RESEARCH ARTICLE

Quantifying Carbon Stock and Tree Species Diversity of Green Infrastructure of Varanasi, India

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DOI: 10.18811/ijpen.v9i01.03

Abstract

The world is undergoing rapid urbanization and experiencing its negative impacts, typically because of the loss of urban green infrastructure. This study focuses on the green infrastructure of Varanasi city, India, and analyses current tree species diversity, and carbon storage in aboveground and belowground biomass and soil. The study calculated the biomass of urban green infrastructure because it serves as a carbon stock reservoir. As a random sampling, data were collected from 24 sample plots across various urban green infrastructure sites via rigorous fieldwork. The biomass was then recorded using a non-destructive approach and a standard equation. The diversity of tree species was recorded across urban green infrastructure sites, and was found to be higher in the BHU site, and lower in the MA site. Pielou's evenness index and Margellef's richness index were found to be higher in the BHU site, while they were found to be lower in UPAC and MA sites, respectively. Aboveground biomass and total carbon stock were found to be high in the BLW site, with values of 1939.84 ton/ha and 7806 ton/ha, respectively, with trees having a larger girth circumference being the primary contributors. This study improves understanding of tree species diversity, biomass, and carbon stock of different green infrastructure sites of Varanasi city and generates evidence on how urban green space conservation and green infrastructure development may help the countries' green economic transformation and sustainable, resilient, and low-carbon cities.

Keywords: Biomass**,** carbon stock, tree species diversity, Urban forest, green infrastructure, Varanasi.

International Journal of Plant and Environment (2023); **ISSN:** 2454-1117 (Print), 2455-202X (Online)

Introduction

The world's population is becoming urbanized. Approximately two-thirds (approx. 63 %) of the world's human population will live in cities by 2050. The global urban population has grown considerably from 751 million in 1950 to 4.2 billion in 2018 (UN DESA, 2018). Despite its low urbanisation rate, Asia has 54% of the world's urban population, followed by Europe and Africa, each with 13%.

Like many other countries, India is getting more urbanised as well. According to a Statista report, published by Aaron O'Neill on July 29, 2022, in 2021, nearly one-third of India's total population resided in urban areas. Urbanization in India has expanded by roughly 4% during the past decade. According to World Urbanization Prospects: 2018 revision, in 2020, India's urban population was estimated to be approximately 35% of its total population. In 2021, nearly one-third of India's total population lived in urban areas (O'Neill, 2022). According to Mell (2015), the proportion of India's urban population will increase to about 50 % by 2050. Urbanization, particularly in India, is devouring a considerable section of peri-urban arable land, resulting in a significant loss of green space (Lahoti *et al.,* 2020).

Population growth has a growing impact on the local, regional, and global environments (Nowak *et al.,* 2001). This effect is most pronounced in urban areas, where the concentrated human presence fragments and modifies natural resources, resulting in large-scale environmental implications. The blending of natural resources with human development is what defines the urban forest (Nowak, 1994a). According to Konijnendijk *et al.* (2006), The management of trees and other forest resources in and near urban environments to benefit people physically, socially, economically, and aesthetically is known as urban forestry.

Through proper planning, design, and management practices, Urban trees may moderate the climate, reduce building energy usage, absorb UV radiation and atmospheric CO_2, improve air and water quality, reduce rainfall runoff and flooding, and reduce noise levels (Nowak and Dwyer, 2000).

In general, CO_2 is the most common greenhouse gas (GHG) in the atmosphere and a significant (>50%) cause of global warming (Sahoo *et al.,* 2021). An urban forest can help the atmosphere by lowering the amount of carbon dioxide and other greenhouse gases (GHG). Urban forests reduce GHG emissions and the energy required to heat and cool buildings by sequestering carbon dioxide (CO_2) from the atmosphere (McPherson *et al.,* 2008).

In the tropical zones, atmospheric CO_2 concentrations increased to >400 parts per million in 2015 (Betts *et al.,* 2016), and by 2050, this concentration is expected to increase by 500 parts per million (Cai *et al.,* 2014). Additionally, the earth's surface temperature will increase due to the rapid increase in atmospheric CO_2 concentration, which will also harm the ecosystem and people's health (such as sea level rise and

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How to cite this article: Singh, A.K., Singh, J.S., Singh, H., Mishra, R.K. (2023). Quantifying carbon Stock and tree species diversity of green infrastructure of Varanasi, Indiae. International Journal of Plant and Environment. 9(1), 15-23.

