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Biomass Production and Carbon Sequestration by *Azadirachta indica* in Coal Mined Lands

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Abstract

Carbon management is a serious concern confronting the world today. The importance of carbon sequestration in tree biomass has long been recognized, but few attempts have been made to estimate tree biomass accumulation and its contribution to sequestration of carbon on mined areas. Carbon sequestration rates vary by tree species, soil type, regional climate, and topography and management practice. We quantified biomass accumulation and carbon sequestration by Azadirachta indica A. Juss raised on coal mine overburden at Singrauli, Madhya Pradesh, India, adopting non harvest methods. A. indica, of the family Meliaceae, is one of the most widely distributed and multipurpose tree species occurring in dry regions of the country. Growth data were collected for 115 trees (>5 cm DBH) covering the overburden plantations of Northern Coal Field Limited, Singrauli (India). Plantation varied from 2-18 years. Significant correlations were identified between basal area and volume, DBH and volume and basal area and total biomass.

Keywords*: Carbon sequestration, biomass accumulation, standing volume, non harvest technique, allometric equation.*

1. Introduction

In response to climate change (Manua Loa Observatory, 2013) and in support of Reducing Emissions from Deforestation and Forest Degradation (REDD) and REDD plus (ISFR, 2011; Ravindranath *et al.*, 2012), ecological restoration of degraded ecosystems is an important option. Afforestration of degraded ecosystems, in particular, coal mine overburden, was attempted in Australia, USA, China, India and other countries (Heilman, 1983; Packer *et al.*, 1982; Rechardson, 1984; Hannan, 1979; Prasad, 1988 &1993; Prasad *et al.*, 2009). The selection of suitable species is fundamental to restoration of degraded ecosystems. Many workers study biomass production of tropical forests and plant species by harvest at a predetermined age and allometric equations relating biomass with one or more tree dimensions (Enright, 1979; Tanner, 1980; Negi *et al.*, 1984; Prasad and Mishra, 1984; Prasad *et al.*, 1984; Rai, 1984; Sharma and Srivastava, 1984). We studied the suitability of *Azadirachta indica* for biomass accumulation and carbon sequestration on re-contoured mined lands.

2. Materials and Methods

Singrauli (24^o 46’ 60’’- 24^o 78’ 33’’N, 82^o 49’ 59’’- 82^0 83’ 30’’E, 275 -500m AMSL) was granted District Status on 24^{th} May 2008, with its headquarter at Waidhan. It is the 50^{th} district of Madhya Pradesh. Considering the geological and technical feasibility of mining, and environmental conditions, the opencast mining is prevailing in the entire area. 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 (5B/C_2). Due to

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mining, the large forest areas were clear felled and laid barren. The present study covered artificial plantations raised in the mined out Northern Coal Field Limited (NCL) area. For the estimation of biomass, non harvest technique was adopted.

Growth data were collected for total height and girth at breast height (GBH) at over-bark. The length of trees was divided into segments of one meter from breast height to the tip of the crown. The girth at over-bark of each segment was measured at the center of each segment throughout the height of the tree to account for tapering. Segment girth was measured without felling trees with the help of climbers. Girth was converted to diameter by dividing by π rounded to 3.14. Volume was calculated for each designated segment using cylindrical cross sectional areas multiplied by the height of each segment ($\pi r^2 h$). Total volume of the bole was calculated by adding the volumes of the segments from breast height to the top of the crown to the volume of the base segment (i.e. below breast height). The DBH, total height and total volume were entered to a database for analyses using SPSS. 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 used to identify correlations between DBH and height, DBH and volume, and biomass and DBH.

