International Journal of Ecology and Environmental Sciences
www.ecologyjournal.in
Online ISSN: 2664-7133, Print ISSN: 2664-7125
Received: 29-03-2022, Accepted: 15-04-2022, Published: 30-04-2022
Volume 4, Issue 2, 2022, Page No. 36-45

Carbon mitigation and sequestration by urban forest at Okhla bird sanctuary, Delhi, India

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Abstract
Cities have been identified as key stakeholders in climate change mitigation. Nature based carbon sinks have been suggested as means of mitigating the greenhouse gas emissions of cities. Delhi is one of the most polluted city in northern India. It is due to ever increasing population pressure, urbanization and luxurious life style among rich and growing class of the society. In this context, urban green spaces act as large "carbon sinks" and provides a variety of ecosystem services including carbon storage and mitigation. In this backdrop, the functional role played by urban trees in carbon offsetting was analyzed at Okhla Bird Sanctuary (OBS) which lies in between Delhi- Noida border and represents a perfect example of a man- modified floodplain wetland which enjoys a high human impact. The study is first of its kind as only phytosociological analysis was conducted from time to time and role of urban trees in carbon mitigation was not evaluated till date. The study suggested that green planning could contribute more strongly to CO_2 mitigation by encouraging the use of planting and conservation of more trees in urban areas, in addition to ensuring favorable growing conditions for them. More studies should come up discussing the adaptive ecology of trees in an urban environment, with particular reference to function- derived relative growth rates. Moreover, biomass partitioning, eco-physiological and biochemical adjustments made by trees in an urban stressful environment should also be explored in future for better management practices.

Keywords: climate change mitigation, nature based carbon sinks, greenhouse gas emissions, carbon storage and sequestration, urban green

Introduction

Urban greenery assists in offsetting climate change impacts via carbon sequestration and thus offer several co-benefits in cities. This contribution is however omitted in most national and regional carbon stock estimates, as the literature available is quite fragmented. The gradual increment of built- up area along with rise in urban population and its associated ill effects on the environment is a matter of serious concern in Delhi/NCR region. The investments in new infrastructures and buildings, and the residents demand for goods and services are major drivers of greenhouse gas (GHG) emissions and other environmental burdens in the city. However, the capital city of India, is a driver of human development and sustainable innovations as well. Much has been written about the significance of urban green spaces and the ecosystem services which it provides in an urban environment. Its role in carbon storage and sequestration (Novak and Crane, 2002) [14] and climate change adaptation (Keeley *et al*., 2013) [10] is very well recognized. It has also been acknowledged in national and international forest policies in the western world. The European Union has adopted a strategy on green infrastructure in order to preserve biodiversity and ecosystem services in both urban and rural settings (EC, 2013) [4] and is currently promoting nature-based solutions and re- nurturing of cities (EC, 2018 [5]; IUCN, 2019 [9]). Accordingly, many cities in several countries have developed strategies and applications to support urban green infrastructure and nature based solutions especially related to biodiversity and climate change adaptations (Urban Nature Atlas, 2020) [26]. The concept of forest- based city development is the need of the hour, as the ecosystem services provided by urban green spaces in crowded cities cannot be undermined. Sustainability between different environmental components and stakeholders should be managed efficiently for a better and secured future. Urban green infrastructure in Delhi includes parks and gardens of different sizes which are fragmented and spread across the entire area; roadside-avenue trees; forest cover comprising the Delhi ridge; National Zoological Park; open areas surrounding historical- monumental buildings and of course the Okhla Bird Sanctuary which comes under National Capital Territory and acts as a key element of urban green space in Delhi. In addition, city has nine biodiversity parks established by Delhi Development Authority (DDA) in assistance with the technical experts which forms an important component of green Delhi. Apart from this, there are about fourteen city forests covering an area of 300 ha and are developed and managed by Department of Forest and Wildlife, Government of NCT, Delhi. Various agencies as: Department of Environment and Forest, Government of NCT, Delhi; Municipal Corporation of Delhi (MCD); East Delhi Municipal Corporation (EDMC); New Delhi Municipal

