Proposition of an index for quantifying the amount of vegetated fraction needed for air temperature changes in urban locations

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1. INTRODUCTION

The presence of vegetated spaces in urban areas can affect the thermal field in adjacent streets and even interfere with thermal changes at the urban scale. Due to a selective behavior in different wave lengths, solar radiation can be depleted by trees between 60-90% in visible and infrared wavelengths, respectively, thereby reducing air and surface soil temperature (Labaki et al., 2011; Olgyay, 1998). Underneath dense canopy air temperature drop can reach up to 4°C relative to areas deprived of vegetation (Cohen, Potchter and Matzarakis, 2012; Mascaró, 1996). According to Bowler et al. (2010), based on a review of 24 studies focused on urban parks, vegetated areas can be responsible for a mean daytime reduction in ambient temperature by 0.9°C as compared to nearby areas. The dimensional extent of vegetated areas as well as their distribution over an urban array will have an effect on the magnitude of their thermal impacts.

The aim of the present study is to introduce an empirical index relating the vegetated fraction and ambient temperature changes at pedestrian scale during daytime in summer conditions.

2. METHOD

Curitiba (25.5ºS, 49ºW, 910 a.m.s.l.) is located in a tropical climate zone in a relatively high-altitude region of Brazil (Cfb/Koeppen). It often experiences unstable meteorological conditions with large daily and annual air temperature fluctuations. Average air temperature in summer is approximately 20ºC, though average air temperature in winter is quite low for tropical standards, reaching 13ºC in June/July.

For the present study two urban locations have been chosen for analysis: at a monitoring site at 'Sete de Setembro Avenue', where a linear park is being proposed: at a former industrial artery 'Linha Verde', where a highway is being transformed into an urban avenue with vegetation as guiding element for such redevelopment. The monitoring sites were selected as representative for both areas.

2.1 Monitoring campaigns

Microclimate monitoring was carried out during two days in March (spring) at each location, between 9am to 3pm. For that, a HOBO H21-001 weather station was used, equipped with a three cup anemometer (at approximately 1.9m height), air temperature and relative humidity sensors at 1.3m, a copper gray-colored globe thermometer (Ø=2", painted with RAL-7001) and a silicon pyranometer at 1.6m. The mean radiant temperature was post-processed from wind speed, air and globe temperature data, for forced convection (ISO 7726). Data were recorded in 10-second intervals and sampled for the minute.

Fisheye images were obtained at each point with a Sigma Fisheye 8 mm F-35 attached to a Nikon D80, at an equivalent height of the air temperature sensors (1.3m). Rayman model (Matzarakis, Rutz and Mayer, 2007) was used for generating sky view factors as well as the solar path plotted over the fisheye image.

2.2 Simulation package ENVI-met

ENVI-met 3.1, Beta 5 (Bruse and Fleer, 1998) was used for urban climate simulations of the two areas of analysis. Climate data from official meteorological sites were used as input data in ENVI-met. The INMET station was used in this case, which is located in the east part of Curitiba (http://www.inmet.gov.br/sonabra/maps/automaticas.php).

