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Effect of street trees on microclimate and air pollution in a tropical city

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ABSTRACT

One of the fastest growing cities in India, Bangalore is facing challenges of urban microclimate change and increasing levels of air pollution. This paper assesses the impact of street trees in mitigating these issues. At twenty locations in the city, we compare segments of roads with and without trees, assessing the relationship of environmental differences with the presence or absence of street tree cover. Street segments with trees had on average lower temperature, humidity and pollution, with afternoon ambient air temperatures lower by as much as 5.6 °C, road surface temperatures lower by as much as 27.5 °C, and SO_2 levels reduced by as much as 65%. Suspended Particulate Matter (SPM) levels were very high on exposed roads, with 50% of the roads showing levels approaching twice the permissible limits, while 80% of the street segments with trees had SPM levels within prescribed limits. In an era of exacerbated urbanization and climate change, tropical cities such as Bangalore will have to face some of the worst impacts including air pollution and microclimatic alterations. The information generated in this study can help appropriately assess the environmental benefits provided by urban trees, providing useful inputs for urban planners.

Introduction

In the century of urbanization, as urban population densities continue to increase, living conditions continue to deteriorate. This impact may be especially severe in the tropics, where most developing countries are located, and where as much as 90% of the urbanization of the coming decades is predicted to take place (Emmanuel, 2005). Tropical cities will experience especially severe consequences of urbanization, with accelerated urban heat island effects, changes in microclimate and thermal discomfort, because of their location in hot areas (Burkart et al., 2011). This is exacerbated by the rapid growth in many tropical cities, with large scale conversions of open areas and green spaces to concreted and built land cover (Emmanuel, 2005; Kant et al., 2009; Nagendra and Gopal, 2010). The consequences can be wide ranging, including increased probability of heat strokes and health disorders, and the altered distribution of precipitation events (Dixon and Mote, 2003; Vinoj et al., 2004; Chang et al., 2007).

Urban tropical locations also face challenges of air pollution (Ghose et al., 2005; Kuvarega and Taru, 2008). As levels of industrialization increase in these cities, coupled with high densities of vehicular movement, the exposure of urban dwellers to air pollutants is anticipated to rise exponentially (Parrish and Zhu, 2009). Many South Asian cities currently deal with problems of atmospheric pollution due to vehicular traffic, with unacceptably high levels of Suspended Particulate Matter (SPM), NO_2, SO_2, and other air pollutants (Khan and Abbasi, 2000; Emmanuel, 2005; Ghauri et al., 2007). These air pollutants can cause severe respiratory and health problems for urban residents (Pope et al., 2000), particularly impacting vulnerable sections of society such as children (Kuvarega and Taru, 2008).

Mechanisms for mitigating these challenges of urban microclimatic variations and air pollution, although much in need, have not been well developed in most tropical developing countries (Escobedo et al., 2011). While much of the discussion has remained focused on the need for phasing out old technologies and promoting public transport, the potential role of urban vegetation in such mitigation has been largely ignored by planners. Most research has been conducted in developed countries as well, although issues of microclimate maintenance and air pollution control are just as important, if not even more so, in rapidly expanding developing country cities (Escobedo et al., 2011).

Trees in cities can reduce air pollution levels significantly, by the removal of pollutant gases such as SO_2, NO_x, CO and O_3 through leaf stomata, and through the dry deposition of suspended particulate matter on leaf surfaces (Smith, 1984). Urban vegetation can also contribute to the reduction of the urban heat island effect, and trees have a clear role to play in microclimate amelioration (Chang et al., 2007). Trees in cities can further contribute to reduction of air pollution by reducing the need for air conditioning, leading to concomitant decreases in fossil-fuel generated air

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pollution (Chang et al., 2007; Escobedo et al., 2008; Jim and Chen, 2009).

This study explores the impact of street trees on reducing daytime temperatures and mitigating air pollution levels in the south Indian city of Bangalore. Internationally known for its technologically intensive industries, Bangalore is the second fastest growing city in India, with a population over 9.5 million. Given the deficiency of information on the environmental benefits of trees in tropical developing cities such as Bangalore, such exploratory studies are important to provide insights into potential benefits, which can then provide the basis for in depth, long term research and monitoring.