Conflict of interest: None

Submitted: 02/01/2023 **Accepted:** 24/01/2023 **Published:** 30/03/2023

flooding) (IPCC, 2007; IPCC, 2014; Kumar *et al.,* 2021). The United Nations Framework Convention on Climate Change (UNFCCC) developed the "Reduction of Emissions from Deforestation and Forest Degradation" (REDD) policy in 2007 to combat these effects of climate change. This policy was later implemented as REDD+ in 2010 (UNFCCC, 2008) to conserve and manage the 2015 Pg of the global terrestrial C stock.

The link between tree diversity and carbon stock has emerged as an important concern in the carbon cycle and climate change adaptation (Gebrewahid and Meressa, 2020). In addition, forest diversity plays an important role in maintaining ecosystem processes, functions, and services, which has become a concern in ecology and the environment (Loreau *et al.,* 2001). In this context, tree diversity, often assessed as tree species richness per area, is viewed as an essential factor impacting global and local tree productivity and carbon storage (Liu *et al.,* 2018). According to the niche complementarity hypothesis, Species diversity enhances resource utilisation and nutrient retention, hence allowing for bigger carbon stores per area (Tilman, 1997). It has been demonstrated that tree species richness has a favourable impact on soil C storage, above-ground stand productivity, above-ground tree C storage, leaf litter output, and litter decomposition (Liu *et al.,* 2018; Kothandaraman *et al.,* 2020).

Understanding the structure and composition of trees, forest patches, and the dynamic variability between and within different types of green space is essential for the successful ecological management of the urban forest (Nero *et al.,* 2018).

The current analysis is the first of its kind to account for carbon emissions from various green infrastructure sites in Varanasi. Inadequate information on carbon stocks and sequestration capacity under varied green infrastructures renders this study essential. Therefore, the current study's goal was to assess the diversity of trees, their biomass, carbon stocks, and sequestration potential in Varanasi, India, under various green infrastructures. To create effective mitigation and adaptation plans in advance to fight future climate change, it also made effort to connect tree basal areas, biomass carbon storage, and density at various green infrastructure sites.

Material and Methods

Study Sites

Varanasi, also known as Kashi or Banaras, is India's religious, cultural, and educational centre. It is located on the banks of the Ganga River and spans 1,535 square kilometres in the state of Uttar Pradesh in the Indo-Gangetic plains of northern India. The Ganga River flows from south to north, with the world-famous Ghats on its left bank. Varanasi's urban agglomeration extends between 82° 56′ to 83° 03′ East longitude and from 25° 14′ to 25° 23.5′ North latitude.

Varanasi is situated 121 kilometres east of Prayagraj and 320 kilometres south of Lucknow at an altitude of 80.71 metres along the left crescent-shaped bank of the Ganga. Varanasi has a total population of 3,676,841 and a geographical area of 1535 km2 (Nistor *et al.,* 2018).

According to the Koppen Climate Classification, "Varanasi district has a humid subtropical climate" (Kottek *et al.,* 2006)).

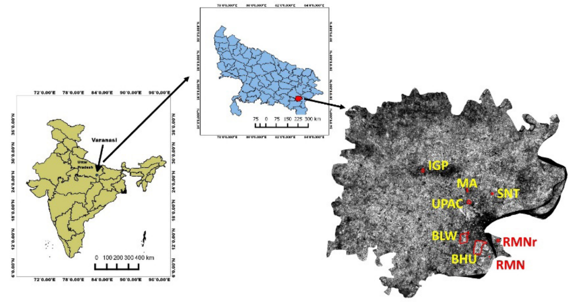

Fig. 1: Location of the study area

These climate types are typified by dry winters with average temperatures ranging from 3 to 18°C, and by summers with constant precipitation and mean temperatures above 22°C (Nistor *et al.,* 2020). Throughout the day, hot waves of air, also known as loo, blows, causing the temperature to be exceedingly dry. The monsoon season follows the summer season. From July to September, this season is in effect. The city receives 1,110 mm of rain per year on average (Ghosh, 2019). Varanasi experiences substantial diurnal temperature changes during the winter. The nights are extremely cold despite the warm days. Temperatures below 5°C are frequently experienced during the season due to cold waves from the Himalayan range, and the dense fog is also typical.

This study focuses on eight sites of green infrastructure in the city, including the Indane gas plant (IGP), Matridham ashram (MA), Udai Pratap Autonomous College (UPAC), Sarnath temple (SNT), Banaras locomotive works (BLW), Banaras Hindu University (BHU), PSC camp of Ramnagar (RMNr) and Ramna (RMN) (fig. 1). These are effective illustrations of the existing green infrastructure in the city. These locations were located and chosen through extensive visits to the city as well as observation of satellite imagery.

