	3.10 ±0.42	3.56 ±1.06	0.89 ±0.26	4.44 ±1.32	2.22 ±0.66	8.15 ±2.43
3	2004-05	5	5.5 ±0.66	4.65 ±0.92	21.51 ±7.24	5.39 ±1.81	26.90 ±9.06	13.44 ±4.53	49.31 ±16.61
4	2003-04	6	6.7 ±0.72	4.80 ±0.87	34.86 ±5.62	8.72 ±1.40	43.59 ±7.02	21.80 ±3.51	79.91 ±12.88
5	2001-02	8	8.8 ±1.08	5.10 ±0.98	59.12 ±11.03	14.78 ±2.75	73.89 ±13.79	36.95 ±6.89	135.47 ±25.29
6	2000-01	9	10.2 ±1.64	6.10 ±1.10	85.19 ±16.37	21.30 ±4.09	106.49 ±20.46	53.25 ±10.23	195.23 ±37.51
7	1999-00	10	11.5 ±1.25	6.50 ±1.26	108.66 ±20.68	27.17 ±5.17	135.83 ±25.85	67.91 ±12.92	249.02 ±47.39
8	1996-97	13	15.0 ±1.43	8.10 ±1.36	197.87 ±33.12	49.47 ±8.28	247.34 ±41.41	123.68 ±20.70	453.45 ±75.92
9	1995-96	14	16.9 ±1.73	8.35 ±1.90	248.49 ±25.02	62.13 ±6.25	310.62 ±31.28	155.31 ±15.64	569.46 ±57.35
10	1994-95	15	19.7 ±1.81	9.20 ±2.20	347.57 ±45.92	86.90 ±11.48	434.45 ±57.40	217.23 ±28.70	796.50 ±105.25
11	1991-92	18	27.8 ±3.52	12.15 ±2.59	749.15 ±96.97	187.29 ±24.24	936.44 ±121.21	468.21 ±60.60	1716.80 ±222.23

Table 2. Net accumulation of biomass and carbon during growth of *Pongamia pinnata* in plantation forests

S. N.	Plantation year	Age (years)	Biomass and carbon content accumulation after planting (Biomass accumulation - Biomass of seedling)				
			Above ground biomass (Tonne ha^{-1})	Below ground biomass (Tonne ha^{-1})	Total biomass (Tonne ha^{-1})	Carbon (Tonne ha^{-1})	CO$_2$ (Tonne ha^{-1})
1	2007-08	2	3.11	0.78	3.90	1.94	7.15
2	2002-03	4	3.55	0.88	4.43	2.21	8.12
3	2004-05	5	21.50	5.38	26.88	13.43	49.28
4	2003-04	6	34.85	8.71	43.58	21.79	79.88
5	2001-02	8	59.11	14.77	73.88	36.94	135.44
6	2000-01	9	85.18	21.30	106.47	53.24	195.20
7	1999-00	10	108.65	27.16	135.81	67.90	248.99
8	1996-97	13	197.86	49.47	247.32	123.67	453.43
9	1995-96	14	248.48	62.13	310.61	155.30	569.44
10	1994-95	15	347.56	86.89	434.43	217.22	796.48
11	1991-92	18	749.14	187.29	936.42	468.20	1716.77

Table 3 : Volume, total biomass, carbon stock and CO_2 tables of *Pongamia pinnata* in relation to DBH and total height of standing trees

(DBH = Diameter at breast height in cm, VOB= Volume over bark in m3, TB= Total biomass in tonnes tree[-1], C= Carbon stock in tonnes tree[-1], CO_2= Carbon dioxide in tonnes tree[-1])

