



Street trees in Bangalore: Density, diversity, composition and distribution

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ARTICLE INFO

Keywords:

Avenue trees
Cities
Green spaces
India
Urban biodiversity
Urban ecology

ABSTRACT

Once renowned as India's "garden city", the fast growing southern Indian city of Bangalore is rapidly losing tree cover in public spaces including on roads. This study aims to study the distribution of street trees in Bangalore, to assess differences in tree density, size and species composition across roads of different widths, and to investigate changes in planting practices over time. A spatially stratified approach was used for sampling with 152 transects of 200 m length distributed across wide roads (with a width of 24 m or greater), medium sized roads (12–24 m) and narrow roads (less than 12 m). We find the density of street trees in Bangalore to be lower than many other Asian cities. Species diversity is high, with the most dominant species accounting for less than 10% of the overall population. Narrow roads, usually in congested residential neighborhoods, have fewer trees, smaller sized tree species, and a lower species diversity compared to wide roads. Since wide roads are being felled of trees across the city for road widening, this implies that Bangalore's street tree population is being selectively denuded of its largest trees. Older trees have a more diverse distribution with several large sized species, while young trees come from a less diverse species set, largely dominated by small statured species with narrow canopies, which have a lower capacity to absorb atmospheric pollutants, mitigate urban heat island effects, stabilize soil, prevent ground water runoff, and sequester carbon. This has serious implications for the city's environmental and ecological health. These results highlight the need to protect large street trees on wide roads from tree felling, and to select an appropriate and diverse mix of large and small sized tree species for new planting.

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Introduction

There is increasing recognition of the fact that cities constitute a new type of environment with species compositions and habitats peculiar to urban-industrial areas. City residents interact with trees in diverse ways, and trees are found to be located in parks, along streets, near waterways, planted in home gardens, commercial zones, and protected in sacred locations. Of these, tree lined avenues have come to constitute one of the most significant visual features of green space in urban landscapes, becoming a standard feature in most European cities and those colonized by European settlers, by the mid-19th century (Lawrence, 1994).

The list of benefits provided by street trees is long and diverse. Tree lined streets provide much-welcomed aesthetic beauty and visual relief in concretized city settings, and supply a range of psychological, social and economic benefits for residents and

businesses including reductions in domestic violence, lowering of obesity, higher property values, reductions in asthma levels, traffic speeds, and auto accidents, and overall improvements in human well-being and community vitality (Wetter et al., 2001; Maco and McPherson, 2003; Dumbaugh, 2005; Wolf, 2005). Especially critical in sub-tropical and tropical climates, street trees protect pedestrians from the sun and the rain, and provide critical spaces and shelter for street vendors. While street trees may constitute only a small fraction of green cover in most cities, wooded streets constitute the most accessible green spaces for the vast majority of low to medium income city dwellers who lack access to other green spaces in residential and commercial areas (Heynen et al., 2006), thus playing an extremely significant and irreplaceable role in urban lives.

Other, equally significant ecological and environmental benefits are provided by street trees. Wooded streets constitute important habitats for birds and other urban taxa in urban landscapes, and provide critical landscape connectivity by acting as corridors between urban parks (Fernandez-Juricic, 2000). Street trees and other urban trees play a significant role in lowering urban temperatures and mitigating the intensity of urban heat island effects (Chow and Roth, 2006), thereby providing significant savings in electricity (McPherson et al., 1997; Maco and

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McPherson, 2003). These trees help in reducing storm water runoff, thus reducing the likelihood of flooding and damage to urban properties (McPherson et al., 1997). They act as noise filters, purify air and sequester carbon. Further, due to their proximity to traffic and consequently to higher loads of atmospheric pollutants, street trees are likely to capture higher amounts of particulate matter, carbon dioxide, ozone and other air pollutants than trees located in parks and green spaces distant from traffic, thus contributing more significantly in reducing atmospheric pollution in the city (McPherson et al., 1997; Beckett et al., 2000).

Yet, despite extensive evidence of the critical role played by street trees in city environments, urban planners and managers have often undervalued the role played by street trees. Street-side trees are often the first to be sacrificed when infrastructural developments such as road widening take place, especially in fast growing cities. City managers are concerned about the possible hazards posed by street trees to traffic management and pedestrian safety, and often unwilling to spend money on the maintenance and renewal of trees on city streets (Pauleit, 2003; Dumbaugh, 2005). Roadside trees are also especially subject to stresses due to their proximity to atmospheric pollutants, poor drainage, inhospitable soil, and lack of space for growth (Ware, 1994; Jim, 1999; Thaiutsa et al., 2008).

For more effective long term management of street trees, it is essential to have data on tree distribution including species composition, size and age structure, and spatial inventories. Such information is also useful for urban managers seeking to maximize the environmental benefits provided by street trees, as factors such as species composition, size, canopy, and age structure critically impact the environmental functions of these trees (Maco and McPherson, 2003). Yet, in many developing countries, forest managers in charge of maintaining urban tree populations do not have the knowledge necessary for appropriate species selection, care and maintenance (Chacalo et al., 1994), and lack information on street trees including basic data such as city street surveys (Escobedo et al., 2006; Alvey, 2006; Jim and Chen, 2008). This is especially true, sadly, of many Asian cities despite the fact that these constitute some of the most densely populated parts of the world (Jim and Chen, 2008). The few Asian cities that have been studied in this regard mostly come from South East and East Asia, with little published research from South Asia.

This study aims to fill a critical gap by surveying street tree distribution in the fast growing southern Indian city of Bangalore. Embodying concepts of both “high-tech” and “green”, the garden city of Bangalore – which can trace its history as far back as 900 AD – is now the second fastest growing city in India, with a growth rate of 38% between 1991 and 2001 and a population of over 7 million (Sudhira et al., 2007). Once known as the garden city of India, the city was famous for its tree lined avenues, but these have come increasingly under threat, with large sections of roads having been cleared in recent years for road widening, amongst numerous protests by local citizens (Nair, 2005; Sudhira et al., 2007). One preliminary study by Sudha and Ravindranath (2000) on the diversity of the urban forest in Bangalore provides some initial information indicating that there appear to be visual differences in the street tree species planted in different socio-economic parts of the city. More detailed information on the diversity and distribution of street trees can be significant for urban managers.

