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ARE GREEN WALLS A SUITABLE ENVIRONMENTAL COMPENSATION IN DENSIFYING CITIES? QUANTIFYING THE URBAN MICROCLIMATE EFFECTS AT THE PEDESTRIAN LEVEL IN SAO PAULO

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ABSTRACT

In the city of Sao Paulo, green spaces are few and uneven. Between 2015-2018, to increase greenery, the municipality promoted green walls as an environmental compensation solution for the loss of urban trees. This study aimed to quantify the impact of these green façades on urban microclimate at the pedestrian level, considering the following variables: air temperature, air humidity, and mean radiant temperature. We reviewed local planning documents and the microclimatic performance of green wall technologies, establishing the effects of wall greening based on simulations — using the ENVI-met V4 Science model. Although the main difference was measured 15 cm far from the walls' surface, the 60 cm away differences from the green wall were insignificant. The results indicate: (a) the impact of the green walls on outdoor microclimates at the pedestrian level is minimum, and (b) Sao Paulo's policy for environmental compensation using green walls was poorly supported by scientific evidence. Therefore, green walls are a highly questionable alternative for environmental compensation from the perspective of urban microclimate. As much as promoting green walls for potential benefits is desirable, they are unsuitable to compensate the range of ecosystem services lost by the elimination of trees.

Keywords: Green Walls. Urban Greenery. Urban Microclimates. Urban policies. ENVI-met. Environmental compensation.

RESUMO

Na cidade de São Paulo, os espaços verdes são poucos e irregulares. Entre 2015-2018, para aumentar a vegetação, o município promoveu os muros verdes como solução de compensação ambiental pela perda de arborização urbana. Este estudo teve como objetivo quantificar o impacto dessas fachadas verdes no microclima urbano ao nível do pedestre, considerando as seguintes variáveis: temperatura do ar, umidade do ar e temperatura radiante média. Revisamos os documentos de planejamento local e o desempenho microclimático das tecnologias de paredes verdes, estabelecendo os efeitos do esverdeamento das paredes com base em simulações — usando o modelo ENVI-met V4 Science. Embora a principal diferença tenha sido medida a 15 cm da superfície das paredes, as diferenças de 60 cm da parede verde foram insignificantes. Os resultados indicam: (a) o impacto das paredes verdes nos microclimas externos no nível do pedestre é mínimo, e (b) a política de compensação ambiental de São Paulo usando paredes verdes foi pouco apoiada por evidências científicas. Portanto, os muros verdes são uma alternativa altamente questionável para compensação ambiental sob a ótica do microclima urbano. Por mais que seja desejável promover muros verdes para benefícios potenciais, eles são inadequados para compensar a gama de serviços ecossistêmicos perdidos pela eliminação de árvores.

Palavras chave: Paredes verdes. Vegetação urbana. Microclimas urbanos. Políticas urbanas. ENVI-conhecido. Compensação ambiental.

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1. INTRODUCTION

Considering the lack of knowledge about the benefits of green walls to subtropical climates, this research was especially motivated by the decision of the city of Sao Paulo, in 2015, to allow the installation of a modular system of green walls as a compensation for the felling of urban trees for building construction in the already densely built city centre (Municipal Law nº 16402, of March 22, 2016. It disciplines the parcelling, use and occupancy of the land in the Sao Paulo Municipality. Sao Paulo City Official Gazette, 61). Moreover, the green walls were meant to improve urban climates in the high-density inner city of Sao Paulo, where air temperatures are much elevated when compared to outside the city (i.e. the urban heat island effect (Oke et al., 2017)), and thermal comfort for pedestrians is much reduced on hot days (Duarte et al., 2015; Ferreira, 2019).

Urban green areas contribute to reducing the urban warming effects as well as human thermal stress (Bowler et al., 2010; Zölch et al., 2016). Since thermal stress is affected by climatic energy exchange, the presence of vegetation may have a strong influence, reflecting a great part of incident radiation. Evapotranspiration allows lower temperatures on the surface when compared to paved surfaces (Snir et al., 2016). Soil moisture affects the replenishment of the water lost in transpiration; since a wetted soil allows an easy water extraction, whereas a dryer soil hinders water extraction by the roots (Bonan, 2016). Green urban areas can increase air humidity and minimize human thermal stress, encouraging physical activities and promoting social interaction and community cohesion (Brown et al., 2016; Santamouris, 2014).

