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Tree Diversity and Tree Community Composition in Northern Part of Megacity Bengaluru, India

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Abstract: Trees are natural capital assets, especially for cities, as they provide immense environmental benefits and improve urban biodiversity and ecology. However, urbanization has largely destroyed the original native ecosystems and has caused a homogenization where frequently native species are replaced by non-native species. When attempting to understand the role of trees in urban settings, it is important to generate science-based data on the spatial distribution of trees, their species composition and tree species diversity as a function of the degree of urbanization. Such information may specifically inform the planning of effective long-term management of trees across urban and rural gradients. A total of 23 of 1 ha each were surveyed along a Northern research transect laid out along the urban–rural gradient of the metropolitan area of Bengaluru, India. Plots were randomly selected from the stratum "settlement areas", where WorldView-3 imagery supported both stratification and plot selection. The plots were fully mapped for trees, where a total of eleven variables had been observed for each tree. In addition, the basal area and wood volume was calculated to understand the biomass potential of the trees in the plots. The diversity indices such as the Shannon index, Simpson index, Pielou's evenness and Margalef's richness were considered for comparing the species diversity, composition and distribution along the gradient of Bengaluru. A total of 1128 individuals of 93 tree species were recorded. Among 92 species identified along the northern gradient, 53 are exotic, and 39 are native species. The Shannon–Wiener index varied from 1.33 to 2.72; Simpson's index varied from 0.65 to 0.90; Pielou's index varied from 0.66 to 0.90, and Margalef's index ranged from 1.41 to 5.20 along the gradient. The basal area increased from 96.39 m^2 to 102.76 m^2 from 2017 to 2019 along the transect, with a net gain of 6.37 m^2. Similarly, the wood volume increased from 1819.57 m^3 to 1926.23 m^3 with a net gain of 106.66 m^3. The present study reports on tree distribution, species composition and tree species diversity along a gradient from the city center to the rural surroundings of northern parts of Bengaluru city. The information generated may support the city planners/administrators by providing a holistic understanding of the species composition and abundance for a further selection of adaptive species and appropriate tree and vegetation management practices to conserve the existing green spaces and contribute towards sustainable urban planning. The sample plots laid out may also serve as permanent observation plots for monitoring the dynamics of tree cover in the city.

Keywords: species distribution; composition; diversity; urban–rural gradient; Bengaluru

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1. Introduction

Urbanization is caused by population growth and population shifts from rural and surrounding areas to progressively developed towns or cities and is also a function of economic, political and geographical factors. Bengaluru is one among the cities, growing by 2.5% annually [1]. The city has experienced urbanization at a rapid pace, including through unplanned and uncontrolled developments, demographical expansion, heterogeneous land use, associated deforestation and other anthropogenic activities [2,3]. Currently, Bengaluru is the second-fastest growing and fifth-largest metropolis in India [2,4], with a current population of about 12.33 million in 2020 with an increase of 3.74% from the previous year [5].

The scientific evidence from the last two decades has emphasized the crucial necessity of green areas within urban ecological systems. However, urban planners and managers underestimate the role played by the trees [6,7]. Their role becomes even more important depending on the intensity of urbanization in the urban and peripheral regions of the sprawling city such as Bengaluru. The progressive developments in the city have negative impacts on biodiversity and ecosystem services, especially urban green spaces and green cover, particularly when trees and green spaces are not specifically and comprehensively considered during the planning of city development. The green spaces are then at high risk of experiencing loss, a decline in the area due to demand for urban expansion, and a lack of space for accommodating the existing and growing population [8,9].

According to [10,11], management and conservation of urban biodiversities may be supported by comprehensive data on urban trees, their distribution and species composition. Some studies on urban green spaces of Bengaluru have been carried out, focusing mainly on the urban areas, and they found that streets and parks are relatively low in density but high in species diversity when compared to other cities [6,12]. According to [13], the city had (approx. 705 parks) small, medium and also large-sized parks. Apart from parks and gardens, there were also 200 open spaces and green areas (roadside and avenue trees) that lacked sufficient infrastructure, and they can be considered for developing green spaces within the city limits [14]. According to [15] and [16], the estimated tree crown cover in the city area (at the respective points in time) was about 19.9%, amounting to a per capita green space availability of about 17 m^2.

A study by [12], with 127 sample plots, found that only 42% of the trees in the cities were native species. However, the parks of Bangalore are leading to homogenization, where every four out of five trees are exotic. This is in contrast to the parks in cities such as Potsdam (Germany) and Jeonju/Chonju (South Korea), where the native species are up to 81% and exotic species are less than 30% in the population, respectively [17,18]. The developmental activities such as road widening projects and encroachment have led to a significant loss in the proportion of prominent and mature large canopy trees, giving rise to urban heat islands [6]. The rapid expansion and growth of cities towards the urban periphery saw a phenomenal change in land use and land cover in Greater Bengaluru, which has resulted in a dramatic fragmentation of the landscape.

Thus, extending the study to the transition and the rural surroundings provides a holistic scenario of tree diversity and composition. Furthermore, it provides information on levels of urbanization in the rural–urban gradient, and data generated provide a better understanding of the species composition and abundance that can contribute towards sustainable urban planning and conservation for greater Bengaluru. Further, data generated may help appropriate tree and vegetation management practices through the selection of adapted species and compliance of safety standards along with proper planning and management for urban environments. Such information is beneficial for urban managers seeking to maximize the environmental benefits provided by trees and to analyze the critical impact of the environmental functions offered by these trees. In view of this, the present study focused on tree species diversity in the urban area along with the transition and the rural area of Bengaluru through spatial inventory.