In particular, the UPAC and the BLW have been categorised as urban forests with grassland. The BLW site has more green space than the UPAC site. The suburban forest includes the BHU and RMN sites. The BHU site has more green space than the RMN site. RMNr and SNT sites are categorised as the periurban forest in which the SNT site includes more green spaces than the RMNr site. In this analysis, we also included the rural forest, namely MA and IGP (Table 1, Fig. 1). Apart from this green infrastructure, there are some other small parks and plantations in this city. And overall, there is a lack of park and roadside planting within the city.

Data Collection and Analysis

Vegetation and Soil Sampling: Using stratified random sampling, the sites for the biomass survey and soil sampling for each green infrastructure site were identified.

For the estimation of biomass, random sampling was employed. Initially, we built a 15 x 15 m sample plot. The diameter at breast height (DBH) and height of the tree were measured using a metre tape and the Brower and Zar (1998) method, respectively. For each measured tree, the species and local name were noted. A total of 24 15 × 15 m (3 plots in each site) sample plots were built between all urban green infrastructure sites.

Table 1: Characteristics of study sites

S.N	*Name*	*Code*	*Vegetation*	*Area (ha)*
1	Ramna	RMN	Suburban Garden, Agriculture	1.84
2	Matridham Ashram	MA	Rural forest, Campus	12.45
3	Ramnagar	RMNr	Periurban forest, PSc camp	23.1
4	Sarnath	SNT	periurban forest, grassland	28.2
5	Indane gas plant	IGP	Rural forest, gas plant	28.48
6	Udai Pratap Autonomous college	UPAC	Urban forest, grassland	37.16
7	Banaras locomotive works	BLW	Urban forest, grassland	127.28
8	Banaras Hindu University	BHU	Suburban forest, grassland	443.58

The soil was collected to a depth of 30 cm since most roots are found in the top 30 cm of soil and root activity is likewise concentrated in this horizon. These samples were taken from three random locations on each site and brought to a laboratory for analysis. The soil samples were mixed thoroughly, and recognisable plant organic materials were hand-picked. Each sample was separated into two portions for analysis. One portion was air-dried for determining bulk density, soil texture, and other physicochemical parameters, while the other portion was maintained field-moist for determining water holding capacity.

Tree species composition analysis:

We used Importance value index and diversity indices to analyse tree species diversity and dominance. The Importance value index (IVI) was computed using the formula given below: detailed by Jarzebski and Gasparatos (2019)

IVI = RD (Relative density) + RF (Relative frequency) + RDo (Relative dominance)

The species diversity indices were calculated by using the formula given by Wang *et al.* (2017)

Margalef Richness Index: $D = (S - 1) \ln N$
Shannon-wiener diversity index: $H' = -\Sigma Pi * \ln Pi$
Simpson index: $\lambda = \Sigma Pi^2$
Simpson diversity index: $D = 1 - \lambda$
Pielou evenness index: $Jsw = (-\Sigma Pi * \ln Pi) / \ln S$

Carbon stock estimation:

The DBH, height, and wood density of each tree were used to calculate its above-ground biomass (AGB). We followed the equation given by King *et al.* (2006):
AGB (kg tree^{-1}) = $0.5 (\pi/4) \rho D^2 H$
where 0.5 = anticipated form factor
H = height (in metres)
DBH = diameter at breast height (in cm)
ρ = wood density

The below-ground biomass (BGB) was calculated by multiplying the above-ground biomass (AGB) by 0.20 (Nguyen 2012).

BGB (kg tree^{-1}) = AGB x 0.20
Total Biomass = AGB+ BGB

The stored carbon and CO_2 sequestered were estimated by the formula given by Nguyen (2012)

CBS = 0.5 x TAB
where CBS = quantity of carbon in tonnes per hectare (tonnes/ha),
TAB = amount of biomass in tonnes per hectare,
0.5 = conversion factor by default and CO_2 sequestered = 3.67 x Carbon

Soil Analysis

The soil organic carbon was determined using the Walkley and Black titration method, as outlined in the Standard operating procedure for Soil organic carbon by the Food and Agriculture Organization of the United Nations (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.fao.org/3/ca7471en/ca7471en.pdf).

The organic carbon in soil was measured by following Walkley and Black (1934).

The stock of soil organic carbon (SOC) was computed by the following formula, given by Kavinchan *et al.* (2015)

SOC stock (tonne/ha) = SOC (g/100g) × soil bulk density (g/cm^3) × soil depth (cm)

We determine the total carbon stock (ton/ha) of each green infrastructure such as IGP, MA, SNT, UPAC, BLW, BHU, RMNr, and RMN site by adding the aboveground, belowground, carbon stored, CO_2 sequestration, and soil organic carbon components.