The objectives of this study are four-fold. Our first goal is to provide basic information on the diversity and distribution of street trees in Bangalore. Second, we examine differences in the distribution of trees in different parts of the city, specifically, we look at wide, medium width and narrow roads to examine if there are differences in tree density, species distribution and age/

girth distributions across road categories, while narrow streets are located in areas that are primarily residential, with greater pedestrian traffic and low hanging electric and telephone poles. The criteria used for selection of trees for planting, as well as the management practices, can be quite different in differently sized roads. Wide roads tend to be located away from residential areas, and have fewer obstacles such as overhanging electrical or cable wires, are not as close to residential homes, and have lower densities of pedestrian traffic, all of which can lead to frequent tree pruning. These roads tend to be planted on both sides and in the median. In contrast, narrow roads tend to be located in residential areas, where there may be less space available on already narrow sidewalks for trees, and a preference for smaller sized fruiting or flowering species, with greater pruning of tree branches that create obstructions for overhanging wires, nearby houses, and pedestrian traffic.

Thus, different road categories can be expected to differ in the density, diversity, distribution and composition of street trees. Third, we investigate whether planting practices have changed over time, by examining the size distributions of the ten most dominant tree species as a proxy for age. Finally, the information gathered on tree distribution, diversity and density is compared with the information from other cities, and used to provide recommendations for urban managers and planners.

This study is part of a larger project on urban biodiversity in Bangalore, which includes ongoing studies on biodiversity in parks, home gardens, religious institutions, educational institutions and other parts of the city with extensive green cover. All data will eventually be provided to the interested public including city planners and urban researchers, but also urban activists, students, educators, and the interested public in a publicly accessible spatial database that overlays biodiversity information onto high resolution satellite imagery.

Methods

Field studies of street tree diversity and distribution were conducted from November 2007 to April 2008. The data was collected with the assistance of students from St. Josephs College of Arts and Science, one of the city's oldest undergraduate colleges. The Outer Ring Road, a large road that circumscribes the majority of the city's roads was used to define the limits of the area within which sampling was conducted. A 1:50,000 scale 2002 Bangalore Guide Map prepared by the Survey of India was used to spatially distribute sampling locations. The map was divided into 1 km² grids, with each alternate grid selected for sampling. Given the rapidity at which urban land use and history are changing in the city, such a spatially distributed approach to sampling enables us to cover a range of localities with different urban histories, land uses and planting conditions, to the extent that these differences are present in the city.

A wide road (24 m or greater width), a medium road (between 12 and 24 m) and a narrow road (less than 12 m) were randomly selected for sampling within each grid using the following procedure. Within each grid, a random point was generated for each category of road width. The road junction corresponding to a road of the specified width that was located nearest to the randomly generated point was identified with reference to a Bangalore city map. From this junction, in a randomly selected direction, a transect of 200 m in length was identified. If the road did not extend for 200 m at this point, the next junction located closest to the random point was then selected, and the above procedure was repeated to identify an alternate transect for sampling.

Road width was used as a criterion for locating sample transects, as we anticipated that roads of different widths may be located in areas dominated by different types of urban land use, leading to differences in tree species selection, and maintenance. Wide roads tend to be located in areas dominated by commercial properties, with high densities of road traffic and comparatively low densities of pedestrian traffic. We therefore hypothesized that the tree species planted on wide roads would preferentially be those used for shade, i.e. large canopied, tall trees, which would not require significant pruning. In contrast, narrow roads tend to be located in predominantly residential neighborhoods. We hypothesized that the species selected for planting on narrow roads would have a greater proportion of flowering and fruiting trees. Trees on narrow roads also tend to be pruned more frequently, as their branches can present a hazard for overhead wires, pedestrians, and houses adjacent to the road. Thus, we expected that small statured, narrow canopy trees would be found to a greater extent on narrow roads.

All road categories could not be sampled in all grids, due to availability. For instance, large parts of land in some grids were owned by the Indian Armed Forces or Public Sector companies, or covered by water bodies, and hence did not have any roads accessible to the public, which could be studied. A total of 53 grids were sampled, within which 152 transects were studied – 51 transects in wide roads, 53 transects in roads of medium width, and 48 transects in narrow roads. Given a total estimated road length of 3500 km in Bangalore, this indicates a sampling intensity of about 0.9%. The starting location of each transect was identified using a Global Positioning System (GPS). Within each transect, all trees (located on either side or in the central median) were identified to the species level, and the diameter at breast height (DBH) and height were measured.

For each transect a number of measures of density, distribution and diversity were calculated. All trees were assigned to the species level (except for trees belonging to the genera *Eucalyptus*, which proved difficult to assign to species). For each transect, the number of trees provided an indication of density. Distribution was assessed using four measures. For each transect, the average and standard deviation in diameter at breast height (DBH) and height of all trees were calculated. Diversity was also assessed using four measures. Species richness (the number of tree species per transect) and the Shannon index of diversity at the species level were calculated for all transects. The Shannon index of diversity or SHDI is one of the most popular indices used in community ecology to quantify biodiversity, and is defined as

$$\text{SHDI} = - \sum_{i=1}^N p_i \times \ln p_i$$

where N is the total number of species and p_i is the proportional abundance of the i th species. This index, ranging in theory from 0 to infinity, combines aspects of species richness and evenness, increasing under conditions where the number of species increases, or the equitability of distribution of individuals belonging to different species increases, or both (Stohlgren, 2007).

A non-parametric Mann Whitney U test (Sokal and Rohlf, 1981) was used to assess whether different road width categories differed significantly in measures of density, distribution and diversity. The species composition of different road width categories was also investigated. For the ten most dominant species in each road width category, relative abundance (percentage of the total number of trees constituted by the species), relative dominance (percentage of total basal area constituted by the species), and species importance (sum of relative abundance and relative dominance) were also calculated, following McPherson and Rowntree (1989), and Welch (1994). Finally, size class

distributions of the ten most dominant tree species were evaluated, using size as a proxy for age to determine whether changes in planting practices have taken place over time.