Stem wood biomass was calculated by multiplying volume by wood density (Reyes *et al.*, 1992; Pearson and Brown, 1932) of A. indica. The stem wood biomass was then "expanded" to total above ground biomass (including leaves, twigs, branches, bole and bark) using a biomass expansion factor (BEF):

Total above ground biomass = stem wood volume X wood density X BEF

A mean BEF value of 1.5 was used for this study, following Brown and Luge (1992). The below ground biomass was calculated by using a default value of 25% (typically applied to hardwood species) of the total above ground biomass (IPCC, 2006). Wood density information was presented in units of oven dry weight in gm^{-3} (i.e. ton m^{-3}) of green volume. Multiple regression equations were used to establish the correlation between 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 tons $tree^{-1}$ and tons ha^{-1}. Carbon content was then multiplied by 44/12 to estimate CO_2.

Nursery seedlings were used for this purpose. Fifteen randomly selected seedlings of the species were harvested for measurement of their height and dry weight (dried at 104°C until a constant weight obtained). The average height and DBH of each species by seedling 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 estimates of biomass accumulation and carbon sequestration by a tree. The 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 tons 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. General volume equations (GVEs), i.e. regression functions for volume, diameter, and height, were selected for each species. The following nine regression equations, as used by Forest Survey of India (FSI, 1996), were used to determine the best equation for estimating volume over-bark (VOB) for A. indica. After deriving values of constants for the 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 A. indica. 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. Biomass was expressed as tons tree^{-1}. Finally, carbon and CO_2 tables for this species were prepared for all diameter and height classes.

3. Results

One hundred fifteen trees (each ≥5 cm DBH) were randomly selected for sampling from all trees to quantify their biomass and carbon. The diameter and girth at breast height varied widely from 5.09 to 38.82 cm and 16 to 122 cm, mainly due to variation in the age of trees in different plantations. Total height ranged from 3.87 to 20 m. The height varied significantly within a GBH or DBH class, indicating that vertical growth of trees varied between sites due to variation in growth factors. For example, the height of trees with DBH of 5.727 cm varied from 3.87 to 6.00 m. Such variations were observed in all age classes. The volume of trees varied positively and linearly in response to variation in basal area (r=0.944, r^2=0.893). The variation in basal area explained nearly 89% of the variation in volume. Therefore, basal area can be a good predictor of volume in trees. The total biomass of trees varied positively and linearly with basal area (r=0.944, r^2=0.893). Basal area explained a higher proportion (i.e. 89%) of variation in total biomass. Although DBH was used to estimate basal area, it explained a lower amount of variation in volume (r=0.960, r^2=0.922). DBH explained 92% of variation recoded in volume of trees (Figure 1).

The minimum and maximum volume of trees ranged from 0.00579 to 0.52155 m^3. Minimum and maximum total biomass of trees ranged from 0.00749 to 0.67475 tons tree^{-1} and the value of carbon sequestered ranged from 0.00374 to 0.33738 tons tree^{-1}, respectively. The linear correlation between basal area and volume, DBH and volume, and basal area and total biomass of 115 sampled trees was significant with the values of R^2 being 0.893, 0.922 and 0.893, respectively. The values of R^2 approached 1, indicating a good fit (Figure 1).

