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Reduction of apparent temperature under urban trees in a hot-humid green area

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Abstract. A thermo-hygrometric analysis was carried out at 9, 12 and 16 hrs, under six groups of urban tree species with different levels of shading, plus a lawn as control area, on a hot and humid day of November 2018 in Campos dos Goytacazes, Rio de Janeiro. Air temperature and relative humidity data were converted into apparent temperature heat indexes (HI). The results obtained were subjected to analysis of variance and, if significant, a regression analysis was performed. Shading indexes were calculated using five fisheye photos taken under each group of tree species, in order to obtain a mean sky view factor (SVF) for each location. Values of SVF and HI of each different evaluation time were subjected to Pearson's correlation analysis. There was a significant difference within the groups of trees at the three evaluation times. The maximum HI (43.91°C) was recorded at midday. On the lawn area, there was a significant positive correlation between the SVF and the HI at different evaluation times, and it was higher at noon. Increased sunlight exposure, due to decreased sky blockage, causes a significant increase in HI.
Keywords: sky view factors; thermal stress; urban parks; urban silviculture

Introduction

Among the factors that affect a system designed for a specific performance, there are some that can be controlled by man and others that cannot. Among the latter are natural forces, for instance, the incident solar radiation that sometimes can cause thermal discomfort (Rizwan et al., 2008).

Although these uncontrollable sources of heat may not be fully controlled, they can be mitigated in urban green areas by using anthropic methods, such as planting urban trees in areas intended for leisure of the population.

The effect of temperature reduction on small green areas, similar to those found in urban areas, is mainly achieved through shadow planning (Oke et al., 1989). Honjo and Takakura (1990) proposed that the existence of several green areas is preferable for reducing the apparent temperature rather than a large green area, within a given space range, reinforcing the importance that small urban fragments of forests contribute to the microclimate.

One of the most commonly used methods for measuring shading is the sky view factor (SVF) calculation and estimative ratios as references. The SVF is an index which shows a portion of the visible part of the sky at any given point. The SVF has already been used for studying the effect of shading levels on thermal comfort researches in green areas and urban parks. For instance, Mahmoud (2011) investigated the relationship of SVF and thermal comfort indexes in the city of Cairo, which is characterized by a hot and arid climate; and also, Ridha et al. (2018) used SVF obtained from a residential complex to perform a series of simulations with different vegetation types in the city of Baghdad.

According to Martini et al. (2013) the microclimatic benefits of tree cover can be estimated by thermal comfort indexes, that consist of the most applied and direct way the planners and designers have to estimate environmental thermal comfort, since in their conception they intrinsically take into account variables that affect the whole thermal perception.

In the last century, about a hundred indexes have been created to explain thermal sensation. These indices may be based on measurements, or on physiological perceptions of the human body when exposed to certain conditions of thermal stress (Blazejczyk et al., 2011).

One of those indices is the Heat Index (HI), which uses the air temperature and relative humidity to explain "how hot it really is" by estimating the apparent temperature (Blazejczyk et al., 2011).

Among researches that used indices based on air temperature and air humidity, the research of Yilmaz et al. (2007) evaluated thermal comfort in areas with different types of surfaces and reported that areas with exposed soil surfaces in full sunlight presented lower apparent temperatures as compared to paved areas also in full sunlight.

Studies on the urban microclimate are fundamental, especially those that seek to investigate the thermal comfort in green areas intended for human leisure, to bring about subsidies for planners that develop projects with characteristics meant to reaching such environmental benefits.

In this context, this research aimed at understanding the extent of the relationship between shading and apparent temperature heat index, by studying groups of tree species regularly planted in rows, providing different levels of shade and sky visibility, on a typical hot and humid day in Northern Rio de Janeiro State, Brazil.

Methods

The study was carried out with groups of tree species planted in rows in the green area at Universidade Estadual do Norte Fluminense Darcy Ribeiro (UENF) (21.76 ° S, 41.29 ° W) in Campos dos Goytacazes - RJ, whose climate is Köppen-Geiger classified as Aw, characterized as a typical humid tropical climate.