Results

Aggregate distributions of street trees

Fig. 1 shows the distribution of sample transects within Bangalore, also depicting the location of the Outer Ring Road as well as the Greater Bangalore administrative boundary. A total of 2339 trees were encountered in 152 transects. The population of street trees in Bangalore appears quite diverse, with 108 species from 33 families encountered in these transects. The four most commonly found species—rain tree (*Albizia saman*), copper pod (*Peltophorum pterocarpum*), African tulip (*Spathodea campanulata*) and pongam (*Pongamia pinnata*) together constitute about one-third of the total population. The most dominant species is the rain tree, which constitutes about 9% of the total population.

As transects were randomly selected, 27 (18%) of the road lengths sampled had no trees, while the maximum number of trees encountered in a 200 m transect was 61, the maximum number of species was 19, and the maximum number of families 9. Correspondingly, species diversity (as measured by the Shannon index) also varied widely between transects, going to a maximum of 2.68. These attributes do not necessarily co-occur. For instance, the transect with the maximum number of trees – 61 – contained just one species, Indian cork (*Millingtonia hortensis*). This transect was taken on a road with trees on both sides as well as the median, and translates to a spacing of about 10 m between trees for this stretch of road. For transects with trees, the average number of trees per transect was 19. Since most roads sampled did not have any planting on the median, the average spacing encountered between trees was about 20 m. The average DBH of trees across all locations was 39 cm and the average height was 9.7 m. The widest tree encountered was a banyan (*Ficus benghalensis*) with a DBH of 232 cm, although with a height of just 15 m – while the tallest tree was a *Eucalyptus* species with a height of 25 m, but a DBH of only 55 cm.

Differences across road categories

Table 1 summarizes differences in tree distribution and diversity across road categories, while Table 2 presents the results of a Mann Whitney U test (a non-parametric test) to assess whether differences in attributes were statistically significant (Sokal and Rohlf, 1981). The number of trees within a 200 m transect was greatest for wide roads (on average, 21 trees per transect), followed by medium roads (on average, 15 trees), with narrow roads having the least amount of trees (on average, 10 trees). Wide roads (average tree DBH 43 cm, and average tree height 10.2 m) and medium roads (average tree DBH 41 cm, and average tree height 10.1 m) did not differ significantly in tree girth or height. As Figs. 2 and 3 indicate, trees in narrow roads were, however, significantly smaller in girth and height (average tree DBH 30 cm, and average tree height 8.2 m). The heterogeneity in tree girths was the greatest in wide roads (standard deviation of 17 cm) followed by medium roads (standard deviation of 14 cm), while narrow roads had a more homogeneous distribution of tree girths (standard deviation of 9 cm), and these differences were statistically significant. Differences in the heterogeneity of tree height distributions were not as marked, although the heterogeneity of tree heights

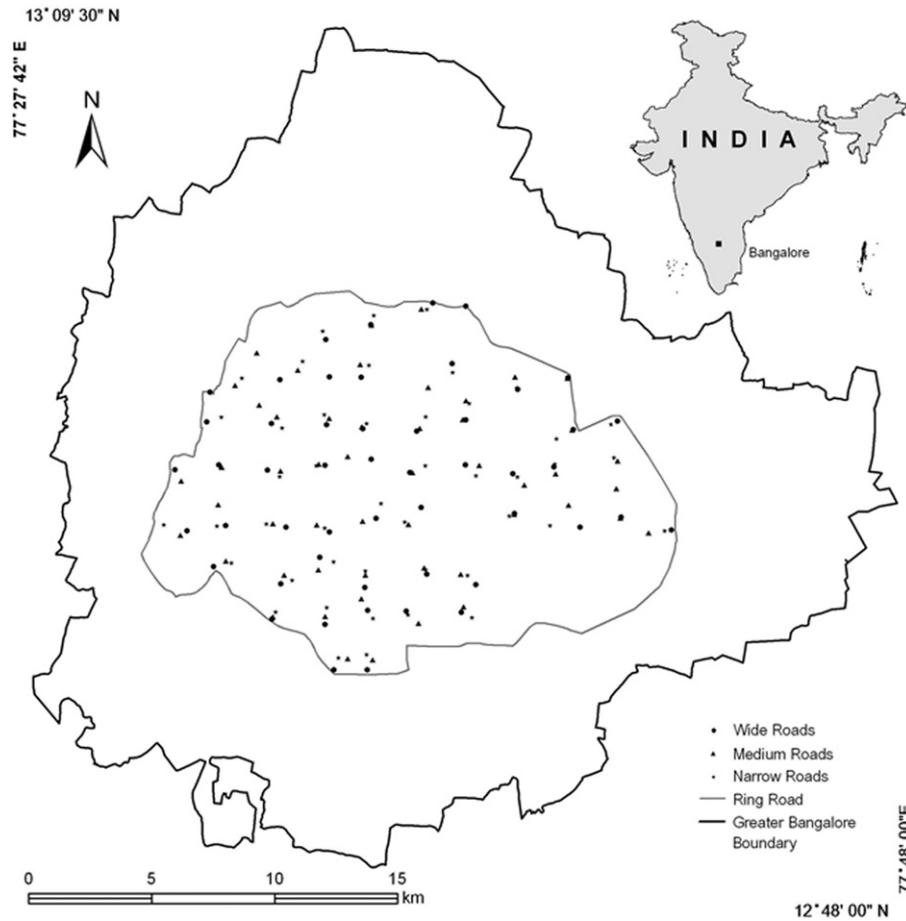


Fig. 1. Location of street tree sample transects.

Table 1
Attributes of street trees – density, size and diversity – summarized for different road categories, based on a sub-sample survey of the street tree population of Bangalore.