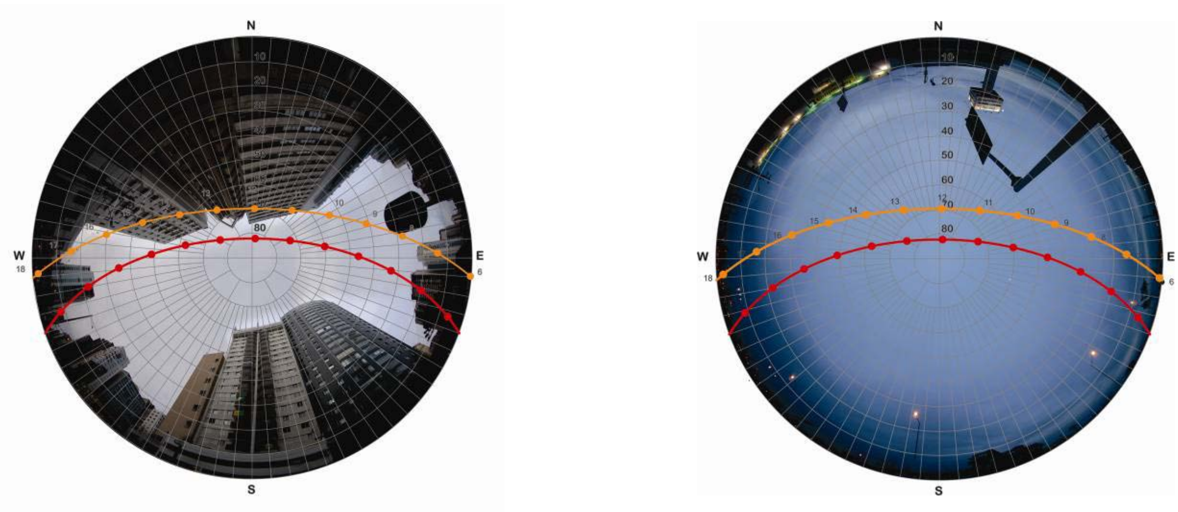
2.3 Modeling

The simulation models of both areas have a grid size of 6m x 6m x 3m (x, y, z, respectively). At Sete de Setembro, the modeled perimeter corresponds to a domain of 840m x 720m which translates to a ~60ha area. Four points of analysis were selected: SS1, SS2, SS3 and SS4. At Linha Verde, the perimeter was 576 m, with a resulting area of ~33ha. Analysis points were LV1, LV2 and LV3.

In both models vertical grids were according to a telescopic factor with 20% increase from about 60m. The nesting area was comprised of five grids. For the sake of simplifying the model asphalt was assumed for the whole model including its borders. For the vegetated areas 15m high trees (LAD: 0,000 0,000 2,180 2,180 2,180 2,180 2,180 2,180 1,720 0,000) as well as grassy surfaces were selected (LAD: 0,300 0,300 0,300 0,300 0,300 0,300 0,300 0,300 0,300 0,300).

2.4 Calibration procedures

Figure 1 shows the solar path (upper curve) corresponding to the monitored days over the background of fisheye images for both points. As existing buildings at Sete de Setembro directly interfere with solar access at the spot, a typical summer day was chosen for testing simulation scenario (lower curve), during which the two points do not have noticeable solar obstructions during the time frame evaluated. Such 'typical day' is a theoretical (probabilistic) condition (Goulart, Lamberts and Firmino, 1998), and corresponds to the solar exposure on January 28.



(a) (b)

Fig 1 – Fisheye image with sun path for (a) Sete de Setembro and (b) Linha Verde

For the typical day input data for ENVI-met were average wind speed/direction and air humidity as given by the typical summer day. Ambient temperature was for neutral atmospheric conditions at midnight. Specific humidity data used was from atmospheric soundings (University of Wyoming's http://weather.uwyo.edu/upperair/) (Table 1). Solar adjustment factor for shortwave radiation was 1.2. Boundary conditions were defined according to the option 'forced'. The first 33 simulated hours were not used, as this period was adopted for reaching steady-state conditions.

Tab 1 – Input data for a typical summer day

Variable	***Sete de Setembro / Linha Verde***	***Configuration***
Start	*00:00:00*	*Neutral atmosphere*
Wind speed (m/s)	*3.2*	*Daily avg*
Wind direction (azimuth degrees)	*90*	*Daily avg*
Roughness length	*0.1*	*From literature*
Air temperature (K)	*293.6*	*At midnight*
Specific Humidity at 2500 m (g/kg)	*9*	*Atmospheric soundings*
Relative Humidity (%)	*80*	*Daily avg*

2.5 Simulation scenarios

Figures 2 and 3 present the urban planning proposals for both sites. Built spaces are represented in grey, vegetated grassy areas are in light green and trees are in dark green.

Fig 2 – Sete de Setembro

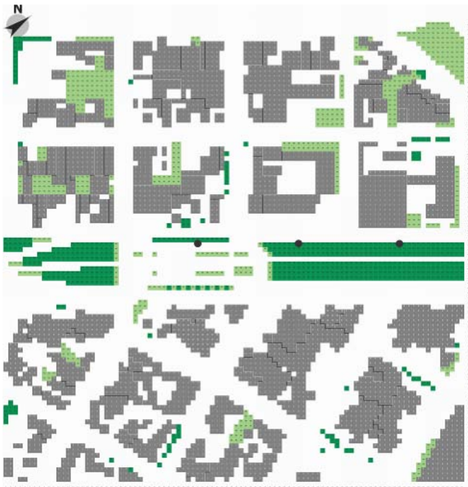


Fig 3 – Linha Verde

3. PROPOSITION OF AN INDEX

The index was developed so that the thermal effect from vegetated areas could be correlated to ambient temperature changes. For a given perimeter, the vegetated fraction over a given built-up area is related to changes in ambient temperature. The index is based on simulation results from a model which was calibrated from field measurements, therefore it is considered to be empirical by nature. The ENVI-met gives the mean Ta for each grid and at a height of 1.5m (pedestrian scale).