Study area

Bangalore is located at 12°59′ N and 77°57′ E, at an altitude of 920 m above mean sea level. The mean annual rainfall is about 880 m, with winter temperature ranging from 12° to 25 °C, and summer temperature from 18° to 38 °C (Sudhira, 2008). Once known as the garden city and the lake city of India, the city's open spaces which included a large number of parks, wetlands and water bodies, have been encroached upon and converted to a variety of urban land uses (Nagendra, 2010). Bangalore has also witnessed widespread clearing of trees and green spaces for road expansion and infrastructure activities in recent years (Nagendra and Gopal, 2010, 2011). Most of these projects are aimed at accommodating an increasing number of vehicles, while the city already contains the highest vehicle to person ratio of any Indian mega city (Sudhira, 2008).

The number of vehicles has multipled many fold in recent decades, with 2.5 million vehicles registered in 2007, of which private 2-wheel vehicles and cars account for the majority. Public transport is limited, with public and private buses together account for less than 1% of the city's total vehicle population (Sabapathy, 2008). Pedestrian traffic constitutes about 26% of all trips (Sudhira, 2008). The city's transport was once dominated by non-motorized vehicles (bicycles) – as recently as 1965, cycles constituted 70% of the traffic, but subsequently steeply declined to 5% in 1998. This is mirrored by a decline in the proportion of people traveling by public transport, while the use of private cars and two wheelers has increased substantially (Jalihal et al., 2005). Traffic generally consists of a mix of two wheelers fueled by petrol, three-wheelers fueled by petrol and liquified petroleum gas, cars fueled by petrol and diesel, and diesel buses (Sabapathy et al., 2012).

Traffic is heavy, and the average speed per hour on many arterial roads is quite slow (Sabapathy, 2008). Thus, transport is a major source air pollution in Bangalore, which has a total estimated pollution load of 54.4 tons/day of Suspended Particulate Matter below 10 μm (PM_{10}), 217.4 tons/day for NO_x and 14.6 tons/day of SO_2. The major sources of PM_{10} include automobiles and transport (42%), road dust resuspension (20%), construction (14%) and industry (14%) (TERI, 2010). Corroborating this, a recent study (Sabapathy et al., 2012) concludes that PM_{10} is much lower on average (150 $\mu g/m^3$) away from heavy traffic roads (375 $\mu g/m^3$). In contrast the main sources of SO_2 emission are from industry (56%), diesel generator sets (23%) and transport (16%) (TERI, 2010).

Methods

Ten major roads that carry high densities of traffic, located in different parts of the city, were selected for study, a relatively small sample size that enables an exploratory analysis of the potential environmental benefits provided by street trees in this tropical city. All roads were paved. We focused on large roads that had at least 2 lanes, and which carried substantial volumes of traffic (based on our own personal knowledge of the city). Within the subset of roads identified, we looked for roads where we could locate adjacent segments such that at least one segment had tree cover for about 150 m, while another segment had no tree cover, affording an opportunity for comparison. We were able to locate such roads and segments in ten different locations, as described further in Table 1. Variation in ambient air temperature, road surface temperature, humidity and air pollution were recorded for paired segments of a road on the same day, during the same time, by two teams using synchronized clocks. Sampling was conducted between 18th May and 3rd June 2010, ensuring that all roads were sampled within a relatively short interval of time of 17 days, to ensure minimal variation in seasonal weather conditions. Sampling was conducted only on working days, avoiding weekends and public holidays. Cloudy days and days with events of precipitation were also avoided to ensure that sampling was conducted during sunny summer days. Comparison of traffic intensities was conducted on the same date during which temperature, humidity and air pollution measurements were taken, to test whether traffic conditions were comparable across the paired locations. Subsequent site visits were conducted between 10 and 15 January 2012 to record information on the number of trees, species and tree height, and the percentage of exposed soil and ground vegetation cover surrounding the monitor. Tree canopy cover was determined at 50 m linear intervals along the 150 m road segment by estimating the percentage of visible sky. Table 1 provides further details on the site location, vegetation around the monitors, and the location of monitors with respect to the road (in addition to the information provided in this Table, percentage of impervious cover can be calculated by subtracting the sum of the percentage of exposed soil and ground vegetation from 100%). Although the information on vegetation cover was recorded at a different dates from the rest of the study, we examined photographs taken at the time of sampling to confirm that there were no differences in the trees and soil/ground vegetation in the area around the monitor between the time of temperature, humidity and air pollution data collection, and the subsequent visit.