Street tree attributes	Wide roads	Medium roads	Narrow roads
Tree density (per km) – mean and standard deviation	104.4 ± 78.2	73.0 ± 63.1	52.1 ± 56.6
Range of tree density (per km) – minimum and maximum	0–305	0–235	0–220
Average DBH (cm) – mean and standard deviation	39 ± 21	42 ± 21	30 ± 12
Range of DBH (cm) – minimum and maximum	0–82	0–130	0–64
Standard deviation in DBH within a transect (cm)	17	14	09
Average height (m) – mean and standard deviation	9.9 ± 3.4	9.9 ± 2.8	8.3 ± 3.3
Range of height (m) – minimum and maximum	0–16.4	0–16.3	0–15.0
Standard deviation in height within a transect (m)	2.7	2.0	2.1
Species richness – mean and standard deviation	5.6 ± 3.9	4.8 ± 4.1	4.4 ± 4.4
Species Shannon diversity – mean and standard deviation	1.1 ± 0.8	1.0 ± 0.8	1.0 ± 0.9

Table 2
Results of a non-parametric, one-tailed Mann Whitney *U* test assessing the statistical significance of differences in tree density, size, and diversity across different road categories, based on a sub-sample survey of the street tree population of Bangalore. Species richness refers to the number of species, while Shannon diversity is an index of biodiversity, calculated as $\sum_{i=1}^N p_i \times \ln p_i$ where *N* is the total number of species and *p_i* is the proportional abundance of the *i*th species.

Street tree attributes	Wide vs. medium	Wide vs. narrow	Medium vs. narrow
Difference in number of trees	Wide > medium**	Wide > narrow***	Medium > narrow*
Difference in average DBH	Wide > medium	Wide > narrow***	Medium > narrow***
Difference in standard deviation of DBH	Wide > medium*	Wide > narrow***	Medium > narrow**
Difference in average height	Wide > medium	Wide > narrow***	Medium > narrow**
Difference in standard deviation of heights	Wide > medium	Wide > narrow*	Medium > narrow
Difference in species richness	Wide > medium*	Wide > narrow	Medium > narrow*
Difference in Shannon diversity – species	Wide > medium	Wide > narrow	Medium > narrow

* Significant at $p < 0.1$.

** Significant at $p < 0.05$.

*** Significant at $p < 0.01$.

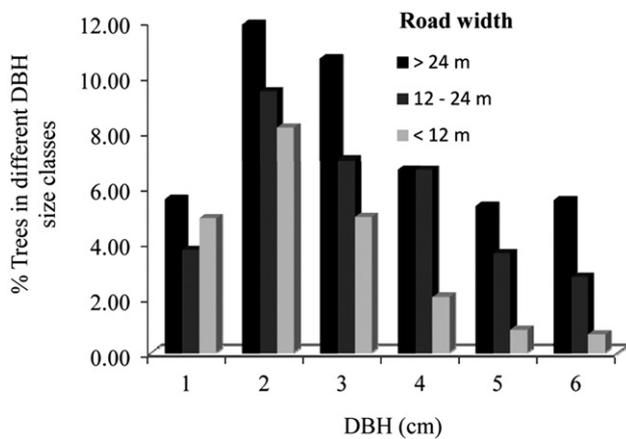


Fig. 2. Proportional distribution of tree DBH across different road width categories, based on a sub-sample survey of the street tree population of Bangalore.

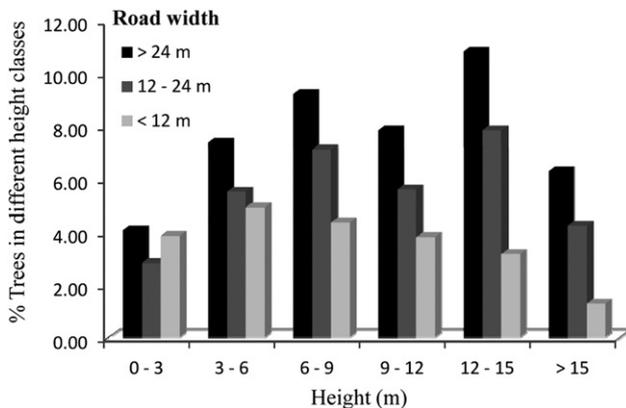


Fig. 3. Proportional distribution of tree heights across different road width categories, based on a sub-sample survey of the street tree population of Bangalore.

in wide roads (standard deviation of 2.7 m) is greater than that of tree heights in narrow roads (standard deviation of 2.1 m).

Differences in diversity followed the same trend, although these differences were not marked as differences in the number of individuals. Wide roads had an average of 6 species per transect while medium roads had an average of 5 species per transect, although these differences were not significant. Narrow roads, with an average of 4 species per transect, had significantly fewer species per transect than the other categories. However, differences in the Shannon index of species diversity were not significant.

Table 3 lists the ten most dominant species found in different road categories. While many of the dominant species are found in all road categories, there are some differences. Table 4 shows some of the reasons underlying these differences in species composition across road categories (Rice, 1897; Issar, 1994; Neginhal, 2006). As many as five of the ten most dominant species on wide roads are absent from the list of dominant species for narrow roads. Of these, the rain tree, copper pod and big leaved mahogany (*Swietenia macrophylla*) are broad canopied tall trees with large roots that may not be suitable for narrow roads with minimal sidewalk space (as can be seen from their relative dominance values in Table 3, these are all very large trees), while Indian cork and *Eucalyptus* sp. are species that can grow extremely tall, and can interfere with telephone lines and electric cables in residential areas where narrow streets predominate (as can also be seen from the fact that trees on narrow streets are significantly

shorter and narrower than those on wide streets, Table 2 and Figs. 2 and 3). Instead, these species are found heavily planted on medium and wide roads, where they provide much needed shade, and aesthetic pleasure (except for *Eucalyptus*, all these species have beautiful floral displays). Two species, Nile tulip (*Markhamia lutea*) and champaka (*Michelia champaca*), which are only dominant on narrow roads are both small trees that do not grow very tall or wide. The flowers of the champaka are commonly used for worship in south India, and thus this tree is particularly sought after in residential areas.

Differences in growth across species

The ten most common species encountered across all road categories are rain tree, copper pod, African tulip, pongam, orchid tree (*Bauhinia variegata*), Indian mast (*Polyalthia longifolia*), big leaved mahogany, gulmohar (*Delonix regia*), Nile tulip and Indian cork. While different species grow at different rates, the size class distributions of these species can provide a fairly reliable overall indication of changes in species selection over time (Sanders, 1983; Welch, 1994). Thus, one should be able to use size class distributions to differentiate between species which have been planted over a number of years (which should have a more evenly distributed age structure), from species which have been selected for planting recently (whose distribution should be dominated by smaller trees), or species which have been planted widely in the past and recently been discontinued (whose distribution should therefore be dominated by larger trees).