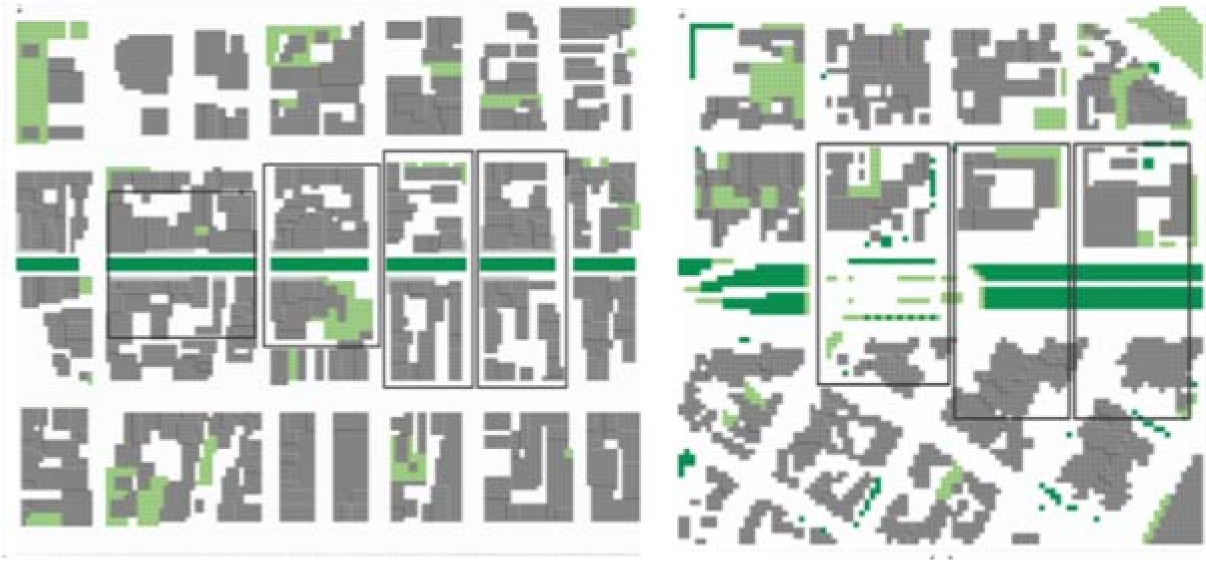
The first step consisted in defining a viable perimeter for the two planning models. The size of the area of influence (perimeter) should be compatible for all evaluated points at both sites, for that a standard area equivalent to 4.0ha was defined (Tables 2 and 3). Discrete regions in each model were then studied: four areas of analysis at Sete de Setembro and three at Linha Verde, as highlighted in Figure 4.

Tab 2 – Perimeter and area of analysis at Sete de Setembro

Point	***Axis***	***Number of grids***	***Grid size (m)***	***Total (m)***	***Area of analysis (ha)***
SS1	*x*	*27*	*6*	*162*	*4.0*
	y	*41*	*6*	*246*	
SS2	*x*	*34*	*6*	*204*	*4.0*
	y	*33*	*6*	*198*	
SS3	*x*	*21*	*6*	*126*	*4.1*
	y	*53*	*6*	*318*	
SS4	*x*	*21*	*6*	*126*	*4.0*
	y	*53*	*6*	*318*	

Tab 3 – Perimeter and area of analysis at Linha Verde

Point	***Axis***	***Number of grids***	***Grid size (m)***	***Total (m)***	***Area of analysis (ha)***
LV1	*x*	*25*	*6*	*150*	*4.0*
	y	*44*	*6*	*264*	
LV2	*x*	*22*	*6*	*132*	*4.0*
	y	*50*	*6*	*300*	
LV3	*x*	*22*	*6*	*132*	*4.0*
	y	*50*	*6*	*300*	



(a) (b)

Fig 4 – Selected regions: (a) Sete de Setembro and (b) Linha Verde

It should be stressed that average ambient temperatures are given for the region as a whole, and not for a particular point. For each square in the maps, changes in vegetated fraction and building density were assessed and simulated.