Tree canopy contributes to decrease the diurnal air temperature, reducing human thermal stress, due to the evapotranspiration, and providing shadow. Tree's performance on human thermal comfort differs according to the climate and plant typology; however, many authors agree that the shadow effect associated with the evapotranspiration makes trees the best option to improve the microclimate and the human thermal comfort (Coutts et al., 2016; Kong et al., 2017; Shashua-Bar et al., 2012; Wong et al., 2010). To quantify the processes related to the leaves performance and the greenery feedback to the climate system, the most appropriated variable is the leaf area index (LAI). Chen and Black (Chen & Black, 1992) define LAI as one half of the total green leaf area per unit horizontal ground surface area. LAI is a critical variable in all the processes developed by the leaves (Fang et al., 2019), directly affecting the evapotranspiration and shade properties of the greenery.

Greenery also provides benefits to the buildings and their occupants, for example: energy-savings, as a consequence of shading, and the opportunity to directly interact with a restoring environment, capable of improving human comfort. The positive psychological effects increase workers' productivity (Mangone & van der Linden, 2014; Wong et al., 2010).

Urbanization is one of the causes of the decrease in plant coverage in urban areas. An action to prevent, mitigate and compensate the impacts of plant coverage decrease is the environmental compensation public policies in different cities throughout the world (Souza, 2017).

The environmental compensation is an agreement with the municipal public authority to provide a compensation for the environmental damage caused by a real estate development. The main idea is to require sufficient high trade-offs to discourage vegetation decrease. The obvious solution requires the plantation of more new younger trees than the removed ones (Coelho, 2009). However, the Municipal Secretariat for Environment of the Sao Paulo Municipal Government in its Environmental Agreement Term (TCA) allows the compensation of urban vegetation loss as services or public works that can be paid by funds or works, including the installation of green roofs and green walls — article 4° of Decree 53889 in force from 2015 to 2018 (Municipal Law nº 16402, of March 22, 2016. It disciplines the parcelling, use and occupancy of the land in the Sao Paulo Municipality. Sao Paulo City Official Gazette, 61).

Furthermore, the current law regarding plant coverage suppression in Sao Paulo is unclear about the criteria considered for environmental compensation definition, which resulted in a parliamentary commission procedure to investigate irregularities (Sao Paulo municipality, 2015). Ferreira (2018) reveals that the environmental compensation did not increase plant coverage in the Vila Andrade neighborhood, highlighting the need to revise the current legislation.

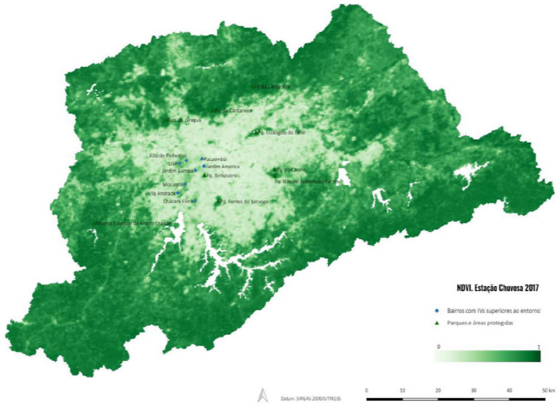
Law nº 16050, of July 31st, 2014, established that the environmental compensation of urban vegetation loss must be held by equivalent species and size, forbidding the environmental compensation by the green walls and green roofs. However, the decree nº 55994 of March 3rd, 2015, established exceptional environmental compensation using green walls and green roofs allowed by the analysis and decision of the Technical Environmental Compensation Chamber. The decree nº 56630 allows cooperation with the private sector, aiming to implement and maintaining public green walls. On November 25th, 2016, Law nº 0584/15 came into force as a financial incentive of 5% decrease of the Property and Urban Territorial Tax to green walls installation.

Despite numerous studies quantifying the effect of green surfaces on the thermal performance of buildings and their benefits for indoor microclimates and cooling energy demand of buildings (Antonyová et al., 2017; Besir & Cuce, 2018; Gunawardena & Steemers, 2019, 2020; Zhang et al., 2019), the knowledge regarding their effects on the tropical urban climates has a limited availability (Gill et al., 2007; Li et al., 2019; Widiastuti et al., 2018; Wong et al., 2010), and even less considering subtropical climates (Yang et al., 2018; Zhang et al., 2019). In Brazil, a country with continental dimensions and several distinct climates (Matheus et al., 2016), the division of the studies can be between the benefits of the green walls to indoor microclimates using prototypes and simulations carried out by Building Energy Models (Morelli, 2016; Sousa, 2020), and their impact on outdoor microclimates, using prototypes and simulations carried out using urban microclimate models (Alchapar et al., 2017; Boa Sorte, 2016; Matheus et al., 2016).