DBH (cm)	Production parameters	Total Height (m)												
		2	4	6	8	10	12	14	16	18	20	22	24	25
4	VOB	0.0020	0.0030	0.0040	0.0040	0.0050	0.0060	0.0070	0.0080	0.0090	0.0090	0.0100	0.0110	0.0110
	TB	0.0021	0.0031	0.0041	0.0041	0.0051	0.0062	0.0072	0.0082	0.0092	0.0092	0.0103	0.0113	0.0113
	C	0.0010	0.0015	0.0021	0.0021	0.0026	0.0031	0.0036	0.0041	0.0046	0.0046	0.0051	0.0056	0.0056
	CO_2	0.0038	0.0056	0.0075	0.0075	0.0094	0.0113	0.0132	0.0150	0.0169	0.0169	0.0188	0.0207	0.0207
6	VOB	0.0070	0.0090	0.0110	0.0130	0.0140	0.0160	0.0180	0.0200	0.0220	0.0240	0.0260	0.0280	0.0280
	TB	0.0072	0.0092	0.0113	0.0133	0.0144	0.0164	0.0185	0.0205	0.0226	0.0246	0.0267	0.0287	0.0287
	C	0.0036	0.0046	0.0056	0.0067	0.0072	0.0082	0.0092	0.0103	0.0113	0.0123	0.0133	0.0144	0.0144
	CO_2	0.0132	0.0169	0.0207	0.0245	0.0263	0.0301	0.0339	0.0376	0.0414	0.0451	0.0489	0.0527	0.0527
8	VOB	0.0120	0.0160	0.0190	0.0220	0.0260	0.0290	0.0320	0.0360	0.0390	0.0420	0.0450	0.0490	0.0500
	TB	0.0123	0.0164	0.0195	0.0226	0.0267	0.0298	0.0328	0.0369	0.0400	0.0431	0.0462	0.0503	0.0513
	C	0.0062	0.0082	0.0097	0.0113	0.0133	0.0149	0.0164	0.0185	0.0200	0.0215	0.0231	0.0251	0.0257
	CO_2	0.0226	0.0301	0.0357	0.0414	0.0489	0.0545	0.0602	0.0677	0.0734	0.0790	0.0846	0.0922	0.0941
10	VOB	0.0180	0.0230	0.0290	0.0340	0.0390	0.0440	0.0490	0.0540	0.0590	0.0640	0.0690	0.0740	0.0770
	TB	0.0185	0.0236	0.0298	0.0349	0.0400	0.0451	0.0503	0.0554	0.0605	0.0657	0.0708	0.0759	0.0790
	C	0.0092	0.0118	0.0149	0.0174	0.0200	0.0226	0.0251	0.0277	0.0303	0.0328	0.0354	0.0380	0.0395
	CO_2	0.0339	0.0433	0.0545	0.0640	0.0734	0.0828	0.0922	0.1016	0.1110	0.1204	0.1298	0.1392	0.1448
12	VOB	0.0250	0.0320	0.0400	0.0470	0.0540	0.0610	0.0690	0.0760	0.0830	0.0900	0.0970	0.1040	0.1070
	TB	0.0257	0.0328	0.0410	0.0482	0.0554	0.0626	0.0708	0.0780	0.0852	0.0923	0.0995	0.1067	0.1098
	C	0.0128	0.0164	0.0205	0.0241	0.0277	0.0313	0.0354	0.0390	0.0426	0.0462	0.0498	0.0534	0.0549
	CO_2	0.0470	0.0602	0.0752	0.0884	0.1016	0.1147	0.1298	0.1430	0.1561	0.1693	0.1825	0.1956	0.2013
14	VOB	0.0310	0.0410	0.0510	0.0610	0.0710	0.0810	0.0900	0.1000	0.1090	0.1180	0.1280	0.1370	0.1410