2. Methods

2.1. Study Area

Bengaluru, the capital of State of Karnataka in India, is located in the south-eastern part of the Karnataka and geographically extends from 77°37′19.54″ E and 12°59′09.76″ N. Greater Bengaluru has an area of 741 km^2 (2020). The city is subdivided into 8 zones with

198 wards under the jurisdiction of Bruhat Bengaluru Mahanagara Palike (BBMP). The spatial extent of Bengaluru is experiencing substantial demographic expansion of its urban area over 10 times during the last five decades from 1949 (69 km^2) to 2006 (741 km^2) [4]. Population density of Bengaluru is 4378 persons per square kilometer.

2.2. Data and Field Procedure

Our study focused on trees in Northern research transects of Bengaluru City, defined and laid out by an Indian–German research consortium (Figure 1). Twenty-three plots of 100 m × 100 m (1 ha) each were selected in the Northern transect. The selection of the field plots followed stratified random sampling: at first, the two strata "built-up" and "others" were distinguished where built-up was defined as those areas with more than 50% impervious surface, identified from WorldView-3 satellite images (Figure 2). We sampled only the stratum "built-up" as our main interest lies in urbanized areas.

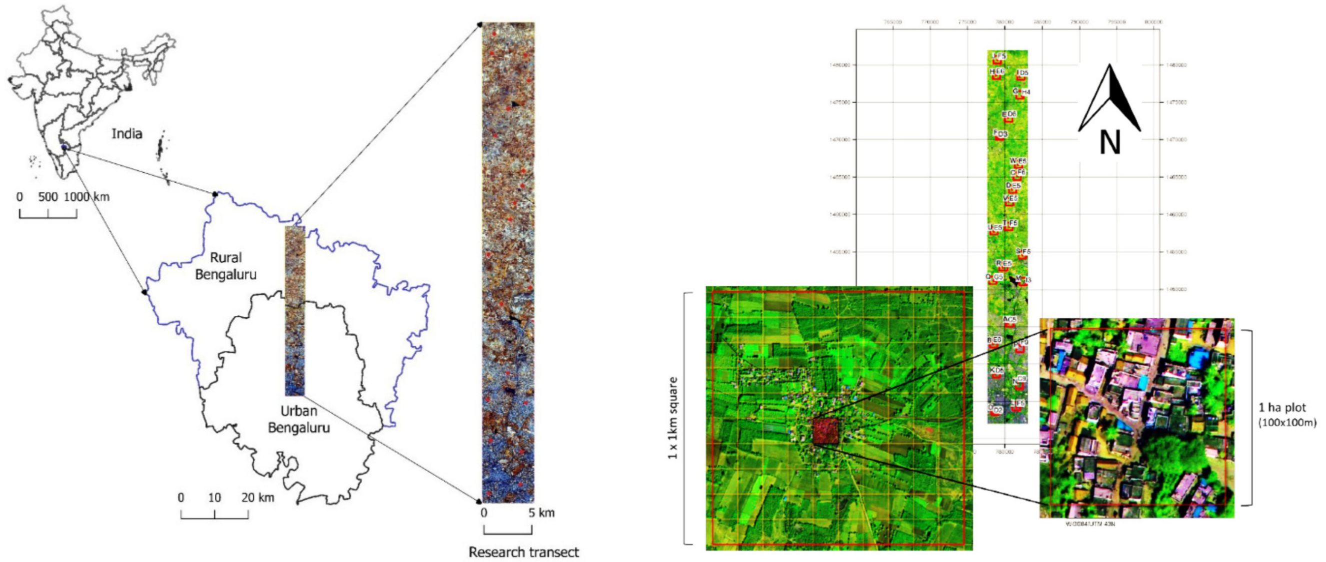

Figure 1. Location of the study area in the northern part of Bengaluru.

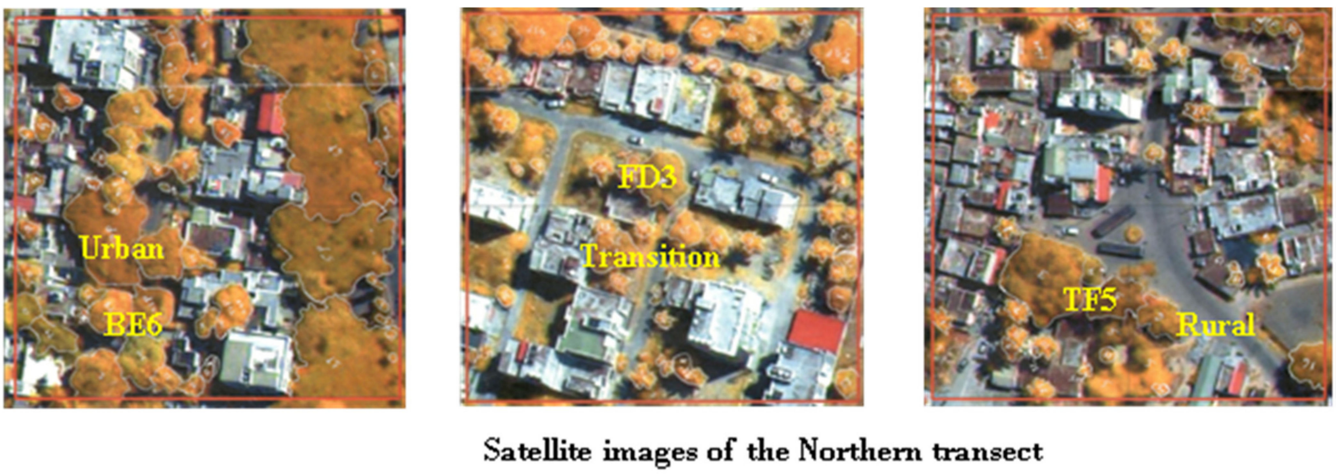

Figure 2. WorldView-3 satellite image of 1 ha representing the three domains.