2. Study area and site

The Sao Paulo metropolitan area is the fourth largest in the world with around 21.6 million inhabitants (Instituto Brasileiro de Geografia e Estatística, IBGE, 2020). The estimated population of the city of São Paulo is 12,3 million inhabitants (IBGE, 2010). The current population growth is at 0.76% p.a. (IBGE, 2010), on a surface area of 1.521,11 km2 (IBGE , 2010). The city is the main Brazilian economic center (Comin, Oliveira, Torres-Freire, & Abdal, 2010), located at 23°32'S, 46°37'W, 60 km away from the sea. The altitude varies between 720 m and 850 m. The climate is subtropical (Cfa according to Köppen classification) with mild temperatures.

Despite having a vegetation index higher than the suggested by World Health Organization, the Sao Paulo metropolitan area has a greenery deficit due to the vegetation suppression caused by urbanization; the city of Sao Paulo has one of the lowest vegetation indexes in Brazil, with 16.59 m² of greenery per inhabitant, unequally distributed in Sao Paulo's urban area (Rede Social de Cidades, 2017). Figure 1 shows the contrast between the city and the metropolitan area through the Normalized Difference Vegetation Index (NDVI).



Traduzido da Figura 1-legenda à direita: NDVI. Rainy Season 2017 Neighborhoods with VI superior to the surroundings Parks and protected areas

Figure 1 - Normalized Difference Vegetation Index of the Sao Paulo Metropolitan Area (Fer-reira, 2019).

Among the first areas where the Decree nº 5663 regulations were applied, the Elevado Presidente João Goulart (Minhocão) is a 3.5 km elevated roadway, which connects the city center to the Barra Funda neighborhood. Inaugurated in 1971, Minhocão caused the devaluation of the area — consequence of environmental degradation — and always generated discomfort, especially to the surrounding buildings, due to the air, sound and visual pollution, since at many points, the roadbed is less than 5 m far from the apartments windows (Fig.2).

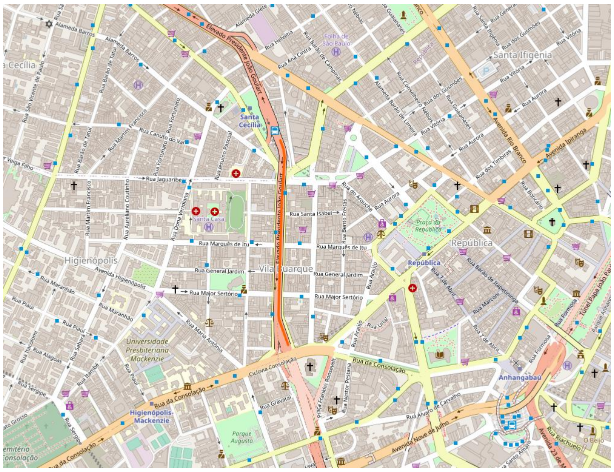


Figure 2- Elevado Presidente João Goulart (Source: Openstreetmap.org; Pauleit, 2018).

The Tishman Speyer company celebrated the first agreement to compensate vegetation loss in green walls. Therefore, to reduce the mentioned discomforts and to promote valorization to the area, the company concerned a real estate development located in the Morumbi neighborhood, where instead of planting 26,281 trees, they should install eight green walls (Rede Nossa São Paulo, 2017).

Six buildings received green walls as part of this environmental compensation in September 2015, which in March 2017, expanded to a retaining wall located along the 23 de Maio Avenue, an important municipal north-south road axis.

The environmental compensation on green walls in Sao Paulo has been questioned by different official entities, under the argument that this kind of environmental compensation would configure deviation in the use of the resources of the Special Fund for the Environment and Sustainable Development.

The final report of the Parliamentary Commission of Investigation highlights that even considering the landscape adorn provided by the green walls and green roofs, adult trees pro-vide s more environmental services than this solution. Green walls have different foliar mass, performing less photosynthesis and evapotranspiration, also because they do not improve the soil permeability, and they are highly dependent on artificial irrigation (Sao Paulo, 2015).

Moreover, in the agreements between the companies interested to make the environ-mental compensation and the apartment buildings using green walls, the cooperation terms have a three-year maximum term of validity (Article 14°, Decree 56630, of November 19th, 2015). After this period, the building managers decide if the dwellers want to continue with the cooperation or to remove the green walls, giving an expiry date for this vegetation and the supposed benefits offered by it.