Corporation (NDMC); DDA, Transport and Education Department; Flood Control Department; and Delhi Metro Rail Corporation (DMRC) along with Ministry of Environment Forest and Climate Change, as the nodal agency works continuously to make the capital green under "green capital' mission. Urban green spaces are defined as public and private open spaces in urban areas, primarily covered by vegetation which is directly or indirectly available for users (Manlun, 2003) [11]. Delhi, despite being one of the greenest cities in the world, it too faces ever escalating environmental burdens due to the rapid pace of increase in population, adverse effect of climate change, greenhouse gas emissions, high level of pollution and low availability of green spaces. Urban green spaces help in climate change mitigation, water management, biodiversity enhancement, recreation and leisure, improving quality of place, physical and mental health etc. Urban green areas further help in regulating the urban temperature, shade and cooling through evaporation. The increased greenery further led to higher absorption of CO_2 while also increasing the release of O_2 into the atmosphere. The National capital of Delhi is demarcated into two distinct ecological zones, an extension of the Aravalli hills and the plains. The Yamuna river, where a large number of water birds assemble during winter, which is the main source of water for the city. Delhi's northeast and east divisions lies on the bank of river Yamuna and this part is crucial for migratory water birds. along with Okhla barrage, which extends to the Okhla Wildlife Sanctuary in UP, identified as significant bird area of the region as Okhla Bird Sanctuary (OBS). The OBS caters to several essential ecosystem services which are: groundwater recharge; soil erosion control; adding recreational, aesthetic and educational value, apart from carbon storage- sequestration and O_2 release by urban flora. As the area is comprised of a dense tree vegetation which is regularly monitored and managed by the concerned authorities, this prompted the authors to evaluate the role of urban trees in carbon mitigation with specific reference to OBS. Various studies were conducted from time to time at OBS, focusing on phytosociological analysis (WII, 2002 [27];Tabasum *et al.,* 2009 [23]; Manral *et al*., 2013 [12]; Mukherjee and Sarma, 2014 [13]) but the aspect of carbon mitigation and sequestration by urban trees was not undertaken till date. However, few investigations regarding carbon sequestration by trees of parks/gardens in Mayur Vihar, Phase I, East Delhi (Tripathi and Joshi, 2015) [24], and at National Zooloical Park (Tripathi, 2016) [25] were conducted by the authors in the recent past. A growing tree faces multiple environmental stresses in an urban ecosystem, the most prominent being air pollution. Delhi- NCR region confronts high human impact which has a negative effect on tree health. This in turn influences overall phenology, ecophysiology and bioenergetics of carbon sequestration of trees. Moreover, trees are also subjected to constantly higher levels of pollution and for extended durations which also impact negatively to tree growth and biomass yield. Thus, site- specific tree performance data is required which can be utilized in future to frame site- specific policies. Though, OBS is at the edge of Delhi- Uttar Pradesh border and managed by the UP government, but the green space which it provides without doubt acts as a thick cushion and adds to urban green infrastructure of Delhi as well. The present study thus highlights on the role of urban trees in carbon mitigation and sequestration, growing at OBS, an area of high anthropogenic activity.

Material and Methods

Site details and climatic conditions

The geographical extension of OBS lies between 28° 32' 43.5" N and 28° 32' 56.3" N latitudes and 77° 18' 41.7" E and 77° 18' 56.6" E longitudes. The altitude is about 200 m above sea level. It is a floodplain wetland, lies within the national capital region (NCR) of Delhi and is a part of protected area network of the state of Uttar Pradesh. A small portion of the river Yamuna has become a static water system due to the construction of Okhla barrage across the river. This wetland acts as a halt for many migrating birds. The wetland was declared a wildlife sanctuary in the year 1990 by Uttar Pradesh government under the Wildlife Protection Act, 1972. The OBS is spread in an area of about 400 ha, with open water covering around 273 ha, reed and sand beds covering 97 ha and roads and bunds comprising the remaining 30 ha. The soil is fertile and alluvial with a gentle southeastern slope. Sediments of the reservoir is manly composed of silt load carried by the river itself. The sanctuary enjoys three main seasons: Summer (April- June, temperature range 40°C- 29°C), winter (November-March, temperature range 21°C- 5°C) and monsoon (July- September).

Experimental Design and sampling procedure

Three sites were randomly selected from the study area. It was assured that the sites didn't overlapped each other. Fifteen (15), eleven (11) and fourteen (14) circular plots (0.025 ha) of plot radius 8.92 m were randomly laid for sampling trees and shrubs. Plot method is one of the most commonly used methods for all kinds of vegetation sampling. The method is versatile and cost- effective too. Circular plots were selected as they can be established easily and with high accuracy (Paudel and Mandal, 2019) [15]. In all, 40 (0.025 ha) plots were laid down covering a total area of 1 ha. Stand density came out to be 1011 stems ha^{-1}.

Biomass and Carbon sequestration calculations

In the present scenario, as destructive harvesting of trees is not permitted in most of the countries, including India, so non- destructive methods were applied for calculating biomass and carbon sequestration of trees. For this, every tree in all the plots was marked and its Circumference at Breast Height (CBH in cm) and height (m) was measured subsequently. The plot wise data collected was further simplified as in Table 1.

The biomass was measured by non- destructive method i.e. without felling the tree. DBH ≥ 5 cm were considered as trees and measured. Initially, CBH was measured which was later converted to corresponding

DBH values. CBH of the trees were measured directly by measuring tape (at 1.3 m from ground). Height of the tree were measured by wooden poles of varying heights (for trees up to 5m) and clinometer (for trees more than 5 m tall).