Result

Tree species diversity

We identified 46 different tree species belonging to 23 families among the various urban green infrastructures. The numbers of species in different green infrastructures namely SNT, RMN, IGP, MA, RMNr, BHU, UPAC, and BLW were 10, 6, 12, 5, 10, 21, 10 and 9 respectively.

The tree density in the BHU site was found to be maximum with a value of 432 tree/ha, followed by IGP (416 tree/ha), RMNr (384 tree/ha), and the value of tree density in the site UPAC, MA, SNT and RMN, BLW were found to be similar i.e. 368 and 320 tree/ha respectively (Table 2).

The most dominant large tree species were *Ficus religiosa* (H-32.8m, IVI- 42.63) in the IGP, *Azadirachta indica* (28.57m, 21.57) in the MA, *Dalbergia sissoo* (18.42m, 14.20) in the SNT, *Azadirachta indica* (32.85m, 63.27) in the UPAC, *Gmelina arborea* (34.53m, 11.18) in the BHU, *Holoptelea integrifolia* (21.95m, 107.52) in RMN site and *Dalbergia sissoo* (32.83m, 137.23) in the site of RMNr. The site-wise IVI scores are summarized in Table 3.

Table 2: Tree density (number of trees/ha), basal area (m2/ha) and, total biomass (ton/ha) in different green infrastructure sites in Varanasi city

S.N	*Green infrastructure*	*Tree density*	*Basal area*	*Biomass*
		(number of trees/ha)	*(m2/ha)*	*(ton/ha)*
1	SNT	368	906.92	144.06
2	RMN	320	3010.12	328.86
3	IGP	416	3146.28	784.58
4	MA	368	4337.44	864.29
5	RMNr	384	4054.40	935.52
6	BHU	432	4753.04	1000.78
7	UPAC	368	5873.47	1468.86
8	BLW	320	8025.88	2327.81

In terms of species diversity index, such as Shannon and Simpson diversity index, were high in the BHU site, followed by IGP, UPAC, SNT, RMNr, BLW, RMN, and the lowest diversity index was found in the MA site (Table 4).

The Pielou's evenness index was high in the BHU site, followed by BLW, IGP, SNT, RMNr, RMN, MA, and the site UPAC, which had the lowest Pielou's evenness index. The trend of Margalef's richness index was BHU> IGP> SNT=UPAC> RMNr> BLW> RMN> MA (Table 4).

The average value of the Basal area was found to be highest in the BLW site (8025.88 m2/ha), followed by 5873.47 m2/ha in the UPAC site, 4753.04 m2/ha in the BHU, 4337.44 m2/ha in the MA, 4054.4 m2/ha in the RMNr site, 3146.28 m2/ha in the IGP site, 3010.12 m2/ha in the RMN site and the lowest value in the SNT site (906.92 m2/ha) (Table 2).

Carbon Stock

The average aboveground biomass was found higher in the BLW site with a value of 1939.84 ton/ha, followed by the UPAC (1224.05 ton/ha), BHU (833.98 ton/ha), RMNr (779.6 ton/ha), MA (720.24 ton/ha), IGP (653.82 ton/ha), RMN (274.05 ton/ha), and the lowest value of aboveground biomass was found in the site SNT, i.e 120.05 ton/ha. The average value of belowground biomass, carbon storage and CO_2 sequestration were showing a similar trend to aboveground biomass viz the maximum value was found in the BLW (387.96 ton/ha; 1163.90 ton/ha; 4271.54 ton/ha) site followed by UPAC (244.81 ton/ha; 734.43 ton/ha; 2695.37 ton/ha), BHU (166.79 ton/ha;500.39 ton/ha; 1836.43 ton/ha), RMNr (155.92 ton/ha; 467.76 ton/ha; 1716.68 ton/ha), MA (144.4 ton/ha; 432.14 ton/ha; 1585.98 ton/ha), IGP (130.76; 392.29 ton/ha; 1439.71 ton/ha), RMN (54.81 ton/ha; 164.43 ton/ha; 603.46 ton/ha), and the site SNT was showing minimum value for belowground biomass, carbon storage and CO_2 sequestration i.e. 24.01 ton/ha; 72.03 ton/ha and 264.35 ton/ha respectively (Table 5, Fig. 2).