Sampling began at 8.30 a.m. each day, and concluded at 3.30 p.m. At the beginning of the study, and subsequent half-hour intervals, ambient air temperature and humidity were recorded using digital meters (Model AZ 7755, manufactured by AZ Instrument Corp, Taiwan; procured from and pre-calibrated by HTA Instrumentation Private Limited, Bangalore) at the edge of the road, at the center of the 150 m sections with and without overhead road trees. The temperature probe was shielded from overhead solar radiation by using a covered cylindrical cardboard tube with large perforated side openings to permit air circulation. Road surface temperatures were also recorded at the same time and at the same locations using an Equinox infrared surface thermometers (Model EQ-DT 8530, manufactured by Sansel Instruments and Controls; Chennai India; procured from and pre-calibrated by HTA Instrumentation Private Limited, Bangalore). In order to ensure that traffic densities were comparable across road segments with and without trees, manual counts of traffic crossing a single point location (where the high volume air sampler was located) were made for 10 min intervals every hour.

Monitech high volume air samplers were placed at the center of each segment of road. For assessment of suspended particulate matter, air was passed through a pre-weighed glass microfiber filter paper (Whatman GF/A; HH) with a size of 20.3 cm by 25.4 cm, and a pore size of about 3 μm, at a flow rate of 1–3 m^3/min of air such that SPM was deposited on the filter paper. After a period of about 8 h, the filter paper was removed and dried in a hot air oven at 105 °C for 1 h, and then cooled and weighed again. The difference in weight of the filter paper before and after sampling was used to calculate the weight of the SPM. The volume of ambient air sampled was derived

Table 1
Comparison of site, tree and ground characteristics for road segments with trees (T) and without trees (W) in the study area in Bangalore.

Road	No. of lanes	Monitor elevation from road surface (feet)	Monitor distance from road edge (feet)	No. of trees (10 m around monitor)	Canopy cover in 150 m segment	No. of individuals of different tree species in each 150 m segment with Girth at Breast Height (GBH)	Distance of monitor from tree trunk (m)	Distance of monitor from tree canopy (m)	% Exposed soil (20 m around monitor)	% Ground vegetation (20 m around monitor)
Bellary – T	2	1	4	2	40–70%	4 *Spathodea campanulata*, GBH 1.9 m, 1.9 m, 1.8 m, 1.6 m 3 *Swietenia macrophylla*, GBH 1.2 m, 1.4 m, 1 m 3 *Swietenia macrophylla*, GBH 0.7 m, 0.6 m, 0.5 m 2 *Peltophorum pterocarpum*, GBH 0.6 m, 0.6 m 1 *Bombax ceiba*, GBH 1.8 m 1 *Broussonetia papyrifera*, GBH 0.4 m	4	7	2	0
Bellary – W	2	1	4	0	–	–	–	–	0	0
Banashankari – T	2	1	4	1	70–90%	8 *Samanea saman*, GBH 2.7 m, 2.6 m, 2.2 m, 2.2 m, 2.1 m, 2.1 m, 2.1 m, 1.9 m	4	10	2	0
Banashankari – W	2	1	4	0	–	–	–	–	0	0
Magadi – T	2	1	4	1	70–90%	4 *Samanea saman*, GBH 2.2 m, 2.1 m, 1.8 m, 1.7 m 2 *Peltophorum pterocarpum*, GBH 1.8 m, 1.7 m	4	8	2	0
Magadi – W	2	2	4	0	–	–	–	–	0	0
Siddapura – T	2	1	2.5	2	70–90%	5 *Samanea saman*, GBH 2.3 m, 2.3 m, 2.1 m, 1.8 m, 1.7 m 2 *Swietenia macrophylla*, GBH 1.1 m, 1.0 m 1 *Peltophorum pterocarpum*, GBH 1.4 m	4	10	2	0
Siddapura – W	2	1	2.5	0	–	–	–	–	0	0
Bannerghatta – T	2	1	5	4	30–40%	19 *Tabebuia rosea*; GBH 0.7 m, 0.7 m, 0.7 m, 0.7 m, 0.6 m, 0.6 m, 0.6 m, 0.6 m, 0.6 m, 0.6 m, 0.6 m, 0.6 m, 0.6 m, 0.5 m, 0.42 m, 0.4 m, 0.4 m, 0.3 m, 0.25 m	4	3	10	10
Bannerghatta – W	2	1	5	0	–	–	–	–	0	0
Jeevanbhima Nagar – T	2	1	5	1	70–90%	5 *Spathodea campanulata*, GBH 2.5 m, 2.2 m, 1,8 m, 1.6 m, 1.4 m 4 *Samanea saman*, GBH 3.2 m, 3.1 m, 3.0 m, 2.4 m 1 *Delonix regia*, GBH 2.0 m	4	12	2	0
Jeevanbhima N Nagar – W	2	1	5	0	–	–	–	–	0	0
Hennur – T	4	1	2	5	30–40%	24 *Swietenia macrophylla*, GBH 1.1 m, 1.0 m, 1.0 m, 1.0 m, 1.0 m, 1.0 m, 0.9 m, 0.9 m, 0.9 m, 0.9 m, 0.8 m, 0.8 m, 0.8 m, 0.8 m, 0.8 m, 0.8 m, 0.8 m, 0.8 m, 0.8 m, 0.7 m, 0.7 m, 0.7 m, 0.6 m, 0.5 m 2 *Jacaranda mimosifolia*, GBH 0.5 m, 0.4 m 1 *Albizia lebbek*, GBH 1.0 m	4	6	10	10