Basal Area (cm^2/tree) was calculated using the formula BA= $\pi * r^2$, where r is the radius of the cylindrical bole of tree. Radius (in cm) was calculated from CBH as r = CBH/2*π. For individual biomass calculations, tree volume (cm^3/tree) was calculated using the equation $V = \pi r^2 H$ where both r and H are in centimeters and respective volumes were multiplied by wood densities (g cm^{-3}) to get the actual aboveground biomass (gm/tree) (Ravindranath and Ostwald, 2008) [18]. Aboveground biomass for all 31 tree species were calculated and extrapolated for total area (Tha^{-1}). The aboveground biomass was multiplied by a conversion factor of 0.26 to get the belowground biomass (Ravindranath and Ostwald, 2008) [18]. Total standing biomass was calculated adding above and below ground biomass (Sheikh *et al*., 2011) [21]. This is the actual biomass calculated using field data. Wood density values for tree species were obtained from web (www.worldagroforestry.org) [28] and from a technical report (Reyes *et al*., 1992) [19]. Whenever, the wood density of tree species was unavailable, the average standard value of 0.6 g cm^{-3} was taken. Generally, for any plant species, 50% of its biomass is considered as carbon (Pearson *et al*., 2005) [16] i.e. carbon storage is Biomass * 50% or carbon stored is Biomass/2.

The carbon content i.e. the weight of carbon in a tree can be converted to weight of CO_2 sequestered in the tree by multiplying the carbon content value by 3.67. The factor of 3.67 was calculated on basis of atomic masses of carbon and oxygen (C=12; O= 16; CO_2= 12+(16*2) =44). One ton of carbon storage in a tree therefore represents removal of 44/12 or 3.67 tons of CO_2 from the atmosphere and releases 2.67 tons of O_2 back into the atmosphere. If the age of the stand is known, then CO_2 removal rates can be calculated by dividing the weight of CO_2 sequestered by stand age. Information regarding stand age is an important aspect in forest management as it reflects competitiveness and resource acquisition among species in a forest stand and also adds information about the site quality. Tree age can be estimated by either counting the number of annular rings of tree stump or with the use of increment borer. Both the methods damage the tree, therefore not recommended for frequent use. In this study, stand age was determined by dividing mean CBH value in cm with a growth factor of 2.5. The value (2.5) is an average annual increment of tree girth in a mixed population. For fast growing species, the factor is 3.13 and for slow growing species it is 1.88. Though, tree growth rates are affected greatly by environmental conditions and overall plant vigor yet this approach gives a rough estimate of the stand age and site quality which can be applied for better management practices of forest stands.

Fig 1: Satellite map of Okhla Bird Sanctuary

Allometric model development/fitting and model evaluation

Mean values of H-D pairs of 31 tree species (Table 1) were utilized for developing the model. A Chapman-Richard, 3- parametric function (Richard, 1959) [20] was selected to establish allometric relationships between different tree variables. The function has been highly valued for its accuracy and it has been applied much more than any other function in investigations related to trees and stand growth. The model type has the functional formula:

$$y= a[1-e^{-bx}]^c$$

Where a, b and c are model parameters (a, b, c >0); a is the upper asymptote, b is the scale parameter and c is the shape parameter and inflection point; *e* is exponential. The growth function is expressed in integral form.

Different allometric relationships between tree variables, based on C-R, 3- parametric function were further evaluated on the basis of performance criteria, significance of model parameters and biological significance of the model function. The model was tested for its precision, accuracy and reliability to predict the dependent variable (y). The model performance was evaluated based on following criteria: Adjusted R^2 (Chenge, 2021) [1], Akaike Information Criteria (Chenge, 2021) [1] and Residual Standard Error (Chenge, 2021) [1]. Model with least RSE, AIC and maximum adjusted R^2 was considered to perform the best.

All statistical calculations were performed in Microsoft excel, 2019 using add- in functions viz. *Real Statistics Resource Pack* and *Data Analysis tools*. Nonlinear curve fitting was performed by excel *Solver*. It is designed on the powerful and reliable generalized reduced gradient (GRG) method and is used as an easy iteration method to work on nonlinear and asymptotic models. It operates by fitting nonlinear regression functions via an iterative algorithm which minimizes the sum of squared errors (SSE) between observed and predicted data sets. Thus, the model obtains maximum likelihood when SSE is minimized. For data fitting, number of iterations was set at hundred (100) with precision level of 0.000001.

Results and Discussions

Total 31 species consisting of 1011 individuals were recorded from forty (40) circular plots at OBS, covering an area of 1 ha. Table 1 demonstrates number of trees of each species and total number of trees sampled under 1 ha. The table also indicated mean DBH and mean height of the species. As the diameter and height of a tree grows over time, its biomass and carbon sequestration capacity also increases though rates are different for different tree species. List of species along with their aboveground, belowground and total standing biomass and aboveground, belowground and total organic carbon is depicted in table 2. Total standing biomass and total carbon stocks sequestered came out to be 38.690 Tha^{-1} and 19.345 Tha^{-1} respectively. Maximum standing biomass (10.217 Tha^{-1}) and maximum carbon sequestered (5.108 Tha^{-1}) was by *Ficus benghalensis* and minimum biomass (0.084 Tha^{-1}) and minimum organic carbon (0.042 Tha^{-1}) was sequestered by *Prosopis cineraria*. Major carbon sequestrating species were: *Ficus benghalensis* (5.108 Tha^{-1}), *Neolamarckia cadamba* (2.919 Tha^{-1}), *Ficus religiosa* (1.354 Tha^{-1}), *Pongamia pinnata* (0.888 Tha^{-1}) *Azadirachta indica* (0.795 Tha^{-1}) and *Delonix regia* (0.727 Tha^{-1}). Mean DBH ranged from 13.833- 70.155 cm and mean height was in the range 5.945- 23.926 m. Growth rate was moderate - fast for most of the species except *Salvadora oleoides*, *Prosopis cineraria*, *Tamarindus indica, Butea monosperma and Kigelia africana* which had slow growth rates.