Table 5 clearly indicates differences between species age structures. At one end of the spectrum lies the rain tree, which is dominated by individuals in the largest size category of > 75 cm DBH, but which has hardly any individuals in the smallest size class of < 15 cm DBH. The other large sized trees, copper pod, African tulip and gulmohar are also dominated by large sized individuals although not to the same degree. All four species have a relative dominance that is greater than their relative abundance (Table 3), indicating that these species are dominated by large sized trees that are older relative to the rest of the population (McPherson and Rowntree, 1989). Visually, these four tree species dominate the Bangalore streetscape. They are large, spreading trees, which require constant pruning, and older less stable trees can pose a considerable threat during the rainy season, when tree falls are frequent. It appears that these trees are being gradually phased out with minimal renewal through new planting. Orchid tree, big leaved mahogany, Nile tulip and Indian cork – all medium sized trees – appear to have a healthy age distribution, with older and younger trees. Pongam and Indian mast appear to be relatively later additions to the Bangalore street tree flora, although they appear to be rapidly gaining popularity. Thus, from this analysis the composition of Bangalore's street trees appears to be changing over time, with large sized tree species gradually giving way to smaller sized species.

Discussion

Bangalore city is considered the “garden city” of India, and is widely famed for its breathtakingly beautiful streets lined with large canopied flowering trees (Issar, 1994; Nair, 2005). Although the first large scale urban horticultural plantations were carried out in the early twentieth century, most of the trees observed on Bangalore streets today date from the early 1980s, when an extensive tree plantation drive was conducted across the city (Neginhal, 2006). Yet, despite the city's identity as a green paradise, it is also a fast growing metropolis subject to demands on streets, sidewalks and street trees. In recent years, several of

Table 3
Ten most frequently encountered species in each road category, and their relative abundance (percentage of the total number of trees constituted by the species), relative dominance (percentage of total basal area constituted by the species), and species importance (sum of relative abundance and relative dominance), based on a sub-sample survey of the street tree population of Bangalore.

Road category	Abundance rank	Species name	Relative abundance	Relative dominance	Relative importance
Wide roads	1	<i>Albizia saman</i>	0.13	0.33	0.46
	2	<i>Peltophorum pterocarpum</i>	0.08	0.12	0.20
	3	<i>Polyalthia longifolia</i>	0.08	0.04	0.12
	4	<i>Swietenia macrophylla</i>	0.08	0.02	0.10
	5	<i>Spathodea campanulata</i>	0.07	0.10	0.17
	6	<i>Millingtonia hortensis</i>	0.07	0.02	0.09
	7	<i>Delonix regia</i>	0.07	0.09	0.16
	8	<i>Eucalyptus</i> sp.	0.05	0.04	0.09
	9	<i>Pongamia pinnata</i>	0.04	0.01	0.05
	10	<i>Bauhinia variegata</i>	0.03	0.01	0.04
Medium roads	1	<i>Peltophorum pterocarpum</i>	0.12	0.12	0.24
	2	<i>Spathodea campanulata</i>	0.10	0.19	0.29
	3	<i>Bauhinia variegata</i>	0.09	0.04	0.13
	4	<i>Albizia saman</i>	0.08	0.24	0.32
	5	<i>Markhamia lutea</i>	0.07	0.02	0.09
	6	<i>Delonix regia</i>	0.05	0.07	0.12
	7	<i>Pongamia pinnata</i>	0.05	0.02	0.09
	8	<i>Swietenia macrophylla</i>	0.05	0.03	0.08
	9	<i>Millingtonia hortensis</i>	0.04	0.04	0.08
	10	<i>Jacaranda mimosifolia</i>	0.03	0.03	0.06
Narrow roads	1	<i>Pongamia pinnata</i>	0.15	0.07	0.22
	2	<i>Markhamia lutea</i>	0.08	0.05	0.13
	3	<i>Spathodea campanulata</i>	0.07	0.25	0.32
	4	<i>Bauhinia variegata</i>	0.07	0.06	0.13
	5	<i>Michelia champaca</i>	0.07	0.04	0.11
	6	<i>Dalbergia sissoo</i>	0.04	0.02	0.06
	7	<i>Polyalthia longifolia</i>	0.04	0.02	0.06
	8	<i>Jacaranda mimosifolia</i>	0.04	0.07	0.11
	9	<i>Lagerstroemia speciosa</i>	0.04	0.02	0.06
	10	<i>Delonix regia</i>	0.03	0.08	0.11

Relative abundance represents the percentage of the total number of trees constituted by a species. Relative dominance represents the percentage of total basal area constituted by the species. Species importance is calculated as the sum of relative abundance and relative dominance.

Table 4
Attributes of the most frequently encountered species across all road categories, based on a sub-sample survey of the street tree population of Bangalore.

Scientific name	Proportion of trees (across all roads)	Common names in India	Origin	Phenology	Canopy size	Uses
<i>Albizia saman</i>	8.94	Rain tree	Introduced, Brazil	Deciduous	Large	Ornamental, shade, fodder, timber
<i>Bauhinia variegata</i>	6.28	Orchid tree	Native to Bangalore	Deciduous	Medium	Ornamental, medicinal, timber
<i>Dalbergia sissoo</i>	1.92	Sisham	Introduced from elsewhere in India	Deciduous	Medium	Timber
<i>Delonix regia</i>	5.52	Gulmohar	Introduced, Madagascar	Deciduous	Large	Ornamental, shade
<i>Eucalyptus</i> sp.	2.44	Nilgiri	Introduced, Australia	Evergreen	Medium	Medicinal, firewood
<i>Jacaranda mimosifolia</i>	2.95	Blue Jacaranda	Introduced, Brazil	Deciduous	Large	Ornamental, shade
<i>Lagerstroemia speciosa</i>	1.45	Pride of India	Introduced from elsewhere in India	Deciduous	Medium	Ornamental, shade, firewood
<i>Markhamia lutea</i>	4.75	Nile tulip	Introduced, east Africa	Evergreen	Narrow	Ornamental
<i>Michelia champaca</i>	2.99	Champak	Native to Bangalore	Evergreen	Medium	Ornamental, sacred, medicinal
<i>Millingtonia hortensis</i>	4.40	Indian cork	Introduced, Myanmar	Deciduous	Narrow	Ornamental
<i>Peltophorum pterocarpum</i>	8.42	Copper pod	Introduced, Sri Lanka	Deciduous	Large	Ornamental, shade
<i>Pongamia pinnata</i>	6.88	Pongam	Native to Bangalore	Deciduous	Medium	Ornamental, firewood, timber, biofuel
<i>Polyalthia longifolia</i>	5.56	Indian mast	Native to Bangalore	Evergreen	Narrow	Ornamental
<i>Spathodea campanulata</i>	8.38	African tulip	Introduced, tropical Africa	Deciduous	Medium	Ornamental
<i>Swietenia macrophylla</i>	5.73	Big leaved mahogany	Introduced, tropical America	Evergreen	Medium	Shade, timber