The 23 field plots were classified into the categories "urban", "transition", and "rural". This classification was performed by means of a pixel-wise analysis of the field plot from satellite imagery. The classification rules applied were: "urban" with >50% built-up pixels, transition with 10–50% built-up pixels, and rural with 0–10% built-up pixels. The distance of each plot from the city center was also one of the criteria for the classification (Figure 2).

In the field plots, all trees >10 cm dbh were tallied, including palms. The tree variables observed included, in addition to dbh, tree height, crown height and crown base height, are tree access, tree stand, tree permat, crown symmetry, crown shape, crown density and tree condition (on visual analysis). A detailed description of the tree variables is mentioned in Table 1. Further, using the measured dbh of the standing tree, basal area was calculated to observe the degree of stocking in the plots. In addition, the wood volume was also calculated to gain an idea about the above-ground biomass in the plots.

Table 1. Tree variables observed in the study.

Sl. No.	Tree Variables	Description	
1.	Diameter at Breast height DBH (cm)	Tree stem was measured at 1.33 m above the ground with diameter tape.	
2.	Height (m)	Height is the total height of the standing tree measured as the straight line distance from tip of the leading shoot to the ground level.	
3.	Crown Base Height (m)	The average distance between ground and lowest foliage layer of the tree.	
4.	Crown Height (m)	It is the vertical measurement of the crown of a tree from the tip to the and lowest foliage layer of the tree.	
5.	Tree access	It describes if the tree is directly accessible or in fenced premises.	0 = accessible 1 = not-accessible 2 = tree stands on private property
6.	Tree stand	It describes whether the tree is solitary or part of a tree group.	0 = solitary tree 1 = part of group of trees
7.	Tree permat	It describes the pavement around the tree stem.	1 = non-permeable 2 = permeable pavements 3 = bare soil
8.	Crown symmetry	It describes the symmetry of the crown.	0 = symmetrical 1 = non-symmetrical
9.	Crown shape	Based on visual estimate, crown shape was noted based on crown measurements.	1 = cylinder 2 = horizontal ellipsoid 3 = vertical ellipsoid 4 = paraboloid 5 = upside down paraboloid 6 = sphere
10.	Crown density	Based on visual assessment, the crown hemisphere of the tree was assigned with one of the density classes.	0 = dense (80–100%) 1 = medium (40–80%) 2 = sparse (0–40%)
11.	Tree condition	Based on a visual assessment, tree health condition was noted down based on four categories.	1 = healthy 2 = affected/at risk 3 = dying/declining 4 = dead 7 = Whole crown is visible 8 = Crown only partially visible 9 = Crown not visible

Vegetation composition was quantitatively evaluated for density, frequency and importance value index (IVI) according to [19]. The tree species diversity per sample plot was estimated from indices such as the Shannon–Wiener diversity index [20], Simpson's index of dominance [21], Margalef's Richness index [22] and Pielou's evenness index [23] were used (Table 2). The selected plots were revisited after one year to check the existence of marked trees and also to collect the dbh measurements of the tree species. The dbh measurements were taken to evaluate the growth of trees. Data for two consecutive years

(2018, 2019) were collected to assess the temporal changes in the composition of marked trees for the northern transect.

Table 2. Indices of diversity used in the study.

Sl. No.	Diversity Index	Formula	Range	Description
1	Shannon–Wiener diversity index [20]	$H' = -\sum_{i=1}^{s} P_i(\ln P_i)$	0–1	It characterises both the number of species and their distribution in the community. Higher value indicates high diversity and vice versa.
2	Simpson's index of diversity [21]	$D = 1 - \sum_{i=1}^{s} [n_i/N]^2$	0–1	It give more emphasis on the most abundant species in the community. Higher value indicates high diversity and vice versa.
3	Simpson's index of dominance [21]	$Cd = \sum_{i=1}^{s} [n_i/N]^2$		It considers number of individual species present, as well as the relative abundance of each species.
4	Margalef Richness index [22]	$R = \frac{S-1}{\ln N}$		It is a measure of species richness in the community.
5	Pielou's evenness index [23]	e = H′/ln S	0–1	It is a measure of evenness in the community. 0 stands for low and 1 for high evenness.

Where, H'—Shannon's index of diversity, $P_i - n_i/N$ = Proportion of total sample belonging to the *i*th species, *D*—Diversity, n_i—Number of individuals of the species '*i*', *N*—Total number of individuals in the plot, *Cd*—Concentration of dominance, *R*—Margalef Richness index, *S*—Total number of species in a community, *n*—Total number of individuals observed.