Among the landscape elements present at UENF *campus,* there are groups of different tree species in all transition areas between buildings of the institution. There are six groups of species (Table 1) planted in rows forming a uniform grid spacing.

Figure 1 shows the experimental areas, including the lawn with no trees that was taken as control. Data readings were taken simultaneously at five sites within each group of trees (and the lawn), in the central region between the rows and plants excluding the border, at 9, 12 and 16 h on November 3, 2018, with the aid of Hobo PRO V2 thermo-hygrometers registering atmospheric temperature (° C) and relative humidity (% RH) measured at two meters (6.56 feet) of height from the soil surface.

An analysis was carried out to validate the day of sampling as a typical hot-humid day in November, for this purpose data registered for 17 years of the same day and month (November 3) were obtained from INMET/DBMEP platform.

The shading capacity for each group of trees was measured using the SVF (sky view factor). The SVF is a dimensionless number ranging from 1 (one) to 0 (zero) with the maximum value attributed to a full sky view (1= no canopy blockage of the sky), whereas the minimum value corresponds to a completely blocked sky view (0= complete canopy blockage of the sky). The SVF calculation was performed by RayMan 1.2® software (Matzarakis et al., 2009), using photos (Figure 2) that were taken using a 9.5 megapixels (3088x3088) digital camera attached to a fish-eye wide-angle objective lens. Five photos were taken for each group of trees (and lawn) so that simple arithmetic means were obtained and assigned to their respective experimental area.

The temperature and relative humidity data registered were converted into apparent temperature HI (heat index). Rothfusz (1990) presented an equation for estimating HI (Equation 1), which consists of a series of multiple regressions analyses of air temperature and relative humidity, based on the assumptions described on the very first version developed by Steadman (1979).

The calculations were performed using an online calculator available on the NWS (National Weather Service) website, where the atmospheric temperature in ° C or ° F and relative air humidity data were entered so that the HI for each tree group was calculated. The HI is used to explain how temperature is perceived by the human body when temperature and relative humidity are combined (Steadman 1979), and is calculated as follows:

$$HI = -42.379 + (2.04901523 \times T) + (10.14333127 \times RH) - (0.22475541 \times T \times RH) - (6.83783 \times 10^{-3} \times T^2) - 5.481717 \times 10^{-1} \times RH^2) + (1.22874 \times 10^{-2} \times T^2 \times RH) + (8.5282 \times 10^{-4} \times T \times RH^2 - (1.99 \times 10^{-6} \times T^2 \times RH^2)$$

Equation 1 – Heat Index (HI)

Where:
T = air temperature
RH = relative humidity

Although this paper is presenting data in Celsius degrees, the original equation proposed by Rothfusz (1990) uses Fahrenheit degrees.

The HI was built on various assumptions such as body mass, weight, clothing type, wind speed and blood pressure, all of which may vary significantly among individuals. It is possible that under certain specific conditions HI does not correctly explain the apparent temperature. In this sense, the equation is validated when the atmospheric temperature and relative humidity data are higher than 26.6°C and 40% RH, respectively (NWS, date unknown). The physiological effects of the HI equation are described in Table 2.

The atmospheric temperature and relative humidity data were converted to HI and subjected to ANOVA; when significant (p<0,05), regression analysis was applied. In addition, Pearson's correlation test was performed. All statistical analyses were run in Assistat® software.

Table 1. Group of tree species with common name, English common name, and approximate age* in a green urban area at UENF in Campos dos Goytacazes, RJ.

Tree group	*Tree species	Common name	English common name
B	*Chrysophyllum cainito*	Abiu-do-pará	n/a
C	*Handroanthus chrysotrichus*	Ipê-amarelo	golden trumpet tree
D	*Zeyheria tuberculosa*	Ipê-felpudo	n/a
E	*Ceiba speciosa*	Paineira	silk floss tree
F	*Erythrina velutina*	Mulungu	coral tree
G	*Handroanthus heptaphyllus*	Ipê-rosa	pink trumpet tree

n/a = English common name not available; *trees are approximately 20 years old.