Table 1 (*Continued*)

Road	No. of lanes	Monitor elevation from road surface (feet)	Monitor distance from road edge (feet)	No. of trees (10 m around monitor)	Canopy cover in 150 m segment	No. of individuals of different tree species in each 150 m segment with Girth at Breast Height (GBH)	Distance of monitor from tree trunk (m)	Distance of monitor from tree canopy (m)	% Exposed soil (20 m around monitor)	% Ground vegetation (20 m around monitor)
Hennur – W	4	1	2	0	–	–	–	–	10	0
Sarjapur – T	4	1	2	3	70–90%	8 *Samanea saman*, GBH 1.3 m, 1.2 m, 1.2 m, 1.1 m, 1.1 m, 1.1 m, 1.0 m, 0.7 m 2 *Peltophorum pterocarpum*, GBH 1.1 m, 0.8 m 1 *Spathodea campanulata*, GBH 1.6 m	4	12	10	0
Sarjapur – W	4	1	2	0	–	–	–	–	0	0
Assaye – T	2	1	2	2	70–90%	4 *Parkia biglandulosa*, GBH 2 m, 2 m, 2 m, 1.8 m 2 *Jacaranda mimosifolia*, GBH 2.3 m, 2.0 m 1 *Samanea saman*, GBH 2.2 m 1 *Tabebuia rosea*, GBH 1.3 m 1 *Thespesia populnea*, GBH 0.9 m	4	8	0	0
Assaye – W	2	1	2	0	–	–	–	–	0	0
Kundanahalli ITPL – T	2	1	2	2	70–90%	6 *Tabebuia rosea*, GBH 1.4 m, 1.2 m, 1.2 m, 1.2 m, 1.1 m, 1.0 m 5 *Samanea saman*, GBH 1.3 m, 1.2 m, 1.2 m, 1.1 m, 1.1 m, 1.0 m 2 *Swietenia macrophylla*, GBH 1.1 m, 1.0 m 1 *Michelia champaca*, GBH 0.4 m 1 *Polyalthia longifolia*, GBH 0.3 m	4	8	0	0
Kundalahalli ITPL – W	2	1	2	0	–	–	–	–	0	0
Average values – T	2.4	1.0	3.3	2.3	70%	–	4	8.4	3.8	2
Average values – W	2.4	1.1	3.3	–	–	–	–	–	1	0
Standard error – T	0.8	0.0	1.3	1.3	20%	–	0	2.8	4.4	4.2
Standard deviation – W	0.8	0.3	1.3	–	–	–	–	–	3.2	–

by multiplying the flow rate of the high volume air sampler with the duration of sampling. These two measurements were used to derive an estimate of the concentration of SPM in the ambient air, in particulates per meter^3 (PPM).

For assessment of the levels of SO_2 in the ambient air, air was actively pumped through an impinger containing an absorbing solution of sodium tetrachloromercurate in the high volume air sampler, for about 8 h, following which impinge samples were transferred to a refrigerator, and concentrations of SO_2 analyzed using the West and Gaeke method (Wilson, undated; Ghose et al., 2005).