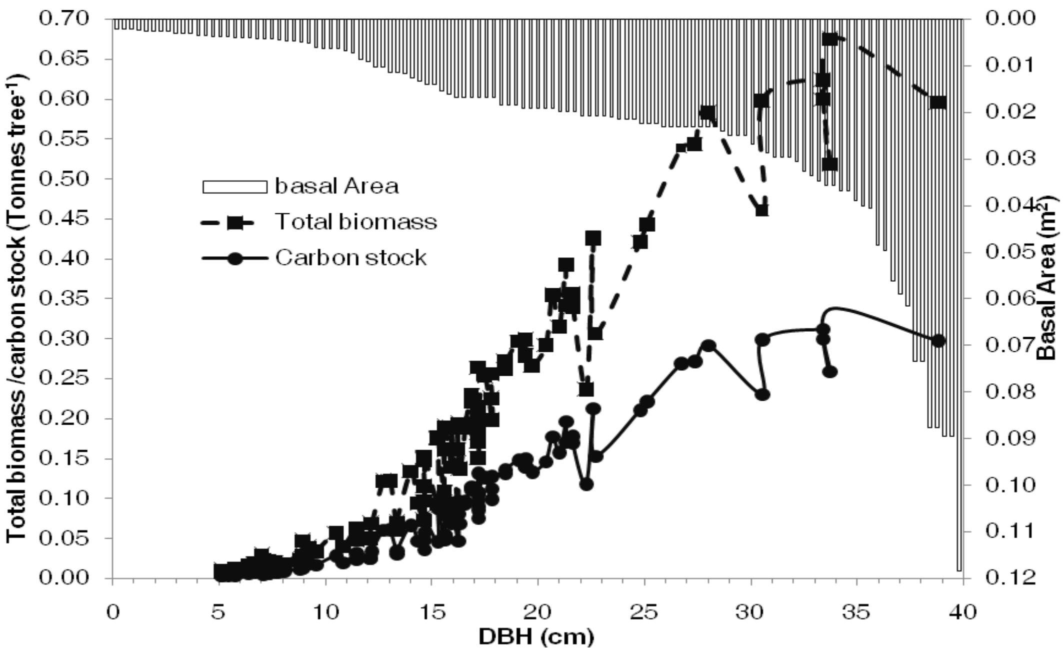

Figure 1. Correlation among Different Growth Parameters in *A. indica*

The 115 sampled trees grew in 2, 5, 6, 7, 8, 10, 14, and 18 year-old plantations raised on overburden in different Open cast mines (OCP) projects. The seedlings used in plantations averaged 1.35 m in height. Mean DBH increased with plantation age. In plantations aged 2, 5, 6, 7, 8, 10, 14 and 18 years, the average DBH values were 2.9, 6.4, 7.1, 8.3, 9.2, 11.5, 16.9 and 22.7 cm. Average heights were 2.63, 5.15, 6.12, 7.20, 7.40, 8.10, 8.20 and 9.25 m, respectively. Estimates of above- and below-ground biomass and total biomass, and carbon content and CO_2 sequestered were calculated for each plantation by using best-fit equations used for individual trees of different DBH and height (Table 1).

Table 1. Biomass and Carbon Content in Azadirachta indica According to Age of the Plantations (values are mean ± standard deviation)

S. No.	Plantation Age (years)	Avg. DBH (cm)	Avg. Height (m)	Above ground Biomass (Tons ha^{-1})	Below ground Biomass (Tons ha^{-1})	Total Biomass (Tons ha^{-1})	Carbon content (Tons ha^{-1})	CO_2 (Tons ha^{-1})
1.	0.5 (6 month Seedling used for planting)	-	1.35	0.73	0.040	0.113	0.57	0.208
2.	02	2.9 ±0.90	2.63 ±0.60	1.83 ±0.25	0.45 ±0.06	2.28 ±0.31	1.14 ±0.15	4.19 ±0.57
3.	05	6.4 ±1.05	5.15 ±1.15	4.28 ±0.33	1.07 ±0.25	5.34 0.39	2.67 ±0.24	9.81 ±0.63
4.	06	7.1 ±1.90	6.12 ±1.88	5.82 ±0.60	1.46 ±0.15	7.29 ±0.75	3.65 ±0.38	13.35 ±1.39
5.	07	8.3 ±2.20	7.20 ±2.14	64.11 ±17.86	16.02 ±4.46	80.13 ±22.33	40.07 ±11.16	146.91 ±40.95
6.	08	9.2 ±3.05	7.40 ±2.24	109.76 ±35.48	27.44 ±8.87	137.19 ±44.35	68.60 ±22.17	251.51 ±81.31
7.	10	11.5 ±3.70	8.10 ±2.94	231.17 ±45.20	57.80 ±11.30	288.96 ±56.53	144.48 ±28.26	529.76 ±103.65
8.	14	16.9 ±4.12	8.20 ±3.16	548.54 ±67.46	137.13 ±16.86	685.67 ±84.33	342.84 ±42.16	1257.06 ±154.60
9.	18	22.7 ±4.95	9.25 ±3.69	998.73 ±187.43	249.68 ±46.85	1248.41 ±234.29	624.21 ±117.14	2288.75 ±429.53