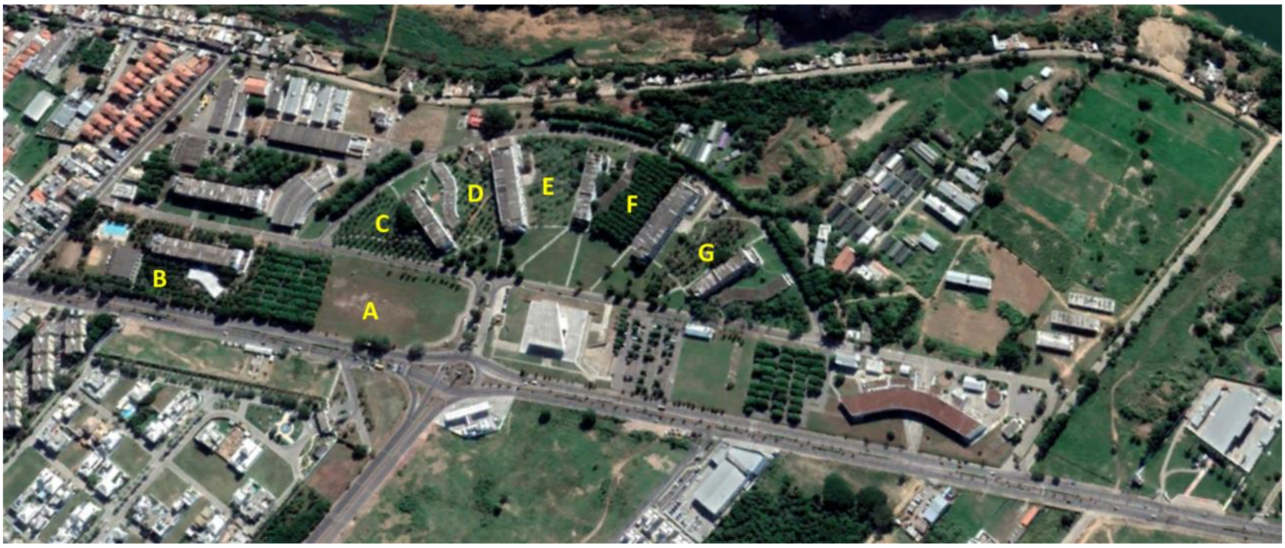

Figure 1. Reference areas of data acquisition: A = open lawn; B; C; D; E; F and G = experimental groups of different trees species. Source: Google Earth Pro/Max Technologies (2019)

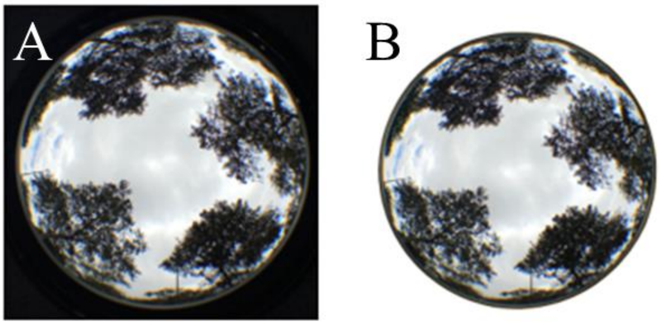

Figure 2. Example of a fish-eye photograph taken: A= Photograph taken; B = Photograph area considered for calculations using the software RayMan 1.2®.

Table 2. Apparent temperature Heat Index (HI) and its respective physiological stress level

Heat Index	Risks	Physiological effects
27-32°C	Caution	Fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
2-41°C	Extreme Caution	Heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
41-54°C	Danger	Heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.
Over 54ºC	Extreme Danger	Heat stroke is imminent.

Source: Steadman (1979)

Results and Discussion

The sampling day (November 3, 2018) presented climatic characteristics that are usual at this time of the year, with both the temperature and relative humidity records within the range of standard deviation of the 17-year historical series for this specific day and month (Table 3).

The HI (heat index) at the three evaluation times showed significant differences; the apparent temperature in area A (lawn) was always higher than under any of the tree species, regardless of evaluation time, reaching the maximum HI, 43.91ºC, at noon (Figure 4). This is classified as a third level risk, i.e., imminent danger in case of continued activity that might result in problems such as cardiac arrhythmia and thermal exhaustion, even followed by a heat stroke (Table 2).