Analyses of differences in traffic densities, SPM and SO_2 levels were conducted to assess the statistical significance of samples from road segments with and without trees. Analysis of differences in ambient air temperature, road surface temperature and humidity were conducted separately for each half-hour interval to assess the statistical significance of samples from road segments with and without trees. All statistical tests were conducted using the academic software STATISTICA (version 10).

Results

Distribution fitting tests for traffic densities, ambient air temperature, road surface temperature, humidity, SPM and SO_2 indicated that all distributions were significantly different from normal ($p < 0.05$). Consequently, all analyses of differences in traffic densities, SPM, SO_2 levels and ambient air and road surface temperatures were conducted using a non-parametric Mann–Whitney *U* test. No significant difference could be observed in vehicular traffic levels in road segments with and without trees ($p = 0.95$, Table 2). Non-parametric Spearman's rank correlation was conducted between the distance of monitor from road edge, bare soil and ground vegetation percentage to assess potential interactions with tree effects. No significant correlations were observed between the percentage of bare soil or ground vegetation around the monitor and other measured environmental variables of ambient air temperature, road surface temperature, humidity, SO_2 and SPM, apart from a single case of significant correlation between percentage of bare soil and ambient air temperatures recorded at 3 p.m. There was however a significant correlation observed between the SO_2 values and the distance of the monitor from road edge ($p < 0.05$). Distance of the monitor from road edge was also significantly correlated with ambient air temperature measurements in a couple of instances, for measurements taken at 1.30 p.m. and 2.00 p.m. ($p < 0.05$), but not shown to be correlated further with measurements of ambient air temperature, road surface temperature or humidity.

The ambient air temperature in road segments with trees ranged from 23.1 °C to 34.2 °C, while road segments without trees had temperature ranges of 23.4–38.3 °C, with maximum temperature observed on an open road segment in the Hennur Ring Road, a wide, open road with high densities of traffic at the periphery of the city, at 2.30 p.m. These temperature differences were significant for all times of day (Mann–Whitney *U* test, $p < 0.05$), with the exception of 9 a.m., when temperature differences were borderline non-significant ($p = 0.052$). In all instances, ambient air temperature measured on tree-lined road segments was less than that measured at the same time on exposed segments from the same road. Fig. 1 describes the median and interquartile distance in ambient air temperatures for road segments with and without roads.

Differences in road surface temperature for road segments with and without trees were even more marked, with significant differences for all times of day (Mann–Whitney *U* test, $p < 0.01$) as can be seen from Fig. 2 which depicts the median and interquartile distance in ambient air temperatures for road segments with and

Table 2
Comparison of vehicular traffic movement on road segments with trees (T) and without trees (W) in Bangalore, recorded for a duration of 10 min once every hour.

Road	Segment	9:00–9:10 AM	10:00–10:10AM	11:00 to 11:10 AM	12:00–12:10 PM	1:00–1:10 PM	2:00–2:10 PM	3:00–3:10 PM
Bellary	T	865	898	771	719	753	1143	755
	W	784	876	752	732	817	1024	761
Banashankari	T	296	356	281	264	242	296	295
	W	289	360	284	293	261	262	288
Magadi	T	421	460	455	369	444	322	413
	W	453	429	448	429	407	420	397
Siddapura	T	506	487	376	461	481	391	338
	W	525	432	461	455	472	351	349
Bannerghatta	T	447	428	433	415	416	359	322
	W	464	426	440	409	401	346	363
Jeevanbhima Nagar	T	372	373	316	275	268	271	264
	W	320	370	314	277	278	269	263
Hennur	T	418	444	378	371	417	277	350
	W	413	434	379	380	414	290	340
Sarjapur	T	683	668	536	503	589	429	428
	W	701	687	521	507	560	400	436
Assaye	T	625	429	345	256	360	239	291
	W	632	456	330	240	380	221	270
Kundanahalli ITPL	T	332	334	290	284	277	243	258
	W	344	340	282	276	298	237	243
Statistical differences in values for road segments with and without trees (p value for a Mann–Whitney *U* test)	–	0.97	0.80	0.91	0.74	0.91	0.74	1.0