	TB	0.0318	0.0421	0.0523	0.0626	0.0728	0.0831	0.0923	0.1026	0.1118	0.1211	0.1313	0.1406	0.1447
	C	0.0159	0.0210	0.0262	0.0313	0.0364	0.0416	0.0462	0.0513	0.0559	0.0605	0.0657	0.0703	0.0723
	CO_2	0.0583	0.0771	0.0959	0.1147	0.1336	0.1524	0.1693	0.1881	0.2050	0.2220	0.2408	0.2577	0.2652
16	VOB	0.0380	0.0520	0.0650	0.0770	0.0900	0.1020	0.1150	0.1270	0.1380	0.1500	0.1610	0.1720	0.1780
	TB	0.0390	0.0534	0.0667	0.0790	0.0923	0.1047	0.1180	0.1303	0.1416	0.1539	0.1652	0.1765	0.1826
	C	0.0195	0.0267	0.0333	0.0395	0.0462	0.0523	0.0590	0.0652	0.0708	0.0770	0.0826	0.0882	0.0913
	CO_2	0.0715	0.0978	0.1223	0.1448	0.1693	0.1919	0.2163	0.2389	0.2596	0.2822	0.3028	0.3235	0.3348
18	VOB	0.0460	0.0630	0.0790	0.0950	0.1100	0.1260	0.1410	0.1550	0.1700	0.1840	0.1970	0.2110	0.2170
	TB	0.0472	0.0646	0.0811	0.0975	0.1129	0.1293	0.1447	0.1590	0.1744	0.1888	0.2021	0.2165	0.2226
	C	0.0236	0.0323	0.0405	0.0487	0.0564	0.0646	0.0723	0.0795	0.0872	0.0944	0.1011	0.1082	0.1113
	CO_2	0.0865	0.1185	0.1486	0.1787	0.2069	0.2370	0.2652	0.2916	0.3198	0.3461	0.3706	0.3969	0.4082
20	VOB	0.0540	0.0740	0.0940	0.1130	0.1320	0.1510	0.1690	0.1860	0.2030	0.2190	0.2350	0.2510	0.2580
	TB	0.0554	0.0759	0.0964	0.1159	0.1354	0.1549	0.1734	0.1908	0.2083	0.2247	0.2411	0.2575	0.2647
	C	0.0277	0.0380	0.0482	0.0580	0.0677	0.0775	0.0867	0.0954	0.1041	0.1123	0.1206	0.1288	0.1324
	CO_2	0.1016	0.1392	0.1768	0.2126	0.2483	0.2840	0.3179	0.3499	0.3818	0.4119	0.4420	0.4721	0.4853
22	VOB	0.0620	0.0870	0.1100	0.1330	0.1560	0.1770	0.1980	0.2180	0.2380	0.2560	0.2740	0.2910	0.3000
	TB	0.0636	0.0893	0.1129	0.1365	0.1601	0.1816	0.2031	0.2237	0.2442	0.2627	0.2811	0.2986	0.3078
	C	0.0318	0.0446	0.0564	0.0682	0.0800	0.0908	0.1016	0.1118	0.1221	0.1313	0.1406	0.1493	0.1539
	CO_2	0.1166	0.1636	0.2069	0.2502	0.2934	0.3329	0.3724	0.4101	0.4477	0.4815	0.5154	0.5474	0.5643
24	VOB	0.0710	0.1000	0.1280	0.1540	0.1800	0.2050	0.2290	0.2510	0.2730	0.2940	0.3130	0.3320	0.3410
	TB	0.0728	0.1026	0.1313	0.1580	0.1847	0.2103	0.2350	0.2575	0.2801	0.3016	0.3211	0.3406	0.3499
	C	0.0364	0.0513	0.0657	0.0790	0.0923	0.1052	0.1175	0.1288	0.1400	0.1508	0.1606	0.1703	0.1749
	CO_2	0.1336	0.1881	0.2408	0.2897	0.3386	0.3856	0.4307	0.4721	0.5135	0.5530	0.5888	0.6245	0.6414