the city's more beautiful, tree covered streets have been denuded of tree cover for road construction and widening activities, and for the new Metro project. Alongside numerous citizen's protests against tree felling (Nair, 2005), and public interest litigations filed in local courts against tree felling (Sudhira et al., 2007),

streets continue to be cleared of trees. The local planning authority in charge of urban tree planting, the Bruhat Bengaluru Mahanagara Palike (BBMP) states that they plan to plant thousands of trees in the city to replace the hundreds that have been cut. No information has been provided about the species that

Table 5

Size class distribution of the ten most dominant tree species, based on a sub-sample survey of the street tree population of Bangalore.

Species	Species percentage of DBH class (cm)						Number of trees
	0–15	15–30	30–45	45–60	60–75	> 75	
<i>Albizia saman</i>	1.44	1.91	3.83	14.35	29.67	48.80	209
<i>Peltophorum pterocarpum</i>	1.02	10.15	34.01	29.44	15.23	10.15	197
<i>Spathodea campanulata</i>	3.06	8.16	16.84	27.55	23.98	20.41	196
<i>Pongamia pinnata</i>	36.02	43.48	16.15	1.86	2.49	0.00	161
<i>Bauhinia variegata</i>	9.53	57.82	29.25	3.40	0.00	0.00	147
<i>Polyalthia longifolia</i>	24.61	33.85	23.85	15.38	1.54	0.77	130
<i>Swietenia macrophylla</i>	31.64	36.15	18.46	8.46	4.62	0.77	130
<i>Delonix regia</i>	0.00	3.88	26.36	39.53	19.38	10.85	129
<i>Markhamia lutea</i>	21.62	54.06	22.52	1.80	0.00	0.00	111
<i>Millingtonia hortensis</i>	2.91	42.72	30.10	14.56	9.71	0.00	103

will be planted, and it is not clear whether these new trees will be planted on streets or in other locations. At this contentious time of change, it is unfortunate that basic information on the city's green cover is lacking, let alone any analysis of structure and composition that would provide guidelines for future management and change. This study aims to fill a critical gap in this regard, also providing one of the first in-depth studies of street trees in a South Asian city.

Street trees tend to have lower life spans compared to trees growing in more "natural" environments, and even compared to trees in other urban locations such as parks, due to stresses of the urban environment. Although we lack quantitative data on arboricultural defects, tree quality, growth problems and growth performance over time, visual observations indicate that tree survival and growth are exacerbated by poor drainage, bad soil conditions, frequent pruning and proximity to traffic pollution. These stressed trees consequently tend to be more prone to attacks by insects and other pests. High species diversity is one way of protecting against such pest attacks, and thus areas with a diverse mix of species are believed to be more robust than locations dominated by a small set of species (McPherson and Rowntree, 1989; Galvin, 1999; Thaiutsa et al., 2008). Bangalore's street trees appear to have quite a healthy diversity, with the most dominant species constituting less than 10% of the total population, while the four most dominant species comprise about one-third of the population. Contrast this to the USA, where the three most common species constitute almost two-thirds of the street trees in Syracuse (Sanders, 1981), or to Chicago where the four most common species comprise two-thirds of the entire population (McPherson et al., 1997). Bangalore's street tree diversity also compares favorably to other highly populated cities in the developing world, including Mexico City where the four most common species constitute 49% of the trees (Chacalo et al., 1994), and to other highly populated Asian cities such as Bangkok, where one species *Pterocarpus indicus* constitutes over 40% of the trees (Thaiutsa et al., 2008) or Hong Kong, where the five most common species constitute over 50% of the total population (Jim, 1987).

The frequency of trees is lower than in other Asian cities, notably in Bangkok, where the number of street trees is approximately 168/km (Thaiutsa et al., 2008), compared to approximately 100/km in Bangalore – or in Beijing, where the spacing between street trees is between 3 and 4 m (Dembner et al., 1993; Profous, 1992), compared to an average of about 20 m in our study.

As with other cities (e.g. Jim, 1999; Escobedo et al., 2006), the location of streets in different parts of the city has influenced density, distribution and composition. In Bangalore, the wider streets are most likely to be planted on both sides, and sometimes

in the central median as well, and are dominated by large, shade providing ornamental trees. Small roads, on the other hand, are located in residential neighborhoods, and require smaller, shorter trees, which are less likely to become unstable during the monsoon, less hazardous for pedestrians, and less likely to interfere with overhead cables and electricity wires. Due to the narrow width of these streets and the crowded sidewalks on either side, often only one side of the street is planted with trees.

In addition to road width, other factors may impact the distribution of trees such as the age of the road, the number of carriageways, the vehicular and pedestrian traffic volume, the width and condition of the planting areas, and the urban land use density and history. Since the life span of street trees in the city spans decades, while urban areas are changing at great rapidity with frequent and rapid changes in road width, planting conditions, it becomes difficult to collect data adequately and accurately representative of these conditions over a period of time. This is especially difficult in a city like Bangalore where basic information on many of these variables is not available. Thus, while this study is able to determine that road width has a significant impact on street trees, we are not able to ascertain other factors that may also have a major impact on shaping street tree distributions. Further, while our sampling has covered 152 transects of 200 m each, Bangalore's road network is estimated to cover approximately 3500 km, and these findings are therefore only indicative of the actual distribution.

Stark differences are observed in species girth distributions, and the city has a dearth of young trees, especially in comparison to other cities like Mexico City (Chacalo et al., 1994), Beijing (Profous, 1992) and Bangkok (Thaiutsa et al., 2008). In the US, studies indicate that urban foresters have moved towards planting small sized trees in order to reduce tree maintenance costs and to increase species diversity (McPherson and Rowntree, 1989). Bangalore appears to be moving towards a similar trajectory.