The information on composition and diversity helps in better understanding both structural and functional dynamics of any ecosystem [24]. In specific, analyzing the diversity of species, vegetation composition, and the structure of any ecosystem assists in understanding ecological systems and also supports in developing sustainable management policies for improving and conserving the existing tree species in the ecosystem [25].

3. Results

In the present study, a total of 1128 individuals belonging to 93 species (92 species identified) were enumerated from 1 ha plots in the northern transect of Bengaluru. Tree species belonging to 39 families were recorded in the city (Table 3).

Table 3. Respective families of the tree species found along the gradients.

Sl. No.	Family	Northern Transect
1	Anacardiaceae	2
2	Annonaceae	1
3	Apocynaceae	2
4	Araucariaceae	1
5	Arecaceae	6
6	Bignoniaceae	7
7	Boraginaceae	2
8	Burseraceae	1
9	Caricaceae	1
10	Casuarinaceae	1
11	Combretaceae	1
12	Cornaceae	1
13	Cupressaceae	1

Table 3. *Cont.*

Sl. No.	Family	Northern Transect
14	Euphorbiaceae	3
15	Fabaceae	16
16	Lamiaceae	1
17	Lauraceae	1
18	Lecythidaceae	1
19	Lythraceae	2
20	Magnoliaceae	1
21	Malvaceae	2
22	Meliaceae	5
23	Moraceae	10
24	Moringaceae	1
25	Muntingiaceae	1
26	Myrtaceae	5
27	Nyctaginaceae	1
28	Oleaceae	
29	Phyllanthaceae	2
30	Podocarpaceae	1
31	Proteaceae	1
32	Rubiaceae	2
33	Rutaceae	5
34	Santalaceae	
35	Sapindaceae	1
36	Sapotaceae	1
37	Strelitziaceae	1
38	Unknown	1
39	Verbenaceae	1
Total		**93**

Among 92 species identified along the northern gradient, 53 are exotic, and 39 were native species. The 23 plots of northern transect were categorized into eight plots of urban, four plots of transition and eleven plots of rural. The urban plots were comprised of 496 trees with 64 species, transition comprising of 180 trees with 37 species and rural plots comprising of 452 trees with 56 species.

Shannon–Wiener index varied from 1.33 to 2.72 with high and low observed diversity in plot 3 (NC9) and plot 21 (ID5), respectively. On the whole, the urban area had higher species diversity (2.42), followed by the transition (2.25) and rural area (1.99). Simpson's index varied from 0.65 to 0.90, with high and low diversity observed in the urban plot (NC9) and rural (JF5), respectively, with an average value of 0.82. Margalef's index also ranged from 1.41 to 5.20, with an average index value of 3.65. The higher species richness was observed in the urban plot (KD5) and lower in the rural plot (ID5). Pielou's index varied from 0.66 to 0.90 with an average value of 0.81 (Table 4). The tree species were more or less evenly distributed along the urban–rural gradient. All the four diversity indices showed a decline towards transition and rural plots, indicating that the tree species were more diverse with species composition and distribution in urban plots. However, a sharp decline was observed towards transition and rural plots for the Shannon–Wiener and Margalef indexes.

Table 4. Species diversity along the gradient of northern transect.

Plot No.	Plot ID	No. of Trees	No. of Species	Shannon–Wiener Diversity	Simpson's Dominance	Simpson's Diversity	Richness	Evenness
1	OD2	42	10	1.893	0.206	0.794	2.408	0.822
2	LF5	49	20	2.577	0.111	0.889	4.882	0.860
3	NC9	103	25	2.720	0.092	0.908	5.178	0.845
4	KD5	47	21	2.656	0.108	0.892	5.195	0.872
5	PF9	48	16	2.285	0.157	0.843	3.875	0.824
6	BE6	89	18	2.325	0.151	0.849	3.787	0.804
7	AC5	61	18	2.358	0.163	0.837	4.135	0.816
8	MI3	57	21	2.592	0.106	0.894	4.947	0.851
9	QG5	37	14	2.229	0.154	0.846	3.323	0.869
10	RE5	63	17	2.468	0.114	0.886	3.862	0.871
11	SF5	35	12	2.024	0.187	0.813	3.094	0.814
12	UE5	45	17	2.283	0.160	0.840	4.203	0.806
13	TF5	48	10	1.658	0.272	0.728	2.325	0.720
14	VE5	36	11	1.830	0.225	0.775	2.791	0.763
15	DE5	49	12	1.947	0.207	0.793	2.826	0.784
16	CF6	26	12	2.086	0.189	0.811	3.376	0.839
17	WE5	44	17	2.444	0.123	0.877	4.228	0.863
18	FD3	76	19	2.287	0.172	0.828	4.156	0.777
19	ED6	19	12	2.233	0.147	0.853	3.736	0.899
20	GH4	52	15	2.395	0.115	0.885	3.543	0.884
21	ID5	17	5	1.335	0.315	0.685	1.412	0.829
22	HE6	50	14	1.979	0.230	0.770	3.323	0.750
23	JF5	35	13	1.685	0.349	0.651	3.375	0.657

The species such as *Cocos nucifera* (100), *Azadirachta indica* (73.91), *Mangifera indica* (73.91), *Artocarpus heterophyllus* (65.22), *Tectona grandis* (56.52), *Grevillea robusta* (52.17) and *Pongamia pinnata* (52.17) were more frequently found along the gradient (Table 5). Tree species such as *Cocos nucifera* (11.91), *Grevillea robusta* (2.83), *Pongamia pinnata* (2.74), *Polyalthia longifolia* (2.48), *Eucalyptus hybrid* (2.13), *Tectona grandis* (2.00), *Mangifera indica* (1.65), *Swietenia macrophylla* (1.17), *Ficus religiosa* (1.04) and *Tecoma stans* (1.04) were densely populated along the gradient (Table 5). The Importance Value index (IVI) of each species in the northern transect is given in Table 6.