| DBH (cm)	Production parameters	Total Height (m)												
		2	4	6	8	10	12	14	16	18	20	22	24	25
26	VOB	0.0800	0.1140	0.1460	0.1760	0.2060	0.2340	0.2600	0.2850	0.3090	0.3310	0.3520	0.3710	0.3800
	TB	0.0821	0.1170	0.1498	0.1806	0.2114	0.2401	0.2668	0.2924	0.3170	0.3396	0.3612	0.3806	0.3899
	C	0.0410	0.0585	0.0749	0.0903	0.1057	0.1200	0.1334	0.1462	0.1585	0.1698	0.1806	0.1903	0.1949
	CO_2	0.1505	0.2144	0.2746	0.3311	0.3875	0.4402	0.4891	0.5361	0.5812	0.6226	0.6621	0.6979	0.7148
28	VOB	0.0890	0.1280	0.1650	0.1990	0.2320	0.2630	0.2920	0.3190	0.3440	0.3680	0.3890	0.4090	0.4180
	TB	0.0913	0.1313	0.1693	0.2042	0.2380	0.2698	0.2996	0.3273	0.3529	0.3776	0.3991	0.4196	0.4289
	C	0.0457	0.0657	0.0846	0.1021	0.1190	0.1349	0.1498	0.1636	0.1765	0.1888	0.1996	0.2098	0.2144
	CO_2	0.1674	0.2408	0.3104	0.3743	0.4364	0.4947	0.5493	0.6000	0.6471	0.6922	0.7317	0.7693	0.7863
30	VOB	0.0990	0.1430	0.1840	0.2230	0.2590	0.2930	0.3240	0.3530	0.3790	0.4030	0.4240	0.4430	0.4510
	TB	0.1016	0.1467	0.1888	0.2288	0.2657	0.3006	0.3324	0.3622	0.3889	0.4135	0.4350	0.4545	0.4627
	C	0.0508	0.0734	0.0944	0.1144	0.1329	0.1503	0.1662	0.1811	0.1944	0.2067	0.2175	0.2273	0.2314
	CO_2	0.1862	0.2690	0.3461	0.4195	0.4872	0.5511	0.6094	0.6640	0.7129	0.7580	0.7975	0.8333	0.8483
32	VOB	0.1090	0.1590	0.2040	0.2470	0.2870	0.3230	0.3560	0.3860	0.4120	0.4350	0.4550	0.4720	0.4790
	TB	0.1118	0.1631	0.2093	0.2534	0.2945	0.3314	0.3653	0.3960	0.4227	0.4463	0.4668	0.4843	0.4915
	C	0.0559	0.0816	0.1047	0.1267	0.1472	0.1657	0.1826	0.1980	0.2114	0.2232	0.2334	0.2421	0.2457
	CO_2	0.2050	0.2991	0.3837	0.4646	0.5398	0.6076	0.6696	0.7261	0.7750	0.8182	0.8559	0.8878	0.9010
34	VOB	0.1200	0.1750	0.2250	0.2720	0.3140	0.3530	0.3870	0.4170	0.4430	0.4640	0.4820	0.4960	0.5010