Mean carbon content came out to be 19.345 Tha^{-1}. Similarly, mean CO_2 sequestered was calculated as 70.996 Tha^{-1} and CO_2 removal rates was estimated as 1.977 T $CO_2ha^{-1}y^{-1}$. Moreover, mean O_2 released was calculated as 51.651 Tha^{-1} and O_2 release rates was estimated as 1.438 $TO_2ha^{-1}y^{-1}$.

Correlations between different tree variables

Chapman- Richard (C-R), 3- parametric function was applied to establish relationships between different tree variables (Table 3). It was observed that the aboveground biomass was strongly and positively correlated with the basal area. This was followed by a strong and positive correlation between total standing biomass and basal area. Moreover, total volume also reflected positive correlation between basal area and DBH of trees. Though, the correlation between tree height and DBH was also found to be strong and positive yet among all tested relationships, height- diameter correlation was put in the last category on the basis of predictive performance (Adj. R^2= 0.865; AIC= 33.658; RSE= 1.562). The variation in tree height in response to its corresponding diameter can be analyzed from table 1 itself.

Chapman-Richard 3- parametric function

There is a long history of applying nonlinear functions to forest growth and yield dynamics. C-R function is quite flexible in nature and can be applied to stand growth as well as establishing correlations between different tree variables. It can be utilized to individual tree species as well as in a mixed forest. The function has an inflection point and an upper asymptote and forms a typical sigmoid curve, imitating a growth process. Both the biotic and the abiotic factors influence model function and its parameters.

Richard (1959) first published the Chapman- Richard function followed by its introduction to forestry applications by (Pienaar and Turnbull, 1973) [17]. The model has a reputation of being very flexible and accurate, on the slight expense of biological realism. It is among the most popular functions for describing the growth of variables within a forest stands, as: individual tree height, dominant tree height; DBH, Basal area, tree volume and biomass etc. It has been widely used in many empirical forest growth simulators, particularly when the accuracy of model prediction is crucial. The function has been used extensively to model site index development along with correlating different tree and stand variables. Moreover, it is being utilized to express dynamic growth in terms of cumulative, absolute and relative growth rates**.**

Population growth and urban green infrastructure in Delhi

Delhi is one of the greenest cities in India (Choubey, 2017) [2], yet it has earned the infamous tag of being one of the most polluted cities (Harris, 2014) [6] in the world. According to the master plan of Delhi, 2021[3], unprecedented scale and speed of urbanization in Delhi/NCR has led to extensive pressure on the physical environment with a highly negative impact of pollution on the lives of its people. All this has led to deteriorating pollution indicators in Delhi, making it almost the most polluted cities in the world. The master plan further stated that all water bodies including river Yamuna have become highly polluted. Either, they have been encroached or have become functionless. Many parts of Delhi have been witnessing heavy metal- laden groundwater due to undocumented precedence on groundwater (Singh, 2019) [22], such as exploitation of groundwater resources leading to exhaustion of water tables and an increase of metallic components.

Table 1: Field data of tree species

S. No	Scientific Name	Mean DBH (cm) ±SE	Mean H (m) ±SE	Frequency
1	*Albizia lebbeck (L.) Benth.*	28.776±0.852	15.956±0.714	43
2	*Morus alba L.*	22.552±1.024	14.576±0.794	47
3	*Dalbergia sissoo DC.*	20.909±0.686	9.722±0.453	68
4	*Bombax ceiba L.*	41.053±2.036	18.428±1.279	17
5	*Prosopis juliflora (Sw.) DC.*	22.933±0.865	7.922±0.346	73
6	*Pithocellobium dulce (Roxb) Benth.*	17.258±1.198	8.019±0.478	52
7	*Azadirachta indica A. Juss.*	34.724±1.483	15.935±0.798	27
8	*Holoptelia integrifoliaPlanch.*	29.734±0.861	16.331±0.392	35
9	*Leucaena leucocephala (Lam.) de wit*	30.134±0.854	16.724±0.355	89
10	*Parkinsonia aculeate L.*	21.540±1.473	11.023±0.844	15
11	*Bauhiana purpuera L.*	21.239±1.121	7.613±0.506	26
12	*Erythrina variegate L.*	23.160±1.442	11.121±0.628	33
13	*Neolamarckia cadamba (Roxb.) Bosser*	62.681±2.141	23.772±0.957	11
14	*Ficus benghalensis L.*	70.115±1.384	23.926±1.826	5
15	*F. religiosa L.*	60.295±4.647	20.365±1.920	8
16	*Kigelia pinnata (Jacq.) DC.*	23.508±1.992	11.778±0.798	21
17	*Salvadora oleoides Decne.*	18.851±1.622	7.466±0.860	15
18	*Prosopis cineraria L.*	13.833±1.625	5.945±0.776	18
19	*Pongamia pinnata (L.) Pierre*	32.116±1.928	15.708±1.241	24
20	*Acacia nilotica (L.) Delile*	20.817±1.161	11.979±0.429	26
21	*Alstonia scholaris (L.) R. Br.*	21.028±1.322	11.475±0.669	29
22	*Delonix regia (Hook) Raf.*	29.492±2.091	12.512±1.070	29
23	*Mangifera indica L.*	34.164±1.008	14.787±0.893	35
24	*Albizia procera (Roxb.) Benth.*	27.011±1.391	12.353±0.686	31
25	*Tamarindus indica L.*	30.231±1.947	12.237±1.011	35
26	*Cordia dichotoma G. Forst.*	18.322±1.064	8.532±0.691	24
27	*Butea monosperma (Lam.) Taub.*	25.520±1.227	14.069±0.962	25
28	*Kigelia Africana (Lam.) Benth.*	24.158±1.309	9.910±0.622	17
29	*Ehretia laevis Roxb.*	20.541±2.060	10.098±0.906	39
30	*Polyalthia longifolia (Sonn.)*	24.872±1.878	11.097±0.901	45
31	*Tectona grandis L. f.*	18.302±1.319	8.132±0.473	49
	Total			1011