Yet, while the financial implications of these changes are often emphasized, the environmental implications are not sufficiently taken into account (McPherson and Rowntree, 1989). The environmental benefits provided by trees with small sized canopies are fewer (Pauleit and Duhme, 2000). Large trees contain more above ground biomass and tend to have larger canopies than small trees, thereby providing greater scenic beauty along city streets (Issar, 1994; Jim, 1999), along with more effective removal of air particulate pollutants, greater shade and more effective cooling (McPherson and Rowntree, 1989; McPherson et al., 1997). Large trees also constitute a better habitat for other urban species such as woodland birds (Pauleit and Duhme, 2000). At a time when the initial impacts of climate change are beginning to be felt across the world, and when the impacts of urban heat

islands are becoming increasingly intensified, more attention requires to be paid to the selection of trees planted in cities. While Bangalore's street tree diversity is adequate, the diversity of trees in the younger size classes appears to be decreasing. Our analysis indicates that the density of street trees in Bangalore is quite low relative to other Asian cities. This, in conjunction with a shift towards the planting of smaller sized species, and large scale felling of street trees in recent months, indicates that Bangalore appears to be moving towards an increasingly brown future.

Tree felling in Bangalore appears concentrated on the larger roads, which are being further widened for conversion into high speed highways, and for the city's Metro project. Given the fact that these roads have the greatest density of trees, and contain the largest trees, it appears that such tree felling is selectively depriving Bangalore's streets of their largest and oldest trees. It is critical to protect the trees on the remaining wooded stretches from further felling. Widening all roads in the city may not be required, and it may be possible to deal with issues of traffic congestion by encouraging the city's public transport system, and providing disincentives for private transport, as is being implemented on other parts of the world. Further, when trees are felled for road widening, compensatory planting should be made mandatory *on the same roads*. A spatial database of trees in the city appears urgently required so that reliable data on tree felling can be obtained over time, facilitating the identification and protection of large trees and enabling the collection of data on basic aspects such as tree growth performance, problems and limitations. With the advent of high resolution satellite imagery such as IKONOS and GeoEye, the preparation of such spatial databases appears increasingly feasible (Nagendra and Rocchini, 2008). This constitutes one of the future goals of our urban program.

These measures, along with increased planting of appropriately selected species, appear essential if we are to preserve the city's environment. Large canopy tree species, which have been a dominant part of Bangalore's visual landscape, need to be planted along with an appropriate mix of small sized flowering and fruiting trees, as has been the case in the past. Reducing species diversity and planting even aged populations, as is the trend on narrow roads, can make the street tree population less expensive to manage. Yet, such an approach also leaves urban tree populations more vulnerable to pest attacks. Thus, it may be worthwhile to selectively remove certain damaged trees, and replace these with trees of different species and ages, thus gradually converting the population to a more diverse one, both in terms of age structure and species composition.

Conclusions

Although Bangalore is widely famed as the garden city of India, and rapidly gaining importance as a global city, little is known about Bangalore's urban environment and ecology. This paper reports the first results of a long term program aimed at monitoring ecological, environmental and land use change in the city. Focusing on studies of street tree density, size, diversity, and distribution, we find that Bangalore's streets are relatively low in density but high in species diversity when compared to other cities. Wide streets have a greater predominance of large sized tree species and a greater density and species diversity compared to narrow streets, which tend to be dominated by a smaller number of short statured species with narrow canopies.

The importance of this observation relates to the patterns of tree felling in the city. Given the recent tree felling in several of Bangalore's wider streets for expansion projects, the city appears to be in the process of losing a significant proportion of its mature,

large canopy trees. Many of the trees on Bangalore's large roads are being cut as these roads are being widened into six lane highways, or to make way for the city's new public transport system, the Bangalore Metro (Bangalore Development Authority, 2005). Consequently, Bangalore appears to be selectively culling its oldest and largest street trees, which has significant implications for the ecological health of the city. These findings hold great importance for urban forest managers and city planners. This pattern of leaving inner city narrow roads largely untouched, while selectively expanding wide roads which cater to high density traffic, is not restricted to Bangalore – indeed, this is the pattern followed by many major cities across the world (Van Rest, 1987). Thus, these findings have significant implications for urban forests in other metropolitan areas.

The species mix has also changed over time. Large sized tree species are no longer being planted, leading to a greater predominance of young trees belonging to small sized species. This has serious implications for the future health of the city, as small sized, narrow canopy trees have a lower capacity to absorb atmospheric pollutants, mitigate urban heat island effects, stabilize soil and prevent ground water runoff. Our findings indicate the critical need to protect the remaining population of street trees, with a focus on large, mature individuals, to plant more trees, and to select an appropriate and diverse mix of large and small sized tree species for such new planting.

Finally, further research is required to understand how the larger climatic and ecological context influences urban forestry in Bangalore. In the context of increasing global warming, while the Indian monsoon has remained relatively stable, an increasing frequency of extreme rain events has been noted, ranging from floods to droughts (Goswami et al., 2006). Further investigations are required to understand how such variability in climate can potentially affect tree growth, and whether there are differences in the tolerance levels of evergreen and deciduous species to variations in the length of the dry season, and extreme rainfall events. Such studies can be very useful in helping to identify characteristics that can be used to select tree species that are better suited for urban forestry in Bangalore.

Acknowledgements

We thank Lionel Sujay Vailshery, Madhumitha Jaganmohan, Srinidhi Kashyap, Vikram Gopal, Bhargava Shastry and Yasir Arafath for assistance with data collection, and Somajita Paul for GIS assistance. Financial support from the International Foundation for Science and from the Stockholm Resilience Center is gratefully acknowledged. Harini Nagendra also acknowledges financial support from a Society in Science: Branco Weiss Fellowship from ETH, and a Ramanujan Fellowship from the Department of Science and Technology, Government of India. We appreciate the detailed suggestions provided by anonymous reviewers of this manuscript.