Table 5. Species occurrence along the northern transect.

Sl. No.	List of Species	Origin	Urban	Transition	Rural	Total	Frequency	RF	Density	RD
1	*Acacia catechu*	Na	1	0	0	1	4.35	0.29	0.04	0.09
2	*Acacia ferruginea*	Na	1	0	0	1	4.35	0.29	0.04	0.09
3	*Aegle marmelos*	Na	0	0	1	1	4.35	0.29	0.04	0.09
4	*Alangium salviifolium*	Na	0	0	1	1	4.35	0.29	0.04	0.09
5	*Alastonia macrophylla*	Ex	3	0	0	3	4.35	0.29	0.13	0.27
6	*Albizia kalkora*	Na	0	0	1	1	4.35	0.29	0.04	0.09
7	*Anthocephalus kadamba*	Na	7	0	0	7	8.70	0.57	0.30	0.62
8	*Araucaria cunninghamii*	Ex	5	0	2	7	21.74	1.43	0.30	0.62
9	*Areca catechu*	Ex	3	4	2	9	21.74	1.43	0.39	0.80
10	*Artocarpus heterophyllus*	Na	10	4	16	30	65.22	4.29	1.30	2.66
11	*Azadirachta indica*	Na	7	10	15	32	73.91	4.86	1.39	2.84
12	*Bauhinia purpurea*	Na	7	0	1	8	13.04	0.86	0.35	0.71
13	*Bougainvillea glabra*	Ex	1	0	0	1	4.35	0.29	0.04	0.09
14	*Callistemon lanceolatus*	Ex	1	0	0	1	4.35	0.29	0.04	0.09
15	*Carica papaya*	Ex	1	1	7	9	13.04	0.86	0.39	0.80
16	*Caryota urens*	Na	8	0	0	8	8.70	0.57	0.35	0.71
17	*Cassia fistula*	Na	1	0	0	1	4.35	0.29	0.04	0.09
18	*Casuarina equisetifolia*	Ex	2	0	0	2	4.35	0.29	0.09	0.18