Wetland and floodplains of river Yamuna are being lost in the name of development, leading to less urban green spaces available in city. Meanwhile, Forest Department of the Government of NCT, Delhi is planning to utilize the banks of Yamuna floodplains for afforestation purpose. The Department has set targets of increasing the green cover of the city by 25% (in 2025) from the present status of 23.06% (2021). The high rate of urbanization with increasing density has lowered the green spaces in Delhi/NCR region. Due to climate change, the city is facing hazardous situations like heat waves, changes in mean annual temperatures etc. On the other hand, anthropogenic activities as pollution and illegal felling of trees has made the city a gas chamber which obstructs the social growth and affects the quality of health of the population in the city. Hence, it impacts negatively on biodiversity which directly or indirectly effects urban green spaces and its residents.

Table 2: Biomass accumulation and carbon sequestration values of 31 tree species

Scientific Name	Mean AGB(Tha^{-1})	Mean BGB (Tha^{-1})	Mean TSB (Tha^{-1})	Mean AGC (Tha^{-1})	Mean BGC (Tha^{-1})	Mean TCS (Tha^{-1})
Albizia lebbeck	1.716±0.146	0.446±0.038	2.162±0.184	0.858±0.073	0.223±0.079	1.081±0.092
Morus alba	1.425±0.174	0.370±0.045	1.795±0.219	0.712±0.087	0.185±0.023	0.898±0.109
Dalbergia sisso	0.807±0.070	0.210±0.018	1.016±0.088	0.403±0.035	0.105±0.009	0.503±0.044
Bombax ceiba	1.718±0.188	0.447±0.049	2.165±0.236	0.859±0.094	0.223±0.024	1.083±0.118
Prosopis juliflora	1.074±0.139	0.279±0.036	1.354±0.175	0.537±0.069	0.140±0.018	0.677±0.087
Pithocellobium dulce	0.499±0.101	0.130±0.026	0.629±0.127	0.250±0.050	0.065±0.013	0.314±0.064
Azardicta indica	3.153±0.445	0.820±0.116	3.973±0.561	1.577±0.223	0.410±0.058	1.987±0.281
Holoptelia integrifolia	1.970±0.165	0.512±0.043	2.482±0.207	0.985±0.082	0.256±0.021	1.241±0.104
Leucaena leucocephala	2.444±0.210	0.635±0.055	3.078±0.265	1.221±0.105	0.318±0.027	1.539±0.133
Parkinsonia aculeata	0.691±0.127	0.180±0.003	0.871±0.160	0.346±0.064	0.090±0.017	0.435±0.080
Bauhiana purpuera	0.565±0.081	0.147±0.021	0.7111±0.102	0.282±0.041	0.073±0.011	0.356±0.051
Erythrina varigata	0.515±0.098	0.134±0.025	0.649±0.123	0.258±0.049	0.067±0.013	0.325±0.062
Neolamarckia cadamba	11.582±1.157	3.011±0.301	14.594±1.458	5.791±0.579	1.506±0.150	7.297±0.729
Ficus bengalensis	8.108±0.539	2.108±0.139	10.217±0.675	4.054±0.268	1.054±0.070	5.108±0.338
F. religiosa	5.373±1.011	1.397±0.263	6.770±1.274	2.686±0.506	0.698±0.131	3.385±0.637
Kigelia pinnata	1.057±0.247	0.275±0.064	1.332±0.311	0.529±0.124	0.137±0.032	0.666±0.156
Salvadora oleoides	0.447±0.124	0.116±0.032	0.564±0.156	0.224±0.062	0.058±0.016	0.282±0.078
Prosopis cineraria	0.167±0.046	0.043±0.012	0.210±0.059	0.083±0.023	0.022±0.006	0.105±0.029
Pongamia pinnata	3.525±0.624	0.916±0.162	4.441±0.786	1.762±0.312	0.458±0.081	2.221±0.393
Acacia nilotica	1.017±0.124	0.264±0.032	1.281±0.156	0.508±0.062	0.132±0.016	0.641±0.078
Alstonia scholaris	0.446±0.075	0.116±0.020	0.562±0.095	0.223±0.038	0.058±0.010	0.281±0.048
Delonix regia	2.883±0.625	0.750±0.163	3.633±0.788	1.442±0.313	0.375±0.081	1.816±0.394
Mangifera indica	2.488±0.296	0.647±0.077	3.134±0.372	1.244±0.148	0.323±0.038	1.567±0.186
Albizia procera	1.385±0.234	0.360±0.061	1.746±0.295	0.639±0.117	0.180±0.030	0.873±0.148
Tamarindus indica	2.773±0.572	0.721±0.149	3.494±0.721	1.386±0.286	0.360±0.074	1.747±0.360
Cordia dichotoma	0.354±0.055	0.092±0.014	0.446±0.070	0.177±0.028	0.046±0.007	0.223±0.035
Butea monosperma	1.111±0.174	0.289±0.045	1.399±0.219	0.555±0.087	0.144±0.023	0.700±0.110
Kigelia africana	0.801±0.154	0.208±0.040	1.009±0.194	0.400±0.077	0.104±0.020	0.505±0.097
Ehretia laevis	0.995±0.234	0.259±0.061	1.254±0.295	0.498±0.117	0.129±0.030	0.627±0.148
Polyalthia longifolia	1.689±0.423	0.439±0.110	2.128±0.533	0.845±0.211	0.220±0.055	1.064±0.266
Tectona grandis	0.615±0.140	0.160±0.036	0.775±0.176	0.308±0.070	0.080±0.018	0.388±0.088
Total	30.706	7.987	38.690	15.354	3.994	19.345