	TB	0.1231	0.1796	0.2309	0.2791	0.3222	0.3622	0.3971	0.4278	0.4545	0.4761	0.4945	0.5089	0.5140
	C	0.0616	0.0898	0.1154	0.1395	0.1611	0.1811	0.1985	0.2139	0.2273	0.2380	0.2473	0.2544	0.2570
	CO_2	0.2257	0.3292	0.4232	0.5116	0.5906	0.6640	0.7279	0.7844	0.8333	0.8728	0.9066	0.9330	0.9424
36	VOB	0.1310	0.1910	0.2470	0.2970	0.3420	0.3820	0.4160	0.4460	0.4700	0.4890	0.5030	0.5120	0.5140
	TB	0.1344	0.1960	0.2534	0.3047	0.3509	0.3919	0.4268	0.4576	0.4822	0.5017	0.5161	0.5253	0.5274
	C	0.0672	0.0980	0.1267	0.1524	0.1754	0.1960	0.2134	0.2288	0.2411	0.2509	0.2580	0.2627	0.2637
	CO_2	0.2464	0.3593	0.4646	0.5587	0.6433	0.7185	0.7825	0.8389	0.8841	0.9198	0.9461	0.9631	0.9668
38	VOB	0.1420	0.2080	0.2690	0.3220	0.3690	0.4100	0.4440	0.4720	0.4940	0.5090	0.5170	0.5190	0.5180
	TB	0.1457	0.2134	0.2760	0.3304	0.3786	0.4207	0.4555	0.4843	0.5068	0.5222	0.5304	0.5325	0.5315
	C	0.0728	0.1067	0.1380	0.1652	0.1893	0.2103	0.2278	0.2421	0.2534	0.2611	0.2652	0.2662	0.2657
	CO_2	0.2671	0.3912	0.5060	0.6057	0.6941	0.7712	0.8352	0.8878	0.9292	0.9574	0.9725	0.9762	0.9744
40	VOB	0.1530	0.2260	0.2910	0.3470	0.3960	0.4370	0.4700	0.4950	0.5120	0.5220	0.5230	0.5160	0.5100
	TB	0.1570	0.2319	0.2986	0.3560	0.4063	0.4484	0.4822	0.5079	0.5253	0.5356	0.5366	0.5294	0.5233
	C	0.0785	0.1159	0.1493	0.1780	0.2031	0.2242	0.2411	0.2539	0.2627	0.2678	0.2683	0.2647	0.2616
	CO_2	0.2878	0.4251	0.5474	0.6527	0.7449	0.8220	0.8841	0.9311	0.9631	0.9819	0.9838	0.9706	0.9593
42	VOB	0.1650	0.2440	0.3130	0.3720	0.4220	0.4620	0.4930	0.5140	0.5250	0.5270	0.5190	0.5010	0.4890
	TB	0.1693	0.2503	0.3211	0.3817	0.4330	0.4740	0.5058	0.5274	0.5387	0.5407	0.5325	0.5140	0.5017
	C	0.0846	0.1252	0.1606	0.1908	0.2165	0.2370	0.2529	0.2637	0.2693	0.2704	0.2662	0.2570	0.2509
	CO_2	0.3104	0.4590	0.5888	0.6997	0.7938	0.8690	0.9273	0.9668	0.9875	0.9913	0.9762	0.9424	0.9198