Biomass accumulation in plantations of 2, 5, 6, 7, 8, 10, 14, and 18 years was 2.17, 5.23, 7.18, 80.02, 137.08, 288.85, 685.55, and 1248.29 tons ha^{-1}, respectively, showing the increasing trend of biomass accumulation with tree age. Mean annual increments of total biomass were 1.08, 1.05, 1.20, 11.43, 17.13, 28.88, 48.97 and 69.35 tons ha^{-1} yr^{-1}, and for carbon content were 0.29, 0.42, 0.51, 5.64, 8.50, 14.39, 24.45 and 34.65 tons ha^{-1} yr^{-1} in 2, 5, 6, 7, 8, 10, 14 and 18 years old plantations, respectively (Table 2).

Table 2. Net and Mean Annual Accumulation of Biomass and Carbon During Growth of *Azadirachta indica* in Plantation Forests

S. No.	Plan-tation Age (year)	Net and mean annual accumulation of biomass and carbon stock									
		Above ground Biomass		Below ground Biomass		Total Biomass		Carbon content		CO_2	
		Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})	Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})	Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})	Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})	Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})
1.	02	1.10	0.55	0.41	0.21	2.17	1.08	0.57	0.29	3.98	1.99
2.	05	3.55	0.71	1.03	0.21	5.23	1.05	2.10	0.42	9.60	1.92
3.	06	5.09	0.85	1.42	0.24	7.18	1.20	3.08	0.51	13.14	2.19
4.	07	63.38	9.05	15.98	2.28	80.02	11.43	39.50	5.64	146.70	20.96
5.	08	109.03	13.63	27.40	3.42	137.08	17.13	68.03	8.50	251.30	31.41

S. No.	Plantation Age (year)	Net and mean annual accumulation of biomass and carbon stock									
		Above ground Biomass		Below ground Biomass		Total Biomass		Carbon content		CO_2	
		Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})	Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})	Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})	Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})	Net (t ha^{-1})	Mean annual (t ha^{-1} yr^{-1})
6.	10	230.44	23.04	57.76	5.78	288.85	28.88	143.91	14.39	529.55	52.95
7.	14	547.81	39.13	137.09	9.79	685.55	48.97	342.27	24.45	1256.85	89.78
8.	18	998.00	55.44	249.64	13.87	1248.29	69.35	623.64	34.65	2288.54	127.14

On the basis of maximum correlation coefficient (R^2) and minimum standard error, the best model was computed to be

$$\text{Volume over bark} = -0.068 + 0.008D + 4.191 \times 10^{-5}D^2H - 1.038 \times 10^{-9}(D^2H)^2$$

Where, D= Diameter at breast height in cm; H= Total tree height in meters.

Because the accuracy of the volume table has been tested statistically, it can be used to predict the volume of single trees of different dimensions as a basis for plantation management. The general volume table was prepared by using the best fit regression equations on the growth data. Independent variables D, D^2H and $(D^2H)^2$ were part of the equation and volume over bark (VOB) was the dependent variable. ANOVA confirmed that regression of VOB on D, D^2H and $(D^2H)^2$ was highly significant ($Fp < 0.001$). This indicates that variability in volume of *A. indica* trees was a function of independent variables D, D^2H and $(D^2H)^2$. The coefficients of the output provided values needed to write the regression equation.