*AGB= Aboveground biomass; BGB= Belowground Biomass; TSB= Total Standing Biomass; AGC= Aboveground carbon; BGC= Belowground carbon; TCS= Total carbon sequestered; ±= Standard Error

Total geographical area of Delhi comprised of 1483 Km^2. Continuous influx of population cannot be averted but sustainability among different stakeholders can obviously be maintained, though the task is daunting. Urban green areas in cities play a significant role in achieving the sustainability development goals. Delhi/NCR is witnessing a constant growth in terms of population size. It rose from 13.85 million in 2001 to 30.7 million till date. Thus, there is an addition of 16.85 million people in a span of over two decades. Credit goes to the compensatory plantation programs, afforestation and annual drives conducted from time to time in the past twenty years, that the overall green cover (forest cover + tree cover) of the city has increased from 151 Km^2 (10.18%) in 2001 (SFR, 2001) [7] to 342 Km^2 (23.06%) in 2021 (SFR, 2021) [8], though the efforts are insufficient in comparison to exponential rise in urbanization and developmental activities within the same period. Green cover of the city should be increased on priority basis to achieve sustainable development goals as the ecosystem services provided by green cover cannot be negated.

Table 3: Model parameters and evaluation statistics

Tree Variables	Model parameters			Model fitting and evaluation statistics		
	a	b	c	R^2 adj.	AIC	RSE
TV Vs BA	79.366	0.617	1.388	0.995	-115.776	0.140
TV Vs DBH	38.268	0.017	3.937	0.994	-107.42	0.161
TSB Vs BA	58.166	0.692	1.397	0.995	-126.971	0.117
AGB Vs BA	52.491	0.617	1.388	0.996	-141.408	0.093
TH Vs DBH	25.390	0.045	1.865	0.865	33.658	1.562

*TV= Tree Volume; BA= Basal Area; DBH= Diameter at Breast Height; TSB= Total Standing Biomass; AGB= Aboveground Biomass; TH= Tree Height

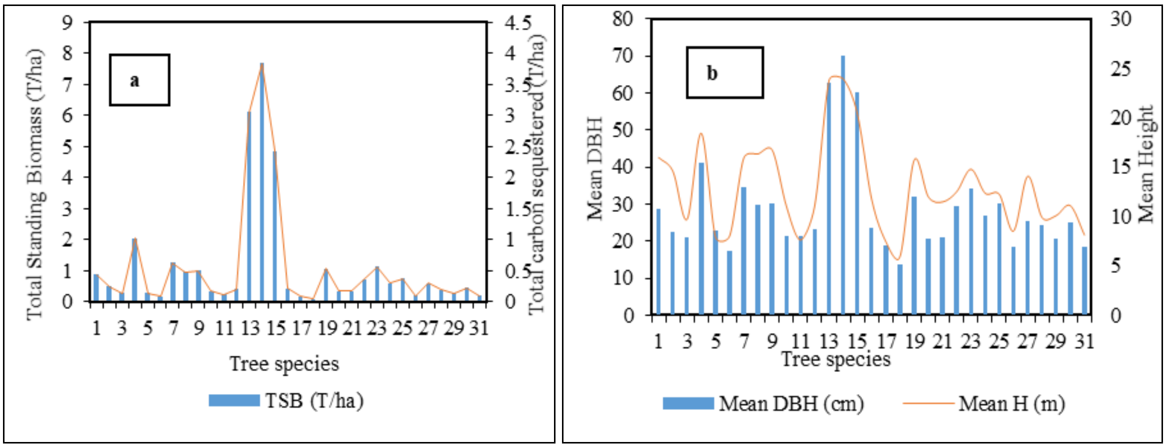

Fig 2 (a): Total standing biomass and total carbon sequestered by 31 tree species; (b) Mean DBH and Mean Height of 31 tree species studied *All numbers represent mean value

As urban greening comes as a rescue to mitigate climate change and pollution impact on the city, so urban green programs should be speeded up by the concerned agencies otherwise the situation will get worse in the coming years. The goal of the agencies should be to create more and more green spaces in the city and try to adhere to National Forest Policy guidelines of 1988 according to which at least $1/3^{rd}$ (33%) of the geographical area should be under green cover. Only this will lead to a better future for the inhabitants as well as the biodiversity of the city.