Soil Organic carbon stock

The average value of soil organic carbon stock was completely different from the trend of the above parameters i.e.the highest soil organic carbon value was found for Bhu, i.e 60.84 ton/ha followed by SNT (43.73 ton/ha), BLW (43.24 ton/ha), RMNr (42.28 ton/ha), RMN (34.67 ton/ha), UPAC (27.51 ton/ha), MA (16.21 ton/ha), And the soil organic carbon stock value was also found to be the lowest for Site IGP, i.e 3.93 ton/ha (Table 5, Fig. 2).

Overall, the highest total carbon stocks were estimated in the BLW site (7806.48 ton/ha) followed by UPAC (4926.17 ton/ha), BHU (3398.43 ton/ha), RMNr (3162.24 ton/ha), MA (2898.61 ton/ha), IGP (2620.51 ton/ha), RMN (1131.42 ton/ha) and SNT (524.17 ton/ha). (Table 5, Fig. 2).

Discussion

In this study, we compared the variation in the structure, composition, diversity, and carbon stock of different green infrastructures in Varanasi city. These variations between different types of green infrastructure imply substantial differences in population and ecological functions and call for distinct management and conservation practices.

Tree species diversity and composition

The results of this study reflect maybe the first comprehensive urban tree inventory in Varanasi. This study reveals that a total of 46 species from 38 genera belong to 23 families. It is lower than the tree species richness of 53 species (47 genera and 24 families) in Gwalior, Madhya Pradesh (Bhat *et al.,* 2016), 60 species (22 families) in Bilaspur, Chhattishgarh (Singh and Tiwari, 2022), 93 species in Bengaluru, Karnataka (Divakara *et al.,* 2022), 64 species (60 genera and 28 families) in Allahabad city, Uttar Pradesh (Pandey and Kuma,r 2018), and 90 species (76 genera and 33 families) in Ulhasnagar, Maharashtra (Menon and Gharge, 2018). Furthermore, the species richness of this study is also lower than in other cities, for example, 176 species (46 families) in Kumasi, Ghana, West Africa, 82 species (35 families) in Pyin Oo Lwin, Myanmar, 89 species in the federal capital territory of Abuja, Nigeria, and again 89 species were reported in Mexico City, North America (Table 6).

The species richness in Varanasi city is very low as compared to other cities because urbanization is increasing continuously in Varanasi. According to McKiney (2006), urbanization has caused species extinction, which frequently has a negative effect on the diversity of existing plants. Based on Census of India reports, and various projections & Low projection estimates,2021-2051, in 1991, the population density per square kilometre in the Varanasi urban agglomeration was 8,625, and it will increase to 21,886 in 2051 (Singh Rana P.B. 2018).

BHU had higher species richness, Shannon-Wiener diversity index, Simpson diversity index, and Pielou's evenness index than

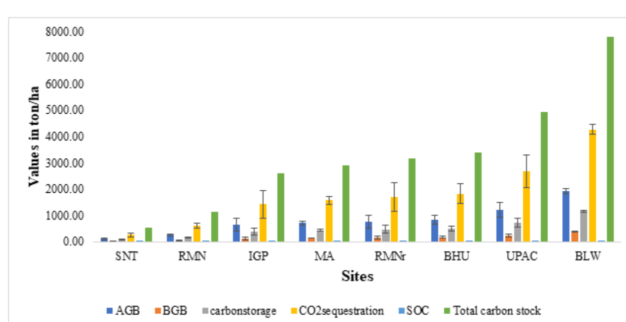

Fig. 2: carbon stock in different green infrastructure sites of Varanasi city

Table 3: Importance value index (IVI) of tree species in the green infrastructure sites