In all cases, actual volume closely approximated predicted volumes. The correlation between actual and computed volume for 115 trees, was found to be highly significant at $p = 0.01$. The general volume table was used for preparing the above-ground biomass using the formula: wood density (g cm^{-3} = tons m^{-3}) x volume of tree (m^3). The above-ground biomass increased with growth (height and DBH) parameters. Minimum and maximum above ground biomass were 0.0014 and 0.7814 tons tree^{-1}, respectively. Minimum and maximum below-ground biomass was 0.0003 and 0.1954 tons tree^{-1}, respectively. Total minimum and maximum biomass were 0.0017 and 0.09768 tons tree^{-1}, respectively. Minimum and maximum values for carbon stock were 0.0009 and 0.4884 tons tree^{-1}, respectively. Minimum and maximum values of CO_2 absorbed from the atmosphere were 0.0032 and 0.1650 tons tree^{-1}, respectively (Table 3).

Table 3. Volume, Total Biomass, Carbon Stock and CO_2 Tables of *Azadirachta indica* in Relation to DBH and Total Height of Standing Trees

(DBH = Diameter at breast height in cm, VOB= Volume over bark in m^3, TB= Total biomass in tons tree^{-1}, C= Carbon stock in tons tree^{-1}, CO_2= Carbon dioxide in tons tree^{-1})

DBH (cm)	Production parameters	Total Height (m)												
		2	4	6	8	10	12	14	16	18	20	22	24	25
6	VOB	-	-	-	-	-	-	-	0.004	0.007	0.010	0.013	0.015	0.017
	TB	-	-	-	-	-	-	-	0.005	0.009	0.012	0.016	0.020	0.022
	C	-	-	-	-	-	-	-	0.002	0.004	0.006	0.008	0.010	0.011
	CO_2	-	-	-	-	-	-	-	0.009	0.016	0.023	0.030	0.037	0.040
8	VOB	0.001	0.007	0.012	0.017	0.022	0.028	0.033	0.038	0.043	0.048	0.053	0.058	0.060
	TB	0.002	0.009	0.015	0.022	0.029	0.036	0.042	0.049	0.056	0.062	0.069	0.075	0.078
	C	0.001	0.004	0.008	0.011	0.014	0.018	0.021	0.024	0.028	0.031	0.034	0.037	0.039