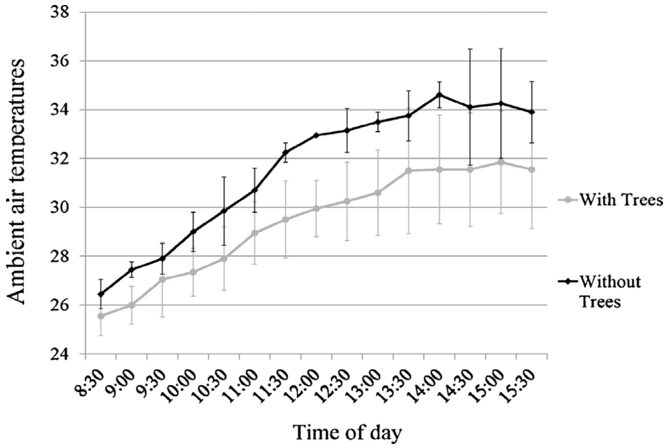

Fig. 1. Median and interquartile difference in ambient air temperature at different times of day, for road segments with and without trees in Bangalore.

without roads. Road surface temperature for segments with trees ranged from 23 °C to 56 °C, and from 27 °C to 62 °C for segments without tree cover. In all instances, temperature on tree-lined road segments was less than that on exposed segments from the same road, with the maximum road surface temperature of 62 °C again observed at an open segment of Hennur Ring Road, at 2 p.m.

No significant differences were however observed in air humidity levels recorded for road segments with and without trees (Mann–Whitney *U* test, $p < 0.05$). The overlap in humidity values for segments of road with and without trees can also be observed from Fig. 3, depicting the median and interquartile distance in air humidity levels for road segments with and without trees. Overall, humidity levels were maximum in the morning at 8.30 a.m., but decreased during the day, with the lowest levels of humidity encountered at around 3.30 p.m.

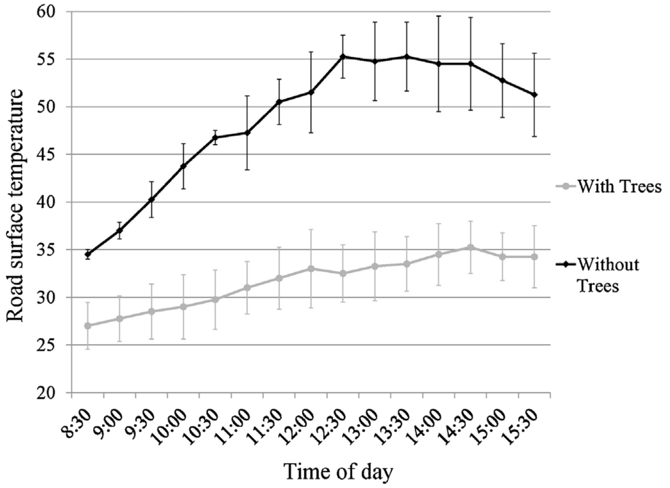

Fig. 2. Median and interquartile difference in road surface temperature at different times of day, for road segments with and without trees in Bangalore.

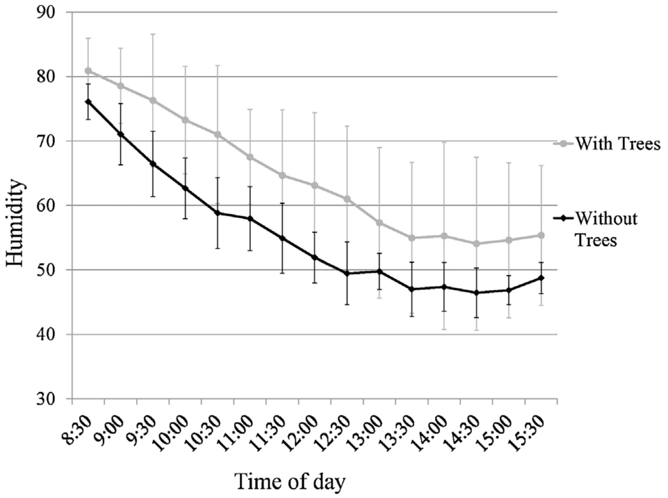

Fig. 3. Median and interquartile difference in air humidity at different times of day, for road segments with and without trees in Bangalore.

SO_2 levels at all sites were within the Indian National Ambient Air Quality Standards for industrial, residential and rural areas. The permissible limits are 80 $\mu g/m^3$, while the maximum level observed in this study was 43.5 $\mu g/m^3$. Significant differences in SO_2 levels were observed between road segments with and without trees (Mann–Whitney *U* test, $p < 0.001$, Fig. 4). In eight of the ten open segments of road, SPM levels exceeded permissible levels of 200 $\mu g/m^3$ specified by the National Ambient Air Quality Standards, climbing to almost double the allowed limits in 50% of the roads, although eight out of ten road segments with trees showed levels of SPM within safety limits (Fig. 5). This difference was also significant based on a Mann–Whitney *U* test ($p < 0.001$).