OBS has a total area of 400 ha out of which approximately 20 ha consist of terrestrial vegetation. More potential sites for afforestation purpose within the OBS should be explored without disturbing the present flora. Moreover, growth performance studies of the tree saplings selected for afforestation should be conducted taking into account function- derived relative growth rates. Biomass partitioning data of species should also be gathered for better adaptation and yield. Growth performance of the sapling trees should be evaluated under different stress levels within the OBS and best performing species should be selected for afforestation drive.

Standard forest-carbon uptake models in the light of fresh findings

Carbon storage and sequestration of urban trees is temporary in long term, since the sequestration and storage process is reversible. Forest carbon-uptake models are gradually becoming popular in the past few decades so they should be reviewed and re- evaluated in the light of fresh evidences before extrapolating the model benefits. As per these models, it is assumed that fast growing species are more suitable in terms of carbon storage and sequestration than slow growing species. This approach is based on a simple principle that under favourable conditions, better acquisition of resources in young and fast growing trees will lead to more carbon storage, with high sequestration rates and in a quick span of time and perhaps for longer durations as well.

Therefore, for large scale afforestation, fast growing species are usually preferred over species with slow growth rates. However, recent investigations contradict the present model system and highlight that increased concentration of CO_2 coupled with high temperatures, catalyse fast growing trees to mature early and at a faster rate. This lead to reduction in their lifespan and thus trees get less chance to absorb atmospheric CO_2 than anticipated. In other words, fast growing species dies before they are big enough to store significant amount of carbon from the atmosphere. This trend is common, regardless of species or ecosystem type in which trees are planted. Thus, it is observed that, as the temperature increases due to climate change, the increased growth rate of fast growing trees seems to increase their chances of dying and therefore forest comprising of mainly fast growing species could store less amount of carbon in the long run due to high tree mortality.

Thus, it can be anticipated that standard forest- carbon uptake models might have overestimated the projected benefits of forests acting as large carbon sinks. On the other hand, role of slow growing species in carbon storage and sequestration was also evaluated from time to time. Investigations revealed that slow growing trees have inherited traits that allow them to withstand harsh environmental conditions, and could be more beneficial to store carbon for longer durations, though sequestration rates could be low. Analysis of more than two lack tree rings, from 82 tree species, ranging from tropical moist to artic forests, around the world have discovered the trade-off between tree lifespans and growth which was found to be universal and occurred in almost all tree-types and climates. According to the studies, the increase in forest carbon stocks across the globe may be short lived and accelerated growth of forests in near future will result in shorter tree lifespans and high mortality rates.

People have greatly benefited by the ability of trees to absorb carbon emissions for years. However, the carbon uptake rate of forests is likely to shrink as slow-growing and persistent trees are being replaced by fast-growing but vulnerable trees. A survey of terrestrial vegetation constituting Delhi urban forests along with OBS was also conducted by the authors during the present investigation. Entire vegetation was grouped into two functional groups, one of fast growing and another of slow growing species. It was observed that more than 80 percent urban flora (84.76%) comprised of trees and shrubs with high growth rates. Trees growing at faster rates are more vulnerable to climate change. On the other hand, slower growing trees have traits that allow them to persist. When fast growing trees reach their maximum potential size under favourable conditions, they face an increased risk of dying. Fast-growing trees also seem to have lesser defences against natural causes like invasive species, drought and herbivory as compared to slow growing trees that invests much more in their defence systems, thus can resist adverse climatic conditions with extended lifespans. Other factors of destruction also make the fast growing trees vulnerable, especially since the earth's mean surface temperature had increased by 0.56°C. The warmer temperature has triggered severe droughts, heatwaves, rising sea levels, and super storms. This means that planting more trees or decreasing deforestation to offset greenhouse gas emissions from fossil fuels really does not stand up to scientific scrutiny.

Delhi urban forest, along with OBS has also vouched for fast growing tree species for large scale plantations in the city. In the present study, out of 31 species, 26 (83.87%) comprised of trees and shrubs with fast growth rates. Thus, in the light of new evidences, standard forest- carbon uptake models in future should be revisited and adopted differently, by taking into consideration high mortality rate of fast growing trees. This should lead to gradually replacing trees with fast growth rates with slow growing ones as far as both natural and urban forests are concerned. More priority should be given to slow growing species for long term carbon storage.