DBH (cm)	Pro-duction para-meters	Total Height (m)												
		2	4	6	8	10	12	14	16	18	20	22	24	25
	CO_2	0.003	0.016	0.028	0.041	0.053	0.065	0.078	0.090	0.102	0.114	0.126	0.137	0.143
10	VOB	0.020	0.029	0.037	0.045	0.053	0.061	0.069	0.076	0.084	0.092	0.099	0.107	0.110
	TB	0.026	0.037	0.048	0.058	0.068	0.079	0.089	0.099	0.109	0.119	0.128	0.138	0.143
	C	0.013	0.018	0.024	0.029	0.034	0.039	0.044	0.049	0.054	0.059	0.064	0.069	0.071
	CO_2	0.048	0.068	0.087	0.106	0.125	0.144	0.163	0.181	0.199	0.217	0.235	0.253	0.262
12	VOB	0.040	0.052	0.063	0.075	0.086	0.097	0.108	0.119	0.130	0.140	0.150	0.160	0.165
	TB	0.052	0.067	0.082	0.097	0.112	0.126	0.140	0.154	0.168	0.181	0.195	0.208	0.214
	C	0.026	0.034	0.041	0.048	0.056	0.063	0.070	0.077	0.084	0.091	0.097	0.104	0.107
	CO_2	0.095	0.123	0.150	0.178	0.204	0.231	0.257	0.282	0.308	0.332	0.357	0.381	0.392
14	VOB	0.060	0.076	0.092	0.107	0.122	0.137	0.151	0.165	0.179	0.192	0.205	0.218	0.224
	TB	0.078	0.099	0.119	0.139	0.158	0.177	0.196	0.214	0.232	0.249	0.266	0.282	0.290
	C	0.039	0.049	0.059	0.069	0.079	0.089	0.098	0.107	0.116	0.124	0.133	0.141	0.145
	CO_2	0.143	0.181	0.218	0.254	0.290	0.325	0.359	0.392	0.424	0.456	0.487	0.517	0.532
16	VOB	0.081	0.102	0.122	0.141	0.160	0.179	0.197	0.214	0.231	0.247	0.263	0.278	0.286
	TB	0.105	0.132	0.158	0.183	0.208	0.232	0.255	0.277	0.299	0.320	0.340	0.360	0.370
	C	0.053	0.066	0.079	0.092	0.104	0.116	0.127	0.139	0.149	0.160	0.170	0.180	0.185
	CO_2	0.193	0.242	0.289	0.336	0.381	0.424	0.467	0.508	0.548	0.587	0.624	0.660	0.678
18	VOB	0.103	0.129	0.154	0.178	0.201	0.223	0.245	0.265	0.285	0.304	0.322	0.339	0.347
	TB	0.133	0.166	0.199	0.230	0.260	0.289	0.317	0.343	0.369	0.393	0.417	0.439	0.449
	C	0.066	0.083	0.099	0.115	0.130	0.144	0.158	0.172	0.184	0.197	0.208	0.219	0.225
	CO_2	0.244	0.305	0.364	0.421	0.476	0.530	0.581	0.629	0.676	0.721	0.764	0.804	0.824
20	VOB	0.125	0.156	0.187	0.215	0.243	0.269	0.294	0.318	0.340	0.361	0.380	0.399	0.407
	TB	0.162	0.202	0.241	0.279	0.314	0.348	0.381	0.411	0.440	0.467	0.492	0.516	0.527
	C	0.081	0.101	0.121	0.139	0.157	0.174	0.190	0.206	0.220	0.233	0.246	0.258	0.263
	CO_2	0.296	0.371	0.443	0.511	0.576	0.639	0.698	0.754	0.806	0.856	0.902	0.946	0.966