S.N	*Species*	*IGP*	*MA*	*SNT*	*RMNr*	*BHU*	*RMN*	*UPAC*	*BLW*
1	Acacia auriculiformis	12.007	-	-	-	-	-	-	-
2	*Aegle marmelos*	-	-	-	-	-	-	17.280	-
3	*Albizia Lebbeck*	-	-	-	-	-	-	-	40.435
4	*Albizia procera*	-	-	-	-	14.832	-	-	-
5	*Alstonia scholaris*	-	-	-	-	8.580	-	-	-
6	*Anogeissus latifolia*	-	-	-	-	9.649	-	-	-
7	*Anthocephalus cadamba*	-	-	-	82.269	-	-	-	88.789
8	*Artocarpus heterophyllus*	-	-	44.758	219.843	43.653	-	17.191	-
9	*Artocarpus lakoocha*	-	-	-	-	-	-	23.919	-
10	*Azadirachta indica*	61.115	21.571	19.832	64.646	-	50.306	63.270	34.405
11	*Borassus flabellifer*	-	-	-	-	-	44.224	-	-
12	*Callistemon lanceolatus*	-	-	22.663	-	-	-	-	-
13	*Cordia dichotoma*	-	-	-	-	-	16.511	-	-
14	*Dalbergia sissoo*	-	-	14.209	137.234	-	44.687	22.794	-
15	*Delonix regia*	10.679	-	-	172.989	-	-	-	-
16	*Diospyros melanoxylon*	-	-	-	-	8.571	-	-	-
17	*Eucalyptus globulus*	25.239	-	-	-	-	-	-	-
18	*Ficus religiosa*	42.630				23.376		13.226	16.936
19	*Ficus benghalensis*	13.356	-	-	152.107	32.701	-	-	-
20	*Ficus racemosa*	48.641	35.828			35.703		21.358	
21	*Ficus virens*	-	-	-	55.435	-	-	-	-
22	*Gmelina arborea*	-	-	-	-	11.188	-	-	-
23	*Holarrhena antidysenterica*		-	-	-	8.448	-	-	-
24	*Holoptelea integrifolia*		53.782	-	-	-	107.521	-	-
25	Madhuca indica	12.078	-	-	-	-	-	-	-
26	*Mallotus philippensis*	-	-	-	-	8.651	-	-	-
27	*Mangifera indica*	-	70.094	67.256	109.065	8.689	-	52.173	30.553
28	*Melia azedarach*	-	-	-	-	-	39.082	-	-
29	*Mitragyna parvifolia*	-	-	-	-	8.917	-	-	-
30	*Moringa oleifera*	-	-	12.394	-	-	-		-
31	*Phyllanthus emblica*	-	-	-	-	-	-	33.415	-
32	*Polyalthia longifolia*	-	-	57.542	-	-	-	-	-
33	*Pongamia pinnata*	10.426	-	-	-	17.515	-	-	-
34	*Premna integrifolia*	-	-	-	-	8.975	-	-	-
35	*Psidium guajava*	-	-	11.045	-	-	-	-	-
36	*Pterospermum acerifolium* -		-	-	-	8.480	-	-	-
37	*Roystonea regia*	-	-	37.068	-	-	-	-	-
38	*Saraca indica*	-	-	-	-	-	-	35.630	-
39	*Schleichera oleosa*	10.506	-	-	-	-	-	-	-
40	*Spondias mombin*	-	-	13.416	-	-	-	-	-
41	Syzygium cumini	24.441	118.982	-	40.763	-	-	-	54.686
42	*Tecomella undulata*	-	-	-	-	8.870	-	-	-
43	*Tectona grandis*	-	-	-	229.630	-	-	-	-
44	*Terminalia arjuna*	28.948	-	-	-	9.311	-	-	36.376
45	*Terminalia bellirica*	-	-	-	-	15.409	-	-	-
46	*Wrightia tinctoria*	-	-	-	-	8.573	-	-	-

Table 4: Species richness and diversity and evenness indices of the tree species across different green infrastructure sites

Sites	*Shannon-Wiener diversity index*	*Simpson's diversity index*	*Pielou's evenness index*	*Margalef's richness index*
IGP	2.29 ± 0.021	0.885 ± 0.003	0.922	3.376
MA	1.365 ± 0.043	0.703 ± 0.034	0.848	1.276
SNT	2.102 ± 0.181	0.854 ± 0.013	0.913	2.870
RMNr	2.082 ± 0.024	0.847 ± 0.007	0.904	2.832
BHU	2.897 ± 0.134	0.938 ± 0.002	0.967	5.765
RMN	1.6 ± 0.207	0.76 ± 0.003	0.893	1.669
UPAC	2.137 ± 0.184	0.865 ± 0.012	0.214	2.870
BLW	1.808 ± 0.026	0.815 ± 0.011	0.929	2.003

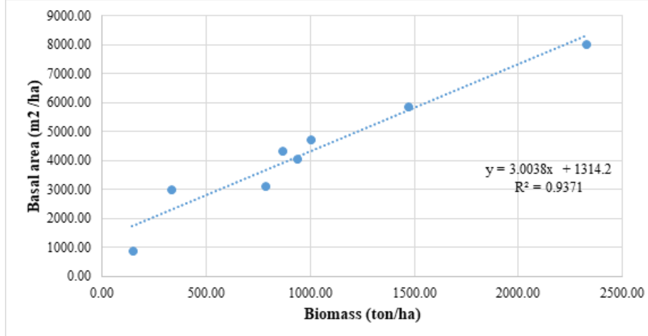

Fig. 3: Relationship between biomass and basal area of tree

Table 5: Average carbon stock in different green infrastructures in the Varanasi region