Discussion

In Bangalore, our results indicate that street trees can have a significant impact on microclimatic buffering. Importantly, the large increases in road surface temperature observed in the absence of trees indicates a substantial increase in discomfort levels, as hot roads radiate this heat upwards, making it even more challenging for pedestrians and bicyclists. In a city where private vehicular transport is already much greater than in other Indian cities (Sudhira, 2008), increases in mid-day temperature can further encourage the use of vehicular air conditioning, and disincentivize the use of public transport and energy-saving methods of transport such as walking and bicycling.

Studies in other parts of the world also corroborate these findings. In Taipei, Chang et al. (2007) found mid-day differences of 0.81 °C in summer temperatures between parks and their surroundings, based on direct measurements. In Beijing, a study by Weng (2001), utilizing the thermal infrared band of Landsat TM to measure surface temperatures, found urban land cover to have

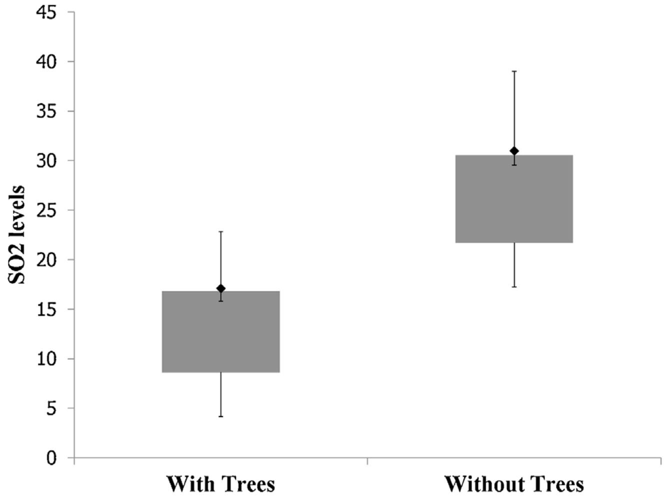

Fig. 4. Box and whisker plot illustrating the mean (diamond), second and third quartile (gray box) and minimum and maximum values (bottom and top whiskers) of SO_2 levels ($\mu g/m^3$) for road segments with and without trees in Bangalore.

Fig. 5. Box and whisker plot illustrating the mean (diamond), second and third quartile (gray box) and minimum and maximum values (bottom and top whiskers) of SPM levels (μg/m^3) for road segments with and without trees in Bangalore.

an average surface temperature of 63.15 °C in December 1989 (winter), as opposed to 35.68 °C for adjacent forest, while urban cover surface temperature in August 1997 (summer) were higher, 65.99 °C – but much cooler in adjacent forests, which displayed an average temperature of 39.76 °C. Chen et al. (2006) found average temperature differences of 0.45–3.33 °C between urban and vegetated surfaces in the Pearl River Delta in Guangdon Province, southern China based on surface temperature estimations derived from Landsat data. In the Tabriz metropolitan area of Iran, Amiri et al. (2009) found areas with urban cover to have an average surface temperature of 38 °C, while green spaces had a lower surface temperature of 34 °C. Yilmaz et al. (2008), based on micro-scale field studies in the Turkish city of Erzurum, found average differences of 11.8 C in surface temperatures between asphalt concrete and grass (there were few trees in this city, and the major type of vegetated cover was grass).

These reports point to the pervasiveness of the urban challenge of ground surface warming, especially in warmer parts of the world where the shade effects of vegetation and trees may be much more important than in north America or Europe – despite which this aspect remains less studied (Popoola and Ajewole, 2001; Escobedo et al., 2008; Jim and Chen, 2009).

This can have major economic implications. For instance, the value of urban forests in terms of providing cooling and reducing electricity consumption for air conditioning in Beijing is estimated to be over 15 million USD per year, while the urban forests of Guangzhou are similarly estimated to provide urban services greater than 92 million USD annually (Jim and Chen, 2009). Thus the economic benefits of street trees in terms of potential amelioration of urban microclimate heating can have potentially substantial economic benefits for Bangalore, as for many other fast growing cities in the tropics.