According to data available on the BDMEP platform (INMET, 2019) (data not shown), Campos dos Goytacazes weather station, recorded on November 3, 2018, a thermal range between minimum and maximum temperature of 10.1°C (minimum 21.6°C and maximum 31.7°C) showing a compatible fluctuation of the HI range recorded in the fully exposed lawn area, where the widest range of HI of all evaluated areas was observed.

The HI range for each area indicates that sites with denser tree canopies, hence greater sky blockage, are more resilient to thermal changes than more exposed areas along the day, which present a higher SVF.

Data obtained from the same platform at the same weather station between the years 2000 and 2017 showed that on November 3 the average relative humidity was 75.5% (Table 3).

When high RH is combined with high temperatures, it increases the thermal discomfort, and it is important to point out that both variable levels are commonly registered at that time of the year (Table 2). According to Blazejczyk et al. (2011) when there is a high humidity condition, it is assumed that water evaporation rate is reduced, so water does not evaporate easily from the skin, and hence heat is removed from the body at a lower rate.

Since the areas under evaluation have a uniform planting and each site has only a single species of tree, it makes the SFV values close to each other, therefore, for simplification, the means of the SVF indices were used. As expected, the open lawn area (A) presented the highest SVF with almost no sky blockage, except for fences at the horizon level and some streetlight poles that have few effects blocking the sky view. In contrast, area F composed by *Erythrina velutina* trees, presented the lowest SVF. The mean SVF results and standard deviations are shown in Table 4.

Data analyses showed significant differences among tree species and HI (heat index) temperature at all evaluation times (Table 5): the specific evaluation time, species, organization and architecture of each group of species led to microclimatic peculiarities in each environment under their influence. The regression analyses of SVF as an independent variable, and HI at 9, 12 and 16 hrs are shown in Figures 3, 4 and 5.

Area B (Chrysophyllum caimito) at 9 hrs showed HI values very similar to those of the tree areas with higher SVF (sky view factor). Although additional research has to be made, it is plausible that area B with dense tree canopies, (Table 3) and also denser planting, may have conserved air humidity overnight. Considering that apparent temperature is closely linked to air humidity, it may have caused the lower thermal comfort condition observed in area B at 9 hrs. This phenomenon was not observed at 12 and 16 hrs, when this area presented a lower HI as compared to areas with higher SVF. It was noticed that in area F (Erythrina velutina), which presented SVF similar to area B, the phenomenon did not repeat itself. This could be due to other non-studied variables that may influence air humidity, e.g., wind drafts.

Table 3. Air temperature (AT) and relative humidity (RH) historical series and data observed on November 3, 2018, Campos dos Goytacazes, RJ

	AT at 12 h	AT at 12 h SD	RH	RH S.D
Historical Series[1]	30.2	3.3	75.5	9.1
Single Day Data[2]	31.5	1.1	78.8	5.5

[1] = INMET/DBMEP; AT = Air Temperature (°C); RH = Relative Humidity; SD = Standard Deviation; [2] Sampling data

Table 4. Mean sky view factor (SVF) and standard deviation for the groups of tree species and a lawn in an urban green area at UENF in early November, 2018. Campos dos Goytacazes, RJ

Local	Tree species	Mean SVF	SVF SD
A	Open lawn	0.972	0.013
B	*Chrysophyllum cainito*	0.273	0.014
C	*Handroanthus chrysotrichus*	0.646	0.036
D	*Zeyheria tuberculosa*	0.666	0.087
E	*Ceiba speciosa*	0.507	0.077
F	*Erythrina velutina*	0.225	0.015
G	*Handroanthus heptaphyllus*	0.701	0.051

SVF = Sky view factor; SD = Standard deviation

Table 5. Evaluation time ANOVA summarized data for HI.