Table 5. *Cont.*

Sl. No.	List of Species	Origin	Urban	Transition	Rural	Total	Frequency	RF	Density	RD
19	*Ceiba pentandra*	Na	0	0	5	5	8.70	0.57	0.22	0.44
20	*Citrus limonum*	Na	0	0	1	1	4.35	0.29	0.04	0.09
21	*Citrus maxima*	Ex	0	1	0	1	4.35	0.29	0.04	0.09
22	*Citrus medica*	Na	0	0	1	1	4.35	0.29	0.04	0.09
23	*Cocos nucifera*	Ex	84	46	144	274	100.00	6.57	11.91	24.29
24	*Coffee arebica*	Ex	1	0	0	1	4.35	0.29	0.04	0.09
25	*Commiphora caudata*	Na	0	0	5	5	13.04	0.86	0.22	0.44
26	*Cordia dichotoma*	Na	0	3	3	6	17.39	1.14	0.26	0.53
27	*Cordia mixa*	Na	1	0	0	1	4.35	0.29	0.04	0.09
28	*Couroupita guianensis*	Ex	2	0	0	2	4.35	0.29	0.09	0.18
29	*Crysalidocarpous lutescens*	Ex	0	0	1	1	4.35	0.29	0.04	0.09
30	*Dead*	Un	1	1	0	2	8.70	0.57	0.09	0.18
31	*Dilonix regia*	Ex	8	1	4	13	34.78	2.29	0.57	1.15
32	*Duranta plumeri*	Ex	0	3	0	3	8.70	0.57	0.13	0.27
33	*Eucalyptus hybrid*	Ex	5	9	35	49	43.48	2.86	2.13	4.34
34	*Euphorbia synadenium*	Na	1	1	0	2	8.70	0.57	0.09	0.18
35	*Euphorbia tirucalli*	Ex	0	0	1	1	4.35	0.29	0.04	0.09
36	*Ficus benghalensis*	Na	0	1	3	4	8.70	0.57	0.17	0.35
37	*Ficus benzamin*	Na	1	0	0	1	4.35	0.29	0.04	0.09
38	*Ficus drupacea*	Na	0	1	6	7	13.04	0.86	0.30	0.62
39	*Ficus elastica*	Na	2	0	0	2	4.35	0.29	0.09	0.18
40	*Ficus glomerata*	Na	3	3	3	9	34.78	2.29	0.39	0.80
41	*Ficus religiosa*	Na	1	6	17	24	43.48	2.86	1.04	2.13
42	*Ficus tinctoria*	Na	0	0	4	4	4.35	0.29	0.17	0.35
43	*Gliricidia sepium*	Ex	0	0	2	2	8.70	0.57	0.09	0.18
44	*Grevillea robusta*	Ex	20	10	35	65	52.17	3.43	2.83	5.76
45	*Jacaranda mimosifolia*	Ex	6	0	6	12	13.04	0.86	0.52	1.06
46	*Kigelia pinnata*	Ex	1	0	0	1	4.35	0.29	0.04	0.09
47	*Lagerstroemia flos-reginae*	Ex	4	1	0	5	13.04	0.86	0.22	0.44
48	*Lannea coromandelica*	Na	0	0	1	1	4.35	0.29	0.04	0.09
49	*Leucaena leucocephala*	Ex	0	2	0	2	8.70	0.57	0.09	0.18
50	*Mangifera indica*	Na	23	6	9	38	73.91	4.86	1.65	3.37
51	*Manilkara zapota*	Ex	1	0	0	1	4.35	0.29	0.04	0.09
52	*Melia azedarach*	Na	1	0	1	2	8.70	0.57	0.09	0.18
53	*Melia dubia*	Na	0	0	5	5	13.04	0.86	0.22	0.44
54	*Michelia champaca*	Na	8	0	0	8	21.74	1.43	0.35	0.71
55	*Millingtonia hortensis*	Ex	3	0	1	4	13.04	0.86	0.17	0.35
56	*Moringa oleifera*	Na	5	4	6	15	30.43	2.00	0.65	1.33
57	*Morus alba*	Ex	0	10	0	10	4.35	0.29	0.43	0.89
58	*Morus papyrifera*	Ex	2	2	0	4	8.70	0.57	0.17	0.35
59	*Muntingia calabura*	Ex	3	3	4	10	34.78	2.29	0.43	0.89
60	*Murraya koenigii*	Na	1	4	13	18	39.13	2.57	0.78	1.60
61	*Parkia biglandularis*	Ex	0	0	1	1	4.35	0.29	0.04	0.09
62	*Peltophorum pterocarpum*	Na	21	0	1	22	21.74	1.43	0.96	1.95
63	*Persea americana*	Ex	1	0	0	1	4.35	0.29	0.04	0.09
64	*Phoenix dactylifera*	Ex	0	0	1	1	4.35	0.29	0.04	0.09
65	*Phyllanthus acidus*	Ex	1	0	1	2	8.70	0.57	0.09	0.18
66	*Phyllanthus emblica*	Na	1	0	1	2	8.70	0.57	0.09	0.18
67	*Pithocellbium dulce*	Ex	1	0	0	1	4.35	0.29	0.04	0.09
68	*Plumeria alba*	Ex	2	0	0	2	4.35	0.29	0.09	0.18
69	*Podocarpus totara*	Ex	0	2	0	2	4.35	0.29	0.09	0.18
70	*Polyalthia longifolia*	Ex	45	0	12	57	26.09	1.71	2.48	5.05
71	*Pongamia pinnata*	Na	32	16	15	63	52.17	3.43	2.74	5.59
72	*Prosopis juliflora*	Ex	0	1	0	1	4.35	0.29	0.04	0.09
73	*Psidium guajava*	Ex	5	5	3	13	30.43	2.00	0.57	1.15
74	*Punica granatum*	Ex	0	0	1	1	4.35	0.29	0.04	0.09
75	*Ravenala madagascariensis*	Ex	2	0	0	2	4.35	0.29	0.09	0.18
76	*Ricinus communis*	Ex	1	1	1	3	13.04	0.86	0.13	0.27
77	*Royestonea regia*	Ex	2	0	1	3	8.70	0.57	0.13	0.27
78	*Samanea saman*	Ex	11	1	4	16	26.09	1.71	0.70	1.42
79	*Sapindus mukorossi*	Ex	1	0	0	1	4.35	0.29	0.04	0.09
80	*Sesbania grandiflora*	Ex	0	0	2	2	4.35	0.29	0.09	0.18
81	*Spathedea campanulata*	Ex	16	2	0	18	26.09	1.71	0.78	1.60
82	*Swietenia macrophylla*	Ex	24	0	3	27	26.09	1.71	1.17	2.39

Table 5. *Cont.*

Sl. No.	List of Species	Origin	Urban	Transition	Rural	Total	Frequency	RF	Density	RD
83	*Swietenia mahagoni*	Ex	16	0	0	16	13.04	0.86	0.70	1.42
84	*Syzygium cumini*	Na	10	1	3	14	26.09	1.71	0.61	1.24
85	*Syzygium jambos*	Ex	0	1	0	1	4.35	0.29	0.04	0.09
86	*Tabebuia aurea*	Ex	2	0	0	2	4.35	0.29	0.09	0.18
87	*Tabebuia rosea*	Ex	16	0	1	17	17.39	1.14	0.74	1.51
88	*Tamarindus indica*	Ex	0	0	2	2	8.70	0.57	0.09	0.18
89	*Tecoma stans*	Ex	22	1	1	24	26.09	1.71	1.04	2.13
90	*Tectona grandis*	Na	2	10	34	46	56.52	3.71	2.00	4.08
91	*Terminalia catappa*	Na	4	1	1	6	26.09	1.71	0.26	0.53
92	*Thespesia populnea*	Na	11	0	1	12	17.39	1.14	0.52	1.06
93	*Thuja biota*	Ex	0	1	0	1	4.35	0.29	0.04	0.09
94	*Unknown*	Un	1	0	0	1	4.35	0.29	0.04	0.09
	Total		**496**	**180**	**452**	**1128**	**1521.74**	**100**	**49.04**	**100**

Origin: Native (Na), Exotic (Ex) and Unknown (Un). Except *Leucaena leucocephala*, *Muntingia calabura* and *Prosopis juliflora* all the exotics are naturalized.