22	VOB	0.148	0.185	0.221	0.255	0.287	0.316	0.344	0.370	0.394	0.416	0.437	0.455	0.463
	TB	0.191	0.240	0.286	0.330	0.371	0.409	0.445	0.479	0.510	0.539	0.565	0.588	0.599
	C	0.095	0.120	0.143	0.165	0.185	0.205	0.223	0.240	0.255	0.269	0.282	0.294	0.300
	CO_2	0.350	0.439	0.524	0.604	0.680	0.750	0.817	0.878	0.935	0.988	1.035	1.079	1.099
24	VOB	0.171	0.215	0.256	0.295	0.331	0.364	0.394	0.422	0.447	0.469	0.488	0.505	0.512
	TB	0.221	0.278	0.332	0.382	0.428	0.471	0.510	0.546	0.578	0.607	0.632	0.653	0.663
	C	0.111	0.139	0.166	0.191	0.214	0.236	0.255	0.273	0.289	0.303	0.316	0.327	0.331
	CO_2	0.405	0.510	0.608	0.700	0.785	0.864	0.936	1.001	1.060	1.113	1.158	1.198	1.215
26	VOB	0.195	0.246	0.293	0.336	0.376	0.412	0.444	0.472	0.496	0.517	0.534	0.547	0.552
	TB	0.252	0.318	0.379	0.435	0.486	0.533	0.574	0.610	0.642	0.669	0.690	0.707	0.714
	C	0.126	0.159	0.189	0.218	0.243	0.266	0.287	0.305	0.321	0.334	0.345	0.354	0.357
	CO_2	0.462	0.583	0.695	0.798	0.892	0.976	1.052	1.119	1.177	1.226	1.266	1.297	1.309
28	VOB	0.219	0.277	0.330	0.378	0.421	0.458	0.491	0.518	0.541	0.558	0.570	0.577	0.579
	TB	0.284	0.359	0.427	0.489	0.544	0.593	0.635	0.671	0.700	0.722	0.738	0.747	0.749
	C	0.142	0.179	0.214	0.245	0.272	0.297	0.318	0.335	0.350	0.361	0.369	0.373	0.374
	CO_2	0.520	0.658	0.783	0.897	0.998	1.087	1.164	1.230	1.283	1.323	1.352	1.369	1.373
30	VOB	0.244	0.309	0.368	0.420	0.465	0.504	0.535	0.560	0.579	0.590	0.595	0.593	0.589
	TB	0.316	0.400	0.476	0.543	0.602	0.651	0.693	0.725	0.748	0.763	0.770	0.767	0.763
	C	0.158	0.200	0.238	0.272	0.301	0.326	0.346	0.362	0.374	0.382	0.385	0.384	0.381
	CO_2	0.579	0.734	0.873	0.996	1.103	1.194	1.270	1.329	1.372	1.400	1.411	1.406	1.398
32	VOB	0.269	0.342	0.406	0.462	0.508	0.546	0.575	0.596	0.608	0.611	0.605	0.591	0.581
	TB	0.349	0.443	0.526	0.597	0.658	0.707	0.745	0.771	0.786	0.790	0.783	0.765	0.751
	C	0.174	0.221	0.263	0.299	0.329	0.353	0.372	0.386	0.393	0.395	0.392	0.382	0.376
	CO_2	0.639	0.812	0.964	1.095	1.206	1.296	1.365	1.414	1.442	1.449	1.436	1.402	1.377
34	VOB	0.295	0.376	0.445	0.503	0.550	0.586	0.610	0.624	0.627	0.618	0.598	0.568	0.548
	TB	0.382	0.486	0.575	0.651	0.711	0.758	0.790	0.807	0.811	0.800	0.774	0.735	0.709
	C	0.191	0.243	0.288	0.325	0.356	0.379	0.395	0.404	0.405	0.400	0.387	0.367	0.355