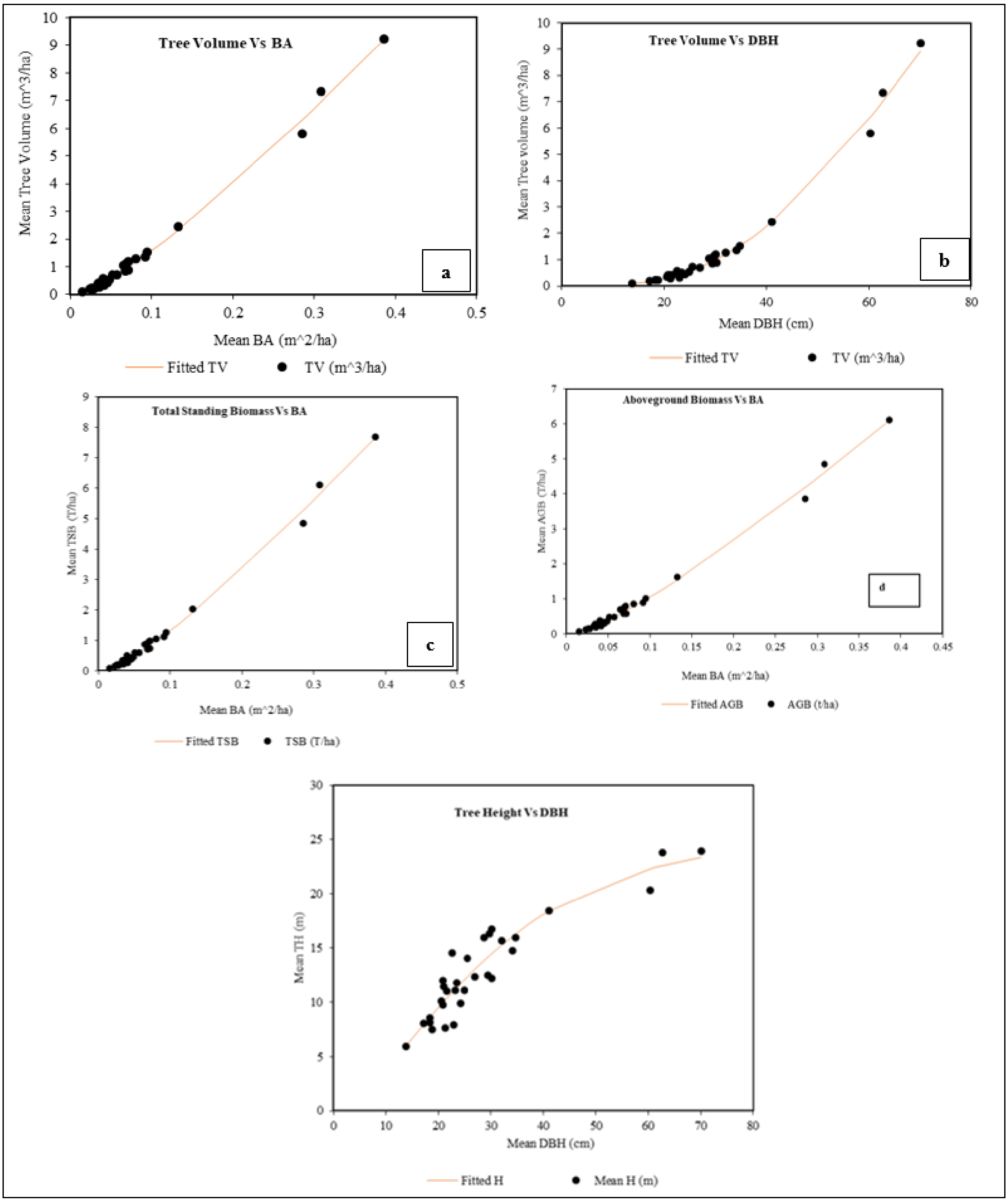

Fig 3: a, b, c, d and e: Allometric relationships between different tree variables obtained using a Chapman-Richard 3- parametric function

Conclusion

Urban green spaces are important component of Delhi and perform a variety of ecosystem services including carbon offsetting. In order to strike a good ecological balance between the inhabitants and its environment, Delhi should be under a substantial amount forest and tree cover. More, open spaces in Delhi should be spotted and utilized to increase the green cover of the city, up to the point where sustainable development goals could be achieved. OBS is also one of the finest areas in Delhi- NCR region where thick tree vegetation is witnessed. These urban green areas cater to the need of people in Delhi/NCR region. Hence, the place should be conserved for future use and additional potential sites should be explored, to add more trees within the premise. Moreover, trees with low growth rates should be given priority over trees with fast growth rates when it comes to conducting large scale afforestation programs. Simple reason being that fast growing trees have a shorter lifespan and high mortality rates.

Thus, it is high time we should incorporate latest findings on forest- carbon uptake models and make appropriate adaptations before conducting massive afforestation-reforestation drives in cities and other areas. This change in strategy should be applicable to Delhi/NCR along with OBS as well.

Acknowledgements

The authors would like to thanks the Head of the Department, Department of Plant Biology, Kumuon University, Almora Campus, Almora for providing all necessary facilities. Assistance provided by the technical staff during field survey is highly appreciated. Finally, thanks to the anonymous reviewer for his review and constructive comments on the manuscript.

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