VS	DF	SS	F	P-Value
-			9 h	
Treatment	6	5.85	37.28	<0.0001
Error	28	0.73	-	-
-			12 h	
Treatment	6	260.93	99.03	<0.0001
Error	28	12.30	-	-
-			16 h	
Treatment	6	7.70	40.47	<.00001
Error	28	0.89	-	-

VS = variation source; DF = degrees of freedom; SS = square sum; F = Statistic test

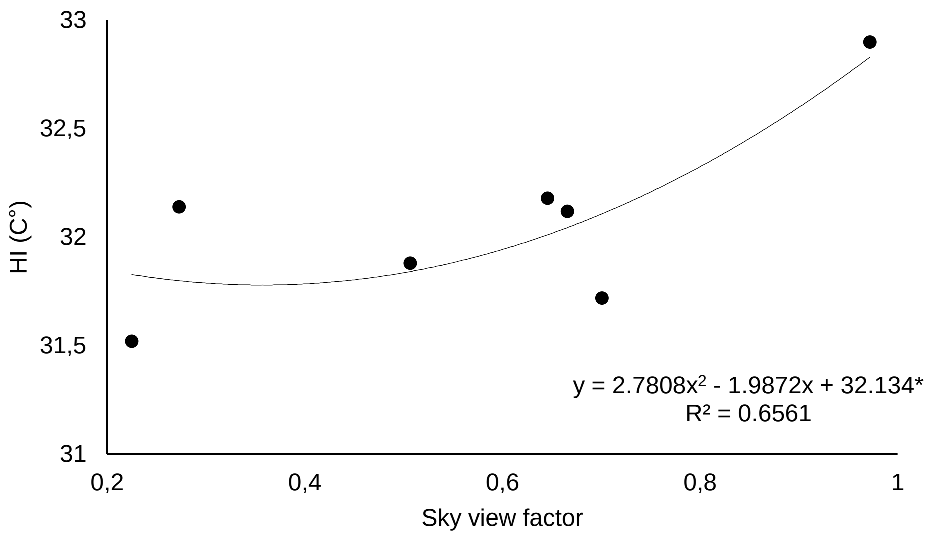

Figure 3. Regression analysis between apparent temperature heat index (HI) and sky view factor at 9 hrs. *Significant at 1% probability level.

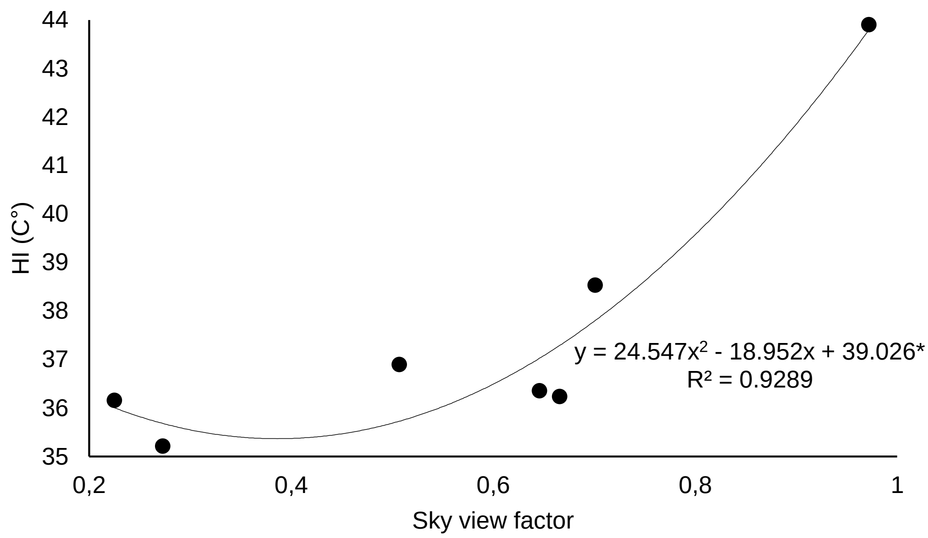

Figure 4. Regression analysis between apparent temperature heat index (HI) and sky view factor at 12 hrs. *Significant at 1% probability level.