Table 6. Importance Value Index (IVI) along northern transect.

Species	Origin	Urban	Transition	Rural
Areca catechu	Na		7.86	
Artocarpus heterophyllus	Na	8.07	7.86	10.99
Azadirachta indica	Na	6.18	16.26	11.33
Cocos nucifera	Ex	39.31	58.18	59.02
Dilonix regia	Ex	6.59		
Duranta plumeri	Ex		6.74	
Eucalyptus hybrid	Ex		11.75	14.75
Ficus benghalensis	Na			7.62
Ficus glomerata	Na		6.74	
Ficus religiosa	Na		10.09	51.89
Ficus tinctoria	Na			8.02
Grevillea robusta	Ex	10.09	14.56	15.50
Mangifera indica	Na	13.99	11.79	7.54
Michelia champaca	Na	6.59		
Moringa oleifera	Na		7.86	
Morus alba	Ex		12.87	
Muntingia calabura	Ex		6.74	
Murraya koenigii	Na		7.86	7.55
Peltophorum pterocarpum	Na	11.17		
Polyalthia longifolia	Ex	20.87		
Pongamia pinnata	Na	16.28	21.27	8.12
Psidium guajava	Ex		10.67	
Samanea saman	Ex	6.46		
Spathedea campanulata	Ex	9.82		
Swietenia macrophylla	Ex	13.05		
Swietenia mahagoni	Ex	8.48		
Syzygium cumini	Na	6.72		
Tabebuia rosea	Ex	8.48		
Tecoma stans	Ex	11.57		
Tectona grandis	Na		16.26	16.79
Thespesia populnea	Na	6.46		

Origin: Native (Na), Exotic (Ex) and Unknown (Un). Except *Muntingia calabura* all the exotics are naturalized.

3.1. Tree Variables

3.1.1. Height

The height of the trees varied from 2.8 m to 22.5 m, 3 m to 20.3 m and 2.5 m to 24.3 m in rural, transition and urban plots, respectively. The highest number of trees, with 199 trees, were found in the range from 11 m to 15 m. A total of 179 and 74 trees from the rural and transition plots, respectively, fell in the range from 6 m to 10 m, with an average height of

8.01 m and 7.57 m. Similarly, 199 trees from the urban plots were found in the range from 11 m to 15 m, with an average height of 13.12 m. The fewest number of trees were found in the range from 21 m to 25 m, with an average height of 21.9 m and 21.77 m from rural and urban plots, respectively.

3.1.2. Crown Base Height and Crown Height

The average crown base height of the trees from rural, transition and urban plots was 4.86 m, 4.77 m and 5.42 m, respectively. The maximum number of trees from all of the three domain (rural, transition, urban) plots was found in the range from 0 m to 4 m, which shows that the stem part of the tree was visible only a few meters above the ground.

Out of 496 urban plot trees, 180 transition plot trees and 452 rural plot trees, 319, 129, and 289 trees ranged between 3.1 m and 9 m, with an average crown height of 6.12 m, 5.62 m and 6.04 m, respectively. The crown heights above 18.1 m were found only in rural plots with a height of 19 m.

3.1.3. Crown Shape, Density and Symmetry

The maximum number of trees was classified under paraboloid and vertical ellipsoid along the gradient.

Along the gradient of the northern transact, irrespective of their domain, most of the tree crowns were non-symmetric. Most of the trees were classified as medium (40–80%) and sparse (0–40%). Few trees had dense crowns (80–100%).

3.1.4. Tree Access

The tree access was categorized to understand the status of the trees as street trees or private/garden trees. The ratio of trees almost remains equal between the categories towards the urban domain. However, the private/farm trees were more towards the rural and transition domain.

The trees were classified as solitary and trees in a patch, as on the field, few of the tree crowns were so compact to delineate on the satellite image. Irrespective of the domain, the maximum number of trees was found to be solitary.

3.1.5. Tree Permat and Tree Condition, Basal Area and Volume

Tree permat describes the pavement around the tree. In the rural plots, the maximum number of trees was planted in bare soil. Gradually, the trees were found with a non-permeable pavement towards the transition and urban plots.

On visual analysis, maximum trees were classified as healthy trees with whole or partial crown visibility along the gradient. Dead and declining trees were found towards the transition and urban domain, probably due to the stress on trees due to pollution.

The basal areas of the northern transact increased from 96.39 m^2 to 102.76 m^2, with a gain of 6.37 m^2 from 2017 to 2019. Similarly, the wood volume increased from 1819.57 m^3 to 1926.23 m^3, with a gain of 106.66 m^3 along the transect. A total of 127 trees were cut, which reduced the tree species to 83, with 1001 individual trees along the gradient. A total of 71, 26 and 30 trees were cut along the rural, transition and urban plots, respectively (Table 7). The loss in the basal area with a reduction in trees over consecutive years was higher in urban plots with 3.66 m^2, followed by rural plots with 2.11 m^2. Though the loss in trees was higher in rural plots compared to transition and urban plots, a greater change in basal area and volume was observed in urban plots with the reduction in higher girth trees. This indicates that the bigger trees are found more in urban compared to transition and rural plots.