Sites	*AGB (ton/ha)*	*BGB (ton/ha)*	*Carbon storage (ton/ha)*	*CO_2 sequestration (ton/ha)*	*SOC (ton/ha)*	*Total carbon (ton/ha)*
SNT	120.05 ± 32.94	24.01 ± 6.59	72.03 ± 19.77	264.35 ± 72.54	43.73	524.17
RMN	274.05 ± 39.76	54.81 ± 7.95	164.43 ± 23.86	603.46 ± 87.55	34.67	1131.42
IGP	653.82 ± 238.95	130.76 ± 47.79	392.29 ± 143.37	1439.71 ± 526.17	3.93	2620.51
MA	720.24 ± 69.65	144.04 ± 13.93	432.14 ± 41.79	1585.98 ± 153.37	16.21	2898.61
RMNr	779.60 ± 246.94	155.92 ± 49.39	467.76 ± 148.16	1716.68 ± 543.76	42.28	3162.24
BHU	833.98 ± 175.89	166.79 ± 35.18	500.39 ± 105.53	1836.43 ± 387.30	60.84	3398.43
UPAC	1224.05 ± 281.55	244.81 ± 56.31	734.43 ± 168.93	2695.37 ± 619.97	27.51	4926.17
BLW	1939.84 ± 86.97	387.96 ± 17.39	1163.90 ± 52.18	4271.54 ± 191.51	43.24	7806.48

Table 6: Comparison of species richness in urban areas in India and across other countries

Study site	Location	Area (ha)	Number of Species	Genera	Family	References
India						
Educational, Religious, Workshop, Campuses	Varanasi, Uttar Pradesh	0.54	46	38	23	This study
Roadside plantation	Gwalior city, M.P	40 km	53	47	24	Bhat *et al.*, 2016
Urban area	Bilaspur, Chhattishgarh	NA	60	NA	22	Singh and Tiwari 2022
Tree in Northern transect Research	Bengaluru, Karnataka	23	93	NA	NA	Divakara *et al.*, 2022
Urban green space	Allahabad, Uttar Pradesh	6.6	64	60	28	Pandey and kumar 2018
Urban green space	Ulhasnagar, Maharashtra	NA	90	76	33	Menon and Gharge 2018
Other countries						
Urban and periurban centre	Federal capital territory, Abuja, Nigeria	surveys	89	NA	29	Agbelade *et al.*, 2017
Urban area	Kumasi, Ghana, South Africa	4.7	176	NA	46	Nero *et al.*, 2018
Urban area	Pyin Oo Lwin, Myanmar, Southeast Asia	575.21	82	NA	35	Jarzebski and Gasparatos 2019
Commercial, Residential, residential-commercial area	Mexico City, North America	22.8	89	NA	NA	Alvarez *et al.*, 2017

other green infrastructure sites. The Shannon-Wiener diversity index may increase in the presence of higher evenness, higher richness, or both (Magurran *et al.,* 2004) (Table 4). The lower value of the Shannon-Wiener diversity index and Simpson diversity index were found on the MA site. Because at the MA site, the evenness and richness both were found to be low compared to other sites (Table 4).

Carbon Stock

Biomass and carbon stocks are crucial quantitative aspects of forest ecology. The average aboveground biomass in this study was comparably higher than the other studies, For example, reported values are 9.58 ton/ha in Tripura University Campus, Northeast (Deb *et al.,* 2016), 79.125 ton/ha in an urban forest, Jodhpur city, Rajsthan (Uniyal *et al.,* 2022), 64.92 ton/ha in an

Table 7: Comparison of AGB, carbon stock and SOC in urban areas in India and across other countries

Study site	*Location*	*AGB (ton/ha)*	*Carbon stock (ton/ha)*	*SOC (ton/ha)*	*References*
India					
Educational, Religious, Workshop, Campuses	Varanasi, Uttar Pradesh	1029.94	617.96	32.38	This study
Urban green site foothill	Eastern Himalayas	808.9	434.72	50.82	Pradhan *et al.*, 2022
Urban forest	Jodhpur, Rajasthan	79.12	NA	NA	Uniyal *et al.*, 2022
Education Institute	Gwalior, Madhya Pradesh	NA	92.13	NA	Anjum *et al.*, 2020
University Campus	Tripura, Northeast	9.58	3.22	NA	Deb *et al.*, 2016
urban forest patch	Pondicherry	220.81	139.11	NA	Khadanga and Jayakumar2018
Urban and periurban forest	Agartala, Tripura	64.92	6.85	NA	Majumdar and Selvan 2018
Other countries					
Main land use of Allada plateau	Southern Benin, West Africa	279	NA	83	Houssoukpevi *et al.*, 2022
Urban freshwater wetland	SriLanka	40.14	NA	NA	Dayathilake *et al.*, 2020
Urban park under cold climate conditions	Finland	NA	25	104	Lin den *et al.*, 2020