44	VOB	0.1770	0.2620	0.3350	0.3970	0.4470	0.4850	0.5120	0.5270	0.5310	0.5230	0.5040	0.4730	0.4530
	TB	0.1816	0.2688	0.3437	0.4073	0.4586	0.4976	0.5253	0.5407	0.5448	0.5366	0.5171	0.4853	0.4648
	C	0.0908	0.1344	0.1719	0.2037	0.2293	0.2488	0.2627	0.2704	0.2724	0.2683	0.2586	0.2426	0.2324
	CO_2	0.3329	0.4928	0.6301	0.7468	0.8408	0.9123	0.9631	0.9913	0.9988	0.9838	0.9480	0.8897	0.8521
46	VOB	0.1900	0.2810	0.3580	0.4210	0.4700	0.5060	0.5270	0.5350	0.5290	0.5100	0.4760	0.4280	0.3990
	TB	0.1949	0.2883	0.3673	0.4319	0.4822	0.5192	0.5407	0.5489	0.5428	0.5233	0.4884	0.4391	0.4094
	C	0.0975	0.1442	0.1837	0.2160	0.2411	0.2596	0.2704	0.2745	0.2714	0.2616	0.2442	0.2196	0.2047
	CO_2	0.3574	0.5286	0.6734	0.7919	0.8841	0.9518	0.9913	1.0063	0.9950	0.9593	0.8954	0.8051	0.7505
48	VOB	0.2020	0.2990	0.3800	0.4440	0.4920	0.5230	0.5380	0.5370	0.5190	0.4840	0.4340	0.3670	0.3270
	TB	0.2073	0.3068	0.3899	0.4555	0.5048	0.5366	0.5520	0.5510	0.5325	0.4966	0.4453	0.3765	0.3355
	C	0.1036	0.1534	0.1949	0.2278	0.2524	0.2683	0.2760	0.2755	0.2662	0.2483	0.2226	0.1883	0.1678
	CO_2	0.3800	0.5624	0.7148	0.8352	0.9255	0.9838	1.0120	1.0101	0.9762	0.9104	0.8164	0.6903	0.6151
50	VOB	0.2150	0.3180	0.4020	0.4660	0.5110	0.5370	0.5430	0.5300	0.4980	0.4460	0.3750	0.2850	0.2330
	TB	0.2206	0.3263	0.4125	0.4781	0.5243	0.5510	0.5571	0.5438	0.5109	0.4576	0.3848	0.2924	0.2391
	C	0.1103	0.1631	0.2062	0.2391	0.2621	0.2755	0.2786	0.2719	0.2555	0.2288	0.1924	0.1462	0.1195
	CO_2	0.4044	0.5982	0.7562	0.8765	0.9612	1.0101	1.0214	0.9969	0.9367	0.8389	0.7054	0.5361	0.4383
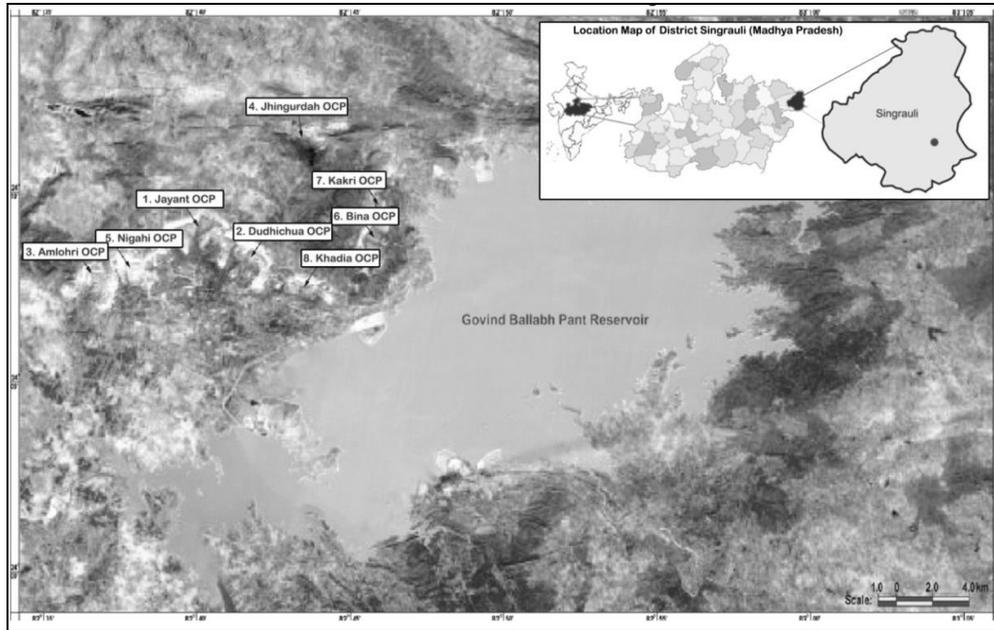
Figure 1. Satellite imagery of the study area showing different opencast project (OCP) site and Govind Ballabh Pant Reservoir at Singrauli, India
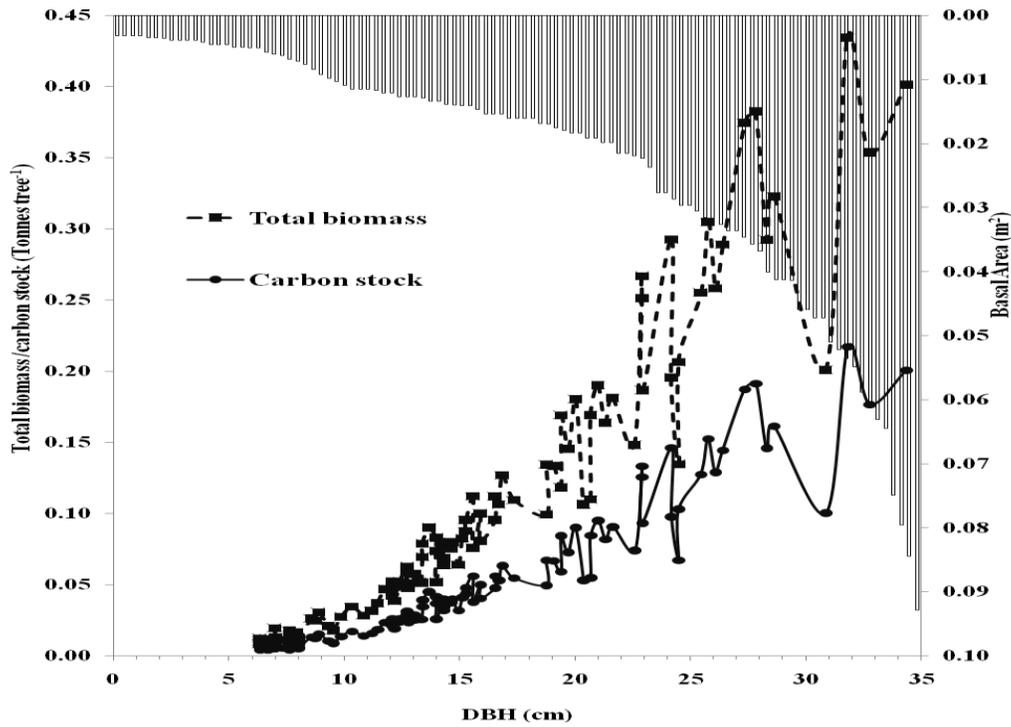