Differences in humidity were also observed, although these were not statistically signficant. Other research in Colombo, Sri Lanka (Johansson and Emmanuel, 2006) also finds higher levels of humidity on streets with shade provided by trees or buildings – however this study and others (e.g. Jauregui (1991) in Mexico City, Mexico and Yilmaz et al. (2008) in Erzurum, Turkey) also point out the impact of wind speeds in influencing temperature and humidity. In our study, as wind speed and direction were not recorded, we do not have information on this aspect which may potentially influence our results on humidity, as well as on ambient air and road surface temperatures, and on air pollution results.

Air pollution, particularly that of SPM, has an adverse impact on human health, leading to disorders ranging from asthma attacks to an increased incidence of fatalities in premature births (Ghose et al., 2005; Nidhi and Jayaraman, 2007). We find 8 out of 10 roads to have SPM levels higher than permissible limits when there are no trees, with five of these reaching levels twice that of the permissible limits. The presence of trees has a significant role to play in reducing SPM levels, such that only 2 out of the 10 roads that had trees showed SPM levels above safe levels. Yang et al. (2005), in a study in Beijing, conclude that fine scale SPM (below 10 μm) constituted the air pollutant most effectively reduced by urban trees, and these were able to remove an estimated 1261 tons of air pollutants from the city in 2002. Escobedo et al. (2008) modeled the impacts of urban forests on air pollution reduction in Santiago, Chile, estimating total annual removal rates of PM_{10} in urban forests to range from 14.8 to 17.3 g/m^2/yr.

In Bangalore, studies indicate that vehicular traffic contributes as much as 42% of the PM_{10} pollution load, but only 16% of city SO_2 levels (TERI, 2010). In response to increasing volumes of traffic (Léfevre, 2009), road infrastructure expansion activities have led to the felling of tens of thousands of roadside trees in recent years (Nagendra and Gopal, 2010). The species selected for planting have also changed over time (Nagendra and Gopal, 2010, 2011), with an increased preference for species with relatively smaller canopy sizes, such as the mast tree (*Polyalthia longifolia)* and royal palm (*Roystonea regia*) (Agarwal et al., 2013). Species selection can play a major role in impacting the amount of pollution reduction offered by city trees. For instance, it has been suggested that trees with compound leaves, particulate hairs, pronounced leaf tips and complex margins are more efficient at capturing dust and suspended matter (Khan and Abbasi, 2000; Chakre, 2006; Leuzinger et al., 2010). Further research is required to understand the optimal mix of species suitable for planting in tropical cities which can maximize the impacts on microclimatic mitigation and reduction in air pollution.

This study provides a preliminary assessment of the potential role of street trees in microclimate amelioration and air pollution reduction in the tropical, rapidly developing city of Bangalore. Limitations of small sample size, lack of information on wind speed and direction, and lack of sufficient data does not permit the use of rigorous non-parametric tests to examine the role of other potentially confounding factors such as the role of bare soil, ground vegetation and distance of monitors from road segments on our results. In particular, results of our non-parametric correlation suggest that distance between the monitor and the road edge have an influence on SO_2 levels that may influence our conclusions on the relationship between tree cover and SO_2 pollution levels, however the data is not conclusive, or large enough to permit rigorous multivariate analysis to explore this further The study however suggests promising directions for future in-depth research at a larger scale on this issue.

Conclusions

This study provides initial, exploratory insights into the possible environmental benefits of street trees in reducing air temperature, humidity and air pollution in tropical developing cities, where insufficient information is currently available. Results indicate that ambient air temperature, road surface temperature humidity and air pollution are lower in road segments with tree cover in Bangalore, although the small sample size and lack of information on wind speed are potentially confounding factors that may influence our results. While this study provides a preliminary exploration of some of these issues, more extended, in-depth research is required to focus the attention of planners on the role of urban greenery in sustainable city management, a role that has been largely ignored in many developing country cities (Kuruneri-Chitepo and Shackleton, 2011). Tropical cities like Bangalore, where the impacts of warming and air pollution may be especially severe, could benefit from programs of large scale tree planting such as those being undertaken in other cities such as Tshwane, South Africa (Stoffberg et al., 2010), and Guangzhou, China (Jim and Chen, 2009). The results of this research suggest that such tree plantation can have greater impact in microclimatic amelioration and air pollution reduction if conducted in urbanized parts of the city with high public movement such as streets and market places, where in fact most trees have been cut rather than planted in recent years (Nagendra and Gopal, 2010).

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