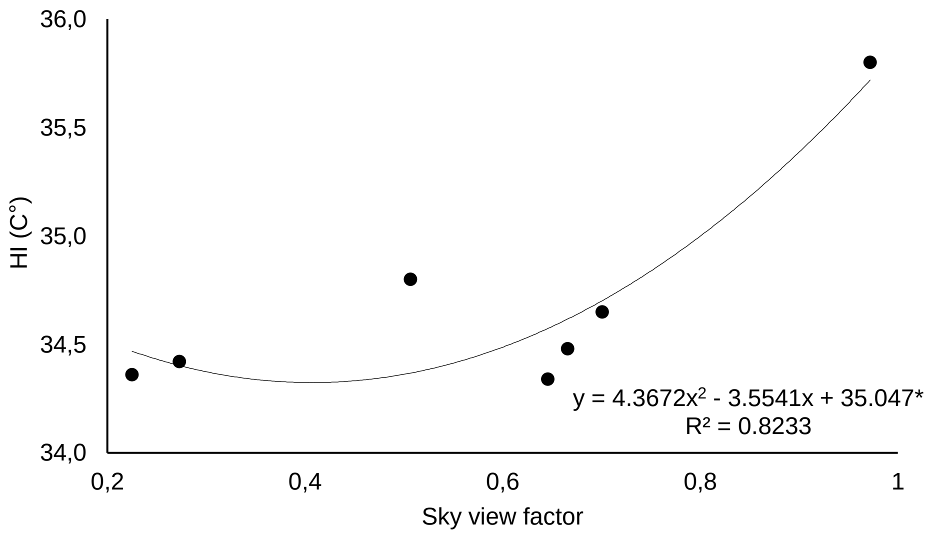

Figure 5. Regression analysis between apparent temperature heat index (HI) and sky view factor at 16 hrs. **Significant at 1% probability level

The correlation between SVF and recording times was strongest at 12 hrs (Table 5), probably because this is the time of the day when incident solar radiation stands out among the other variables, maximizing the effects of shading on apparent temperature. Lin, Matzarakis and Hwang (2010) found that blockages in the visible sky range caused by trees, buildings and other objects, positively influence the thermal comfort, when they investigated the effect of shading on thermal comfort in a humid and hot region using a different index, the physiologically equivalent temperature (PET).

The quadratic behaviour observed in the curves indicates that a specific number of tress, enough to modify the visibility of the sky, may have a significant effect on the HI temperature reduction at the hours of the day when the thermal discomfort is caused, mainly, by direct sunlight incidence, while the air humidity plays a secondary role.

Mahmoud (2011) investigating thermal comfort levels in urban parks in an arid region, also observed that lower SVF indexes made a significant contribution to the apparent temperature reduction by controlling the direct incidence of solar radiation. Thus, preference for species that form large canopies, reduced planting spacing, or some structures such as pergolas that decrease SFV should be considered by planners.

Table 5. Pearson's correlation coefficient between sky view factor (SVF) and apparent temperature heat index (HI)

Variable	Pearson's r			
	SFV	HI at 9h	HI at 12h	HI at16h
SFV	1			
HI at 9 hrs	0.62*	1		
HI at 12 hrs	0.79*	0.68*	1	
HI at 16 hrs	0. 66*	0.60*	0.87*	1

*Significant at the 1% probability level.

Temperature reduction was also observed by Martini et al. (2013) who investigated thermal comfort on the streets of Curitiba-PR and found out that the best rates of thermal comfort were obtained on tree-lined streets, regardless of the time of the year, concluding that tree cover leads to a condition of better thermal comfort for users.

The moderate significant correlation between recording times (9 x 12 hrs; 9 x 16 hrs and 12 x 16 hrs) indicates that the temperature range occurred at some level of linearity, so that it is most likely that the HI obtained at a certain time will reflect at HI from a later time within an uncertain proportionality. Hence, it can be stated that as the SVF increases, so does the HI.

In short, the results imply that trees might help reduce heat discomfort in cities with climatic conditions similar to those observed in Campos dos Goytacazes. Design and planning programs for planting trees in urban areas, provided with strong technical support, should be encouraged for taking initiatives such as planting along the street sides and/or creating structures to block the direct incidence of sunlight, even when there are no vacant lots for stablishing large urban parks.

Conclusion

Tree shades decrease the heat discomfort expressed as apparent temperature heat index. Fully sky-exposed areas should be avoided in urban parks planning for Northern Rio de Janeiro State climate.

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