Figure 2. Correlation among different growth parameters pertaining to DBH, basal area, total biomass and carbon stock in *Pongamia pinnata*

4. Discussion

Perusal of data on biomass accumulation (above ground, below ground and total biomass) showed increasing trend with dbh and height classes. The volume and subsequently, biomass was reported to be related with diameter (dbh) and height (H) (FSI 1996). For determining the best fit equation of volume, independent variables (diameter and height) such as D, D^2H and $(D^2H)^2$ were used for *Pongamia pinnata*. The range of determination coefficient was found to be 94%. This could be explained by the fact that volume (V) and above ground components of trees were dependent upon dbh and height (Bohre *et al.*, 2012).

In terms of vertical and horizontal growth, *Pongamia pinnata* proved as an efficient species with the corresponding heights and dbh of 12.15 m and 27.8 cm, respectively in 18 years old plantations. During initial growth period, the performance of *Pongamia pinnata* was better in terms of both vertical and horizontal growth (Bohre *et. al.,* 2013). This was primarily due to their nitrogen fixing nature. Most of the leguminous species form nodules in the root with the symbiotic association of *Rhizobium s*pecies and fixes atmospheric nitrogen. About 57% of the legume genera comprising 3395 species were examined with nodulation. Of the examined species, about 23% species belonged to Caesalpiniaceae, 97% to Papilionaceae and 90% to Mimosaceae (Srivastava *et al.*, 1999). It might be due to high energy conversion efficiency of these species. The energy conversion efficiency may be defined as the ratio of amount of photosynthetically active radiation (PAR) that falls on the plant canopy to the amount of energy fixed by the plant. The efficiency of utilization of solar energy at cellular level was quite high being 30% (Kok, 1973; Kok *et al.*, 1976). In the present study, the biomass accumulation in *Pongamia pinnata* takes over the lead successive development. Though, the nature of biomass accumulation may vary in the same species under different localities under such factors as accumulation of nutrient in the soil, management practices and availability of light and other environmental factors. The results were in agreement with the findings of Chaturvedi and Behl (1996), Goel and Behl (1999a,b, 2004, 2005), Singh and Goel (2009) who estimated the production potential of exotic and indigenous tree species of degraded soil sites under sodicity stress conditions. The better performance of this species in plantation forests might be primarily due to well drained and highly porous texture of soil media as found in mined overburdens.