References

- Alvey, A.A., 2006. Promoting and preserving biodiversity in the urban forest. *Urban Forestry and Urban Greening* 5, 195–201.
- Bangalore Development Authority, 2005. In: Bangalore Master Plan 2015. Bangalore Development Authority and SCE-CREOCEAN (India) Private Limited, Bangalore.
- Beckett, K.P., Freer-Smith, P., Taylor, G., 2000. Effective tree species for local air-quality management. *Journal of Arboriculture* 26, 12–19.
- Chacalo, A., Aldama, A., Grabinsky, J., 1994. Street tree inventory in Mexico City. *Journal of Arboriculture* 20, 222–226.
- Chow, W.T.L., Roth, M., 2006. Temporal dynamics of the urban heat island of Singapore. *International Journal of Climatology* 26, 2243–2260.

- Dembner, S.A., Ming, S., Profous, G., 1993. Urban forestry in Beijing. *Unasylva* 173, 13–18.
- Dumbaugh, E., 2005. Safe streets, livable streets. *Journal of the American Planning Association* 71, 283–298.
- Escobedo, F.J., Nowak, D.J., Wagner, J.E., de la Maza, C.L., Rodriguez, M., Crane, D.E., Hernandez, J., 2006. The socioeconomics and management of Santiago de Chile's public urban forests. *Urban Forests and Urban Greening* 4, 105–114.
- Fernandez-Juricic, E., 2000. Avifaunal use of wooded streets in an urban landscape. *Conservation Biology* 14, 513–521.
- Galvin, M.F., 1999. A methodology for assessing and managing biodiversity in street tree populations: a case study. *Journal of Arboriculture* 25, 124–128.
- Goswami, B.N., Venugopal, V., Sengupta, D., Madhusoodanan, M.D., Xavier, P.K., 2006. Increasing trend of extreme rain events over India in a warming environment. *Science* 314, 1442–1445.
- Heynen, N., Perkins, H.A., Roy, P., 2006. The impact of political economy on race and ethnicity in producing environmental inequality in Milwaukee. *Urban Affairs Review* 42, 3–25.
- Issar, T.P., 1994. In: *Blossoms of Bangalore*. Mytec Process Pvt Ltd., Bangalore.
- Jim, C.Y., 1987. The status and prospects of urban street in Hong Kong. *Landscape and Urban Planning* 14, 1–20.
- Jim, C.Y., 1999. A planning strategy to augment the diversity and biomass of roadside trees in urban Hong Kong. *Landscape and Urban Planning* 44, 13–32.
- Jim, C.Y., Chen, W.Y., 2008. Pattern and divergence of tree communities in Taipei's main urban green spaces. *Landscape and Urban Planning* 84, 312–323.
- Lawrence, H.W., 1994. Origins of the tree lined boulevard. *Geographical Review* 78, 355–374.
- Maco, S.E., McPherson, E.G., 2003. A practical approach to assessing structure, function and value of street tree populations in small communities. *Journal of Arboriculture* 29, 84–97.
- McPherson, E.G., Rowntree, R.A., 1989. Using structural measures to compare twenty-two U.S. street tree populations. *Landscape Journal* 8, 13–23.
- McPherson, E.G., Nowak, D., Heisler, G., Grimmond, S., Souch, C., Grant, R., Rowntree, R., 1997. Quantifying urban forest structure, function and value: the Chicago Urban Forest Climate Project. *Urban Ecosystems* 1, 49–61.
- Nagendra, H., Rocchini, D., 2008. High resolution satellite imagery for tropical biodiversity assessment: the devil is in the detail. *Biodiversity and Conservation* 17, 3431–3442.
- Nair, J., 2005. In: *The Promise of the Metropolis: Bangalore's Twentieth Century*. Oxford University Press, New Delhi.
- Neginhal, S.J., 2006. In: *Golden Trees, Greenspaces and Urban Forestry*. Self published, Bangalore.
- Pauleit, S., Duhme, F., 2000. GIS assessment of Munich's urban forest structure for urban planning. *Journal of Arboriculture* 26, 133–141.
- Pauleit, S., 2003. Urban street tree plantings: identifying the key requirements. *Municipal Engineer* 156, 43–56.
- Profous, G.V., 1992. Trees and urban forestry in Beijing, China. *Journal of Arboriculture* 18, 145–154.
- Rice, B.L., 1897. *Mysore: A Gazetteer Compiled for Government*, Revised Edition, vol. 2. Archibald Constable and Company, London.
- Sanders, R.A., 1981. Diversity in the street trees of Syracuse, New York. *Urban Ecology* 5, 33–43.
- Sanders, R.A., 1983. Diversity and stability in a street tree population. *Urban Ecology* 7, 159–171.
- Sokal, R.R., Rohlf, F.J., 1981. In: *Introduction to Biostatistics* 2nd edition Island Press, Washington DC, USA.
- Stohlgren, T.J., 2007. In: *Measuring Plant Diversity: Lessons from the Field*. Oxford University Press, New York, USA.
- Sudha, P., Ravindranath, N.H., 2000. A study of Bangalore urban forest. *Landscape and Urban Planning* 47, 47–63.
- Sudhira, H.S., Ramachandra, T.V., Subrahmanya, M.H.B., 2007. City profile Bangalore. *Cities* 24, 379–390.
- Thaiutsa, B., Puangchit, L., Kjelgren, R., Arunpraparut, W., 2008. Urban green space, street tree and heritage large tree assessment in Bangkok, Thailand. *Urban Forestry and Urban Greening* 7, 219–229.
- Van Rest, D., 1987. Policies for major roads in urban areas in the UK. *Cities* 4, 236–252.
- Ware, G.H., 1994. Ecological bases for selecting urban trees. *Journal of Arboriculture* 20, 98–103.
- Welch, J.M., 1994. Street and park trees of Boston: a comparison of urban forest structure. *Landscape and Urban Planning* 29, 131–143.
- Wetter, A., Goldberg, J., King, A., Sigman-Grant, M., Baer, R., Crayton, E., Devine, D., Drewnowski, A., Dunn, A., Johnson, G., Pronk, M., Saelens, Snyder, D., Walsh, K., Warland, R., 2001. How and why do individuals make food and physical activity choices? *Nutrition Reviews* 59, 11–20.
- Wolf, K., 2005. Business district streetscapes, trees and consumer response. *Journal of Forestry* 103, 396–400.