Changes in greenery refer to the horizontal 2D projection of trees with dense canopy in each grid section, which was added to the original scenario (grassy surfaces, when existent, remained unchanged). The built-up area was calculated by the sum of the horizontal projection of buildings and the four wall surfaces according to individual heights of each building, thus it is termed "3D built-up surface area". The two parameters yielded the 'vegetated fraction' VF (VF = *vegetated cover / 3D built-up surface area)* for each area of analysis, which was then linearly correlated to ambient temperature changes (Equation 1) from simulated results (Table 4).

$$Ta_{changes} = coef.a*VF + coef.b \qquad Eq.1$$

Tab 4 – Results for air temperature changes as a function of vegetated fraction

Point-Area	***Vegetated cover (m^2)***	***Built-up area (m^2)***	***Built-up surface area (m^2)***	***Vegetated fraction VF***	***Mean Ta reductions (°C)***
SS1	*2376*	*11412*	*41119*	*0,21*	*0.24*
SS2	*3672*	*25668*	*63687*	*0,14*	*0.31*
SS3	*1944*	*24696*	*66228*	*0,08*	*0.34*
SS4	*1836*	*18864*	*56011*	*0,10*	*0.41*
LV1	*4140*	*12996*	*16245*	*0,32*	*0.58*
LV2	*828*	*9288*	*12052*	*0,09*	*0.42*
LV3	*5544*	*12780*	*15598*	*0,43*	*0.63*

Vegetated fraction can explain changes in ambient temperature (reductions in summer) by 78% (Pearson r-value = 0.89). From the generated regression equation ($Ta_{changes}$=0.9743*VF+0.2994) estimates can be drawn for the required change in vegetated cover in order to reach mean ambient temperature drop by 1°C (Table 5), whereas keeping the 3D built-up area unchanged.

Results suggest that in order to reach a 1°C drop in air temperature by means of increasing vegetated cover substantial changes, in some cases not feasible, would be necessary. The vegetated area required for offsetting the thermal effect by 1°C in heavily built-up areas would surpass the physical space available (SS2, SS3, SS4). Indeed, by drawing a direct relationship between the vegetation cover and the 3-dimensional building density (3D built-up area / overall area), also accounting for the existing building density, a limit of approximately 0.85 is found for the 3D building density. Interestingly, the building density, obtained from the simple horizontal projection of buildings is not as good an indicator as the 3D building density –taking SS1 as an example, with a building density lower than LV1, LV2 and LV3, the required coverage of the area with trees would surpass the physical limit of the overall area.

Tab 5 – Estimates for required vegetated cover for a 1°C ambient temperature drop (mean for an approximately 4.0ha urban area)

Point-Area	***Required VF***	***Required vegetated cover (m^2)***	***Required coverage of the 4.0ha area with vegetation (%)***	***Building density (2D projection)***	***3D Building density***
SS1	*0,72*	*29568*	*74*	*0,29*	*1,03*
SS2	***0,72***	***45796***	***113***	***0,64***	***1,58***
SS3	***0,72***	***47623***	***119***	***0,62***	***1,65***
SS4	***0,72***	***40276***	***101***	***0,47***	***1,40***
LV1	*0,72*	*11682*	*29*	*0,33*	*0,41*
LV2	*0,72*	*8666*	*22*	*0,23*	*0,30*
LV3	*0,72*	*11216*	*28*	*0,32*	*0,39*

4. Conclusions

The application of the developed index is primarily for urban planners. It has been shown that increases in vegetation will not bring substantial results to high-density urban settings. The index developed is meant to be as general guidance for planners, using readily available information. As it requires only the 2D projection of buildings and the average height of buildings over the area of analysis, it can be of benefit for defining land-use policies, plot size and building heights as well as the coverage of trees in preliminary master plans. The intention however is not that such index should be used as a predictive tool, but as general guidance for climate-responsive urban planning.

The limitations of the index are related to the small number of urban situations analyzed; relationships should be drawn for other areas and also for other climatic conditions in future studies.

Acknowledgements

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