urban and peri-urban forest in Agartala, Tripura (Majumdar and Selvan, 2018), 40.14 ton/ha in an urban freshwater wetland in Sri Lanka (Dayathilake *et al.,* 2020), 808.9 ton/ha in urban green site foothill, Eastern Himalayas (Pradhan *et al.,* 2022), 220.81 ton/ha in an urban forest patch, Pondicherry (Khadanga and Jayakumar, 2018), and 279 ton/ha in main land use of Allada plateau, Southern Benin, South Africa (Houssoukpevi *et al.,* 2022) (Table 7). The estimated carbon stock was found also higher in this study compared to other Indian urban forest systems, for example, 3.22 ton/ha in Tripura University Campus, Northeast (Deb *et al.,* 2016), 6.85 ton/ha in an urban and periurban forest in Agartala, Tripura (Majumdar and Selvan, 2018), 92.13 ton/ha in Education Institute, Gwalior, Madhya Pradesh (Anjum *et al.,* 2020), 139.11 ton/ha in an urban forest patch, Pondichery (Khadanga and Jayakumar, 2018), 434.72 ton/ha in urban green site foothill, Eastern Himalayas (Pradhan *et al.,* 2022), and 25 ton/ha in an urban park under cold climate conditions, Finland (Linden *et al.,* 2020) (Table 7).

Several factors influence biomass and total vegetation carbon, including the age of the forest stand, tree density, diversity, and basal area (Sahoo *et al.,* 2021). Among all the sites, the BLW site stores more biomass and carbon, because the trees in the BLW site were very old and their basal area was greater than the rest of the sites (Fig. 3, Table 2). And also, the must be prevented from engaging in deforestation and other human activities.

Soil organic carbon stock

The soil organic matter (SOC) content in the soil is affected by the input and decomposition of litter, the quality of the litter, the rate of mineralization in relation to stand type, and the age of the soil (Sahoo *et al.,* 2019; Cao *et al.,* 2018; Ahirwal *et al.,* 2021b). The findings from this study's average soil organic carbon stock can be compared to those from studies conducted in other parts of India and also in other countries. For example, the value of soil organic carbon stock, in urban green site foothill was 50.82 ton/ha (Pradhan *et al.,* 2022), in main land use of Allada plateau, Southern Benin, West Africa, it was 83 ton/ha (Houssoukpevi *et al.,* 2022), and the value of soil organic carbon stock in an urban park under cold climate conditions, Finland was 104 ton/ha (Linden *et al.,* 2020) (Table 7).

Conclusion

This study focuses on the estimation of tree species diversity, density, composition, and carbon stock at the different green infrastructure sites of Varanasi city. This estimation is very important for the sustainable management of urban green infrastructure undergoing significant anthropogenic changes. The biomass and carbon stock are influenced by several factors, including the age of the forest stand, tree density, diversity, and the basal area of trees. The findings from this study show that the BHU are highly diverse with high tree density. While carbon stock is high on the BLW site. Moreover, the amount of carbon stock varied by site. The site with the highest tree species diversity and a higher value of basal area had a higher carbon stock, indicating a positive relationship between species diversity / basal area and carbon stock. The findings of this study suggest that urban green infrastructure is crucial for carbon storage. However, additional research is needed to fully understand the underlying mechanisms that drive the complicated relationship between tree species diversity and carbon stock.

This paper argues that urban green infrastructure can provide important carbon-storage-related regulatory services. Such ecosystem services can significantly support ongoing initiatives to promote sustainable urban development and the country's transition to a green economy. However, Varanasi City has a limited capacity to accomplish this. It is urgently necessary to create urban strategies and plans in this regard. For the nation's future urbanisation transition, establishing a solid evidence base, increasing awareness, protecting already-existing urban green infrastructure, and creating new urban green infrastructure are all crucial steps.

Acknowledgments

The authors gratefully acknowledge the Coordinator, Centre of Science and Society, University of Allahabad, and Centre of Advanced Studies (CAS), Department of Botany, Banaras Hindu University, for providing the research facilities to carry out this research, and Indian National Science Academy (INSA) for providing the financial support for the research.

Author's contribution

Ashutosh Kumar Singh: collected data and write the manuscript, Jamuna Sharan Singh: Edited the manuscript, Hema Singh: Edited the manuscript, Rohit Kumar Mishra: Edited the manuscript

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