DBH (cm)	Pro-duction para-meters	Total Height (m)												
		2	4	6	8	10	12	14	16	18	20	22	24	25
	CO_2	0.701	0.891	1.055	1.193	1.304	1.389	1.448	1.480	1.486	1.466	1.420	1.347	1.300
36	VOB	0.322	0.409	0.483	0.543	0.589	0.621	0.639	0.643	0.633	0.609	0.571	0.519	0.488
	TB	0.416	0.530	0.625	0.702	0.762	0.803	0.826	0.832	0.819	0.788	0.739	0.672	0.632
	C	0.208	0.265	0.313	0.351	0.381	0.402	0.413	0.416	0.409	0.394	0.369	0.336	0.316
	CO_2	0.763	0.971	1.146	1.288	1.397	1.472	1.515	1.524	1.501	1.444	1.355	1.232	1.158
38	VOB	0.348	0.443	0.521	0.582	0.625	0.651	0.659	0.650	0.624	0.581	0.520	0.442	0.396
	TB	0.451	0.574	0.674	0.752	0.808	0.842	0.853	0.841	0.807	0.751	0.673	0.572	0.513
	C	0.225	0.287	0.337	0.376	0.404	0.421	0.426	0.421	0.404	0.376	0.336	0.286	0.256
	CO_2	0.826	1.052	1.236	1.380	1.482	1.543	1.563	1.542	1.480	1.377	1.233	1.048	0.940
40	VOB	0.375	0.478	0.559	0.618	0.657	0.674	0.670	0.645	0.598	0.530	0.441	0.331	0.268
	TB	0.486	0.618	0.723	0.800	0.850	0.872	0.867	0.834	0.774	0.686	0.571	0.428	0.346
	C	0.243	0.309	0.361	0.400	0.425	0.436	0.433	0.417	0.387	0.343	0.285	0.214	0.173
	CO_2	0.891	1.133	1.325	1.467	1.558	1.599	1.589	1.529	1.418	1.258	1.046	0.784	0.635
42	VOB	0.403	0.512	0.595	0.653	0.684	0.690	0.670	0.624	0.552	0.455	0.331	0.182	0.098
	TB	0.521	0.662	0.770	0.844	0.885	0.893	0.867	0.807	0.714	0.588	0.428	0.235	0.126
	C	0.261	0.331	0.385	0.422	0.443	0.446	0.433	0.404	0.357	0.294	0.214	0.118	0.063
	CO_2	0.956	1.214	1.412	1.548	1.623	1.637	1.589	1.480	1.310	1.078	0.785	0.431	0.231
44	VOB	0.431	0.546	0.631	0.684	0.706	0.697	0.657	0.586	0.484	0.351	0.186	-	-
	TB	0.557	0.707	0.816	0.885	0.914	0.902	0.850	0.758	0.626	0.454	0.241	-	-
	C	0.279	0.353	0.408	0.443	0.457	0.451	0.425	0.379	0.313	0.227	0.120	-	-
	CO_2	1.022	1.296	1.496	1.623	1.675	1.654	1.559	1.390	1.148	0.831	0.441	-	-
46	VOB	0.459	0.580	0.665	0.712	0.722	0.695	0.631	0.529	0.390	0.215	0.002	-	-
	TB	0.594	0.751	0.860	0.921	0.934	0.899	0.816	0.685	0.505	0.278	0.002	-	-
	C	0.297	0.375	0.430	0.461	0.467	0.450	0.408	0.342	0.253	0.139	0.001	-	-
	CO_2	1.088	1.377	1.577	1.689	1.713	1.648	1.496	1.255	0.926	0.509	0.004	-	-
48	VOB	0.487	0.614	0.697	0.736	0.731	0.681	0.588	0.450	0.269	0.043	-	-	-
	TB	0.630	0.794	0.902	0.952	0.945	0.881	0.761	0.583	0.348	0.056	-	-	-
	C	0.315	0.397	0.451	0.476	0.473	0.441	0.380	0.291	0.174	0.028	-	-	-
	CO_2	1.155	1.457	1.653	1.745	1.733	1.616	1.394	1.068	0.638	0.102	-	-	-
50	VOB	0.516	0.647	0.727	0.755	0.731	0.655	0.527	0.348	0.116	-	-	-	-
	TB	0.667	0.837	0.941	0.977	0.946	0.848	0.682	0.450	0.150	-	-	-	-
	C	0.334	0.419	0.470	0.488	0.473	0.424	0.341	0.225	0.075	-	-	-	-
	CO_2	1.223	1.535	1.725	1.791	1.734	1.554	1.251	0.824	0.275	-	-	-	-

4. Discussion

Biomass accumulation (above-ground, below-ground and total biomass) increased with increasing DBH and height. The determination coefficient was 96%. In terms of vertical and horizontal growth, *A. indica* proved an efficient species with heights of 9.25 m and and DBH of 22.7 cm in 18 year-old plantations. Biomass accumulation in *A. indica* increased slowly in early growth phases but increased in later growth stages. This result concurs 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 grown on degraded soil sites under sodicity stress conditions. The better performance of this species in plantation forests might be due to the well drained and highly porous texture of soils found in mined overburden (Roberts *et al.,* 1988; Torbert *et al.,* 1990). Net biomass production of *A. indica* increased with plantation age (from 2 to 18 years). This finding is comparable with the results of Datta and Agarwal (2003), Karmacharya and Singh (1992), Buvaneswaran *et al.* (2006), Nadeswar *et al.* (1996), Pozgaj *et al.* (1996), Leith *et al.* (1986) and Bohre *et al.* (2012, 2013).

In conclusion, *A. indica* proved to be an effective biomass accumulator and sequester of carbon on mined land spoils. The D, D^2H and $(D^2H)^2$ based regression equations were precise for computation of carbon stock by *A. indica* grown on mine spoils.

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