The net biomass production of *Pongamia pinnata* showed increasing trend with the age (from 2 to 18 years) of plantations. The findings were comparable with the results of Datta and Agarwal (2003), Karmacharya and Singh (1992), Buvaneswaran *et al.*, (2006); Nandeswar *et al.,* (1996), Pozgaj *et al.*, (1996), Leith *et al.*, (1986) Bohre *et al.*, (2012, 2013), Chaubey *et al.*, (2012).

5. Conclusions

Looking to the serious concern of carbon management, the role of *Pongamia pinnata* to estimate the biomass accumulation and its contribution for sequestration of carbon in mined out areas, the following conclusions were derived:

1. Actual volume resembled closely with predicted volumes and showed significantly increasing trend with the increase in the height and diameter of trees.

2. The best fit allometric equations developed for volume estimation and subsequently biomass accumulation and carbon sequestration adopting non harvest technique for *Pongamia pinnata* being VOB = -0.007 + 0.002D + 2.638 x $10^{-5}D^2H$ - 3.863 x 10^{-10} $(D^2H)^2$; R^2=0.940; SE= 0.0235515.

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Authors

Dr. Prianka Bohre

Dr. Prianka Bohre has been awarded her Ph.D degree in 2013 on the topic "Biomass accumulation and carbon sequestration by dominant plantation species raised on coal mine overburden at Singrauli" from Rani Durgawati University, Jabalpur (M.P.) India. She did M.Sc in botany (2007-09) and secured first position in III & IV semester from Govt. Autonomous Holkar Science College, Indore (M.P.) India. She had basic trainings in Recombinant DNA technology & PCR held in January 2005 at GENEI, Bangalore, India, One module of the Bioscience

Excellence Graduate Training program on protein and proteomic analysis and molecular & genomic studies at G-Bioscience, New Delhi, India and graduate training program on biotechnology (September2005) organized at Genetic and Plant Propagation Division of Tropical Forest Research Institute, Jabalpur, India. She has to her credit two awards viz., State Level Award (Rajya Puraskar), 28 March 2001: as a Guide, Kendriya Vidyalaya Sanghatans and Tritiya Sopan Testing Awarded, Kendriya Vidyalaya C.O.D, Jabalpur, 4-7 November 1998: as a guide of Kendriya vidyalaya no-2 GCF, Jabalpur. She has 11 papers published in reputed the International and National scientific journals. She has qualified GRE & TOEFL by securing- 1270/1600 and 82/100 marks respectively. She want to pursue postdoctoral in United States university to enhance my knowledge in the field of plant science and contribute in the academic society of the United States as a researcher in your university, which offers both – a healthy environment in learning and excellent opportunities for research in the field of Plant Science. She would like to implement the knowledge gained for the benefit of society at large. She is open to further research studies on projects of the department for my academic development.
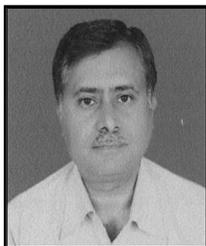
Dr. O. P. Chaubey

Dr. O.P. Chaubey is working as Head of Forest Botany Branch in M.P. State Forest Research Institute, Jabalpur (M.P.) India. He was awarded in Ph.D. degree in Forest Ecology in 1986 from Dr. H.S. Gaur University, Sagar, (Madhya Pradesh, India). He has to his credit three books, 13 monograph of various forestry species and more than 75 research papers published in both National and International journals. He has 30 years of research experience in field of forestry. He has completed more than 22 externally funded research projects in the capacity of Principal Investigator. He has organized a number of symposia/ workshops at National and State levels. He has imparted trainings to field foresters, University scholars, NGOs and Rural Communities engaged in conservation and management of biological diversity.

Dr. P. K. Singhal

Dr. P.K. Singhal is currently working as Professor at Department of Biological Science, Rani Durgavati University, Jabalpur, India. An alumnus of Agra and Saugor Universities, he is actively engaged in research and teaching for the last 30 years in areas of environmental biology and biostatistics, and has published more than 40 research papers and two books. His current research areas are carbon sequestration by natural and artificial plantations, nutrient dynamics in habitats and biotechnological exploitation of microbial enzymes.