Table 7. Species change pattern along the northern transect of urban–rural gradient in Bengaluru.

Domain	Parameters	2017	2018	2019	* Change
Urban	Number of Species	64	58	55	−9
	Number of trees	496	474	466	−30
	Basal area (m^2)	43.01	44.56	46.67	3.66
	Wood volume (m^3)	803.47	827.35	862.17	58.7
Transition	Number of Species	37	32	31	−6
	Number of trees	180	161	154	−26
	Basal area (m^2)	12.8	12.75	13.4	0.6
	Wood volume (m^3)	233.56	233.87	245.23	11.67
Rural	Number of Species	56	53	51	−5
	Number of trees	452	421	381	−71
	Basal area (m^2)	40.58	42.13	42.69	2.11
	Wood volume (m^3)	782.54	810.52	818.83	36.29
Total	Number of Species	93	87	83	−10
	Number of trees	1128	1056	1001	−127
	Basal area (m^2)	96.39	99.44	102.76	6.37
	Wood volume (m^3)	1819.57	1871.74	1926.23	106.66

* change in northern transect during 2017 to 2019.

4. Discussion

Our present study focused on tree species change patterns along the urban–rural gradient of the rapidly growing megacity Bengaluru (India) from the stratum “settlement areas”, where WorldView-3 imagery supported the selection. The study addressed the varied species composition, distribution, density, frequency and diversity (Shannon index, Simpson index, Pielou’s evenness and Margalef’s richness) of the trees in the urban, the transition and the surrounding rural domain of Northern Bengaluru. In addition, basal area and wood volume were calculated to understand the biomass potential of the trees in each plot and a total of eleven tree variables were observed for each tree mapped along the gradient.

The study showed that the tree diversity indices indicated a decline towards transition and rural plots, representing that the tree species were more diverse with species composition and distribution in urban plots. However, a sharp decline was observed towards transition and rural plots for the Shannon–Wiener and Margalef indexes. A similar trend was observed for the percentage of exotic species, which explained the rapidly expanding urbanization in combination with land-use changes along the urban–rural gradient. Importance value index (IVI) values also indicated the significance of ornamental tree species planted in an urban domain for beautification of the landscape, whereas religious/multipurpose trees species were found towards rural and transition domains. Comparatively, urban plots were found with taller and larger trees than transition and rural trees. Few trees in transition and rural areas had widespread canopy because they are solitary in nature. On visual analysis, trees in urban plots were found to be in stress with some dead/declining trees compared to rural and transition plots.

Prior studies on tree diversity are limited to urban vegetation in tropical countries [26,27], particularly in India [28]. Recently, few studies have noted high species richness in cities that include rare species that are absent in the surrounding areas [29]. According to [30], urbanization has led to species extinction, which often leads to a negative impact on existing plant diversity. This, in turn, results in replacing native species with more widely distributed non-native species and thus promotes biotic homogenization [31]. According to [10], the decline in the number of species per km^2 was observed, with only 25% of native plant species currently present in the urban areas. Further, the construction of cities and expansion of urban areas also promote the replacement of native species by non-native species [30]. McKinney [30] also showed the increasing intensity of urban activity has resulted in an increase in abundance and species richness of non-native species over native species. McKinney [32] stated that non-native plant species are often planted in urban and transition areas. According to Nagendra [33], the greater loss in green areas was observed in transition and rural areas compared to urban areas due to the availability of large open spaces leading to unplanned and unidirectional urbanization. In the present study, *Cocos nucifera* was the most frequently occurring species in all three domains in Bengaluru due to its religious significance (https://www.mangalparinay.com/blog/indian-traditions/importance-and-significance-of-coconut-in-indian-culture) (assessed on 16 December 2021), favorable site conditions and, most importantly, its high tradition uses in households. The urban domain had the highest frequency of ornamental and shade tree species, whereas rural domain had timber, multi-purpose and religious tree species. In the transition area, the most frequent species included a combination of timber, ornamental and shade trees species indicating the characteristics of both the urban and the rural domain.

According to McDonell [34], the species richness along the rural–urban gradient depended on the species concerned, but trees often increase towards the city center. Studies by Mutlu [35], Roy and Mukherjee [36], Vakhlamova [37], Nagendra and Gopal [6,12] also showed similar results of the dominance of exotic species over native species in the urban regions. Our results were found in contrast with the study by McKinney [32], which stated that compared to rural areas, the urban region has lower species diversity. However, he specified over increased patchiness and domination by non-native species in urban areas, which is similar to our results. Shannon's index in the present study was in accordance with Nagendra and Gopal [6]. The tree species observed in our study were also similar to the results presented by Nagendra and Gopal [6,12] and Ramachandra [38].

5. Conclusions

The study focused on the changing tree species pattern along the urban–rural gradient in Bengaluru, India. The study is important for the effective management and planning of vegetation within the city. It provides planners and the general public with tree species information, which helps in the selection of adaptive species while designing for the urban plantation. Further, the urban corridors can be planned for the city for conserving the urban biodiversity. The corridor strongly helps in increasing the species richness and habitat quality. However, an increase in the number of samplings along the rural–urban gradient can assist in knowing the pattern of species diversity more accurately. In addition, our sampling approach turned out to be straight forward, and the sample plots laid out can serve as permanent preservation plots for the students, researchers and city planners for regular monitoring and data collection of trees and studying dynamics of tree cover in coming years.

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