3. Methodology

A literature review was conducted to identify public policies that consider green inclusion in urban areas and if the environmental compensation allowed by Sao Paulo municipality was acceptable in other public guides. Similar reference to the policy was not found (Kruuse, A, 2011; City of Seattle, 2015; Landschaft Planen & Bauen, 1990).

To provide numerical answers, a quantitative approach was adopted with a simulation using the ENVI-met V4 Science model (Bruse & Fleer, 1998).

Considering the model constraints, field measurements were carried out, between December 5th to 9th, 2016, to perform the model calibration and validation to the subtropical climate. During the field measurements, the Leaf Area Density (LAD) was also conducted counting onsite, to establish the LAD values to be used as simulation input. The empiric counting was suggested by Helge Simon one of the ENVI-met developers during Dr. Paula Shinzato internship at Johannes Gutenberg-University, Mainz (2016).

The empiric counting established an average value of 500 leaves/m^3 from an imaginary cube of 50 x 50 x 50 cm (Fig. 3). The leaf area calculated was 0,00315 m^2, and consequently LAD=1,5 m^2/m^3 from the function:

$$\text{LAD}= \frac{\text{leaves number x leafe area}}{1\text{m}^3} \qquad (1)$$

Figure 3 – Imaginary cube to LAD counting

4. Microclimatic modeling approach and modeling setup

The choice of using the ENVI-met V4 Science model for the microclimatic simulations; considered the advanced approach of this three-dimensional model to the interactions between soil, vegetation and atmosphere, which made it one of the most appropriated models to carry out the intended microclimate analysis (Bruse & Fleer, 1998; ENVI-met, 2020).

A schematic building and its immediate surroundings were simulated using Trianon Park coordinates. The variables air temperature, humidity and mean radiant temperature were parametrically evaluated to quantify the potential microclimatic impacts for several green wall scenarios as the design and systems used influence the green wall systems. Although the continuous living wall system can provide more effective results in decreasing temperature than direct systems (Jaafar et al., 2013), limitations on ENVI-met V4 Science made it necessary to carry out the computational simulation using a direct green façade system.

Considering the need to adapt the model to the climbing walls, the vegetation modeling was done in 1D to achieve a homogeneous effect, with the leaves starting near the ground level.

The model developed on ENVI-met V4 Science (Bruse & Fleer, 1998) was based on a 1 x 1 x 1 m grid (x;y;z), with a total modelled area of 60 x 60 cells, characterized by a single building with 10 x 10 x 15 m (x, y, z), located at the center of the model surrounded by climbing walls 1 m away from all of its façades (Fig. 6).

Scenarios with and without vegetation located 1 m away from the walls were tested to analyse the impact of LAI variation on air temperature, using the domain averages. The minimum value adopted for the soil moisture to prevent hydric stress during the simulation was 50% (Shinzato et al., 2019). Afterward, the same scenario was simulated using 60% relative soil moisture for comparing the results. LAI varied in the scenarios between LAI from 0.5 to 2.0 m^2/m.

We considered the following microclimate environmental variables: air temperature, air humidity, air velocity, Mean Radiant Temperature (MRT), and Specific Humidity. The results were extracted in extreme situations, at 6 a.m., considering the minimum air temperature; at 2 p.m., the highest air temperature observed in the city, and at 10 p.m., to observe the night cooling effect.

As the field measurement was performed far from the study area, due to the technical impossibility to ensure the equipment safety against vandalism, data from Shinzato (2019), measured in April 2016 in Tenente Siqueira Campos Park (Trianon), located at the vicinity of the Elevado Presidente João Goulart, were used as input data. The simulation considered 30 hours, and Table 1 illustrates the input parameter settings. The results were extracted at 1.50 m high from the soil, to analyse the impact at the pedestrian level. In April, the incidence of the sun in the model for Sao Paulo comes from the Northwest, and the predominant wind comes from 135° Southeast; the wind velocity was 1 m/s and the roughness 0.01 m, to minimize tur-bulences.

Table 1 - Input parameter settings (Shinzato, 2019)

Simulation start (date and time)	02/04/2016 9 p.m.
Total simulation time	30 hours
Wind velocity	1m/s
Wind direction	135° (North=90)
Roughness length at measurement site	0.01 m
Initial atmospheric temperature	0.0 K
Specific air humidity at model top 2500 m	9.0 (g Water/kg air)
Relative air humidity (h=2 m)	75.8%
Initial temperature first layer of soil 0 – 20 cm	294.00 K
Initial temperature for the second layer of soil 20 – 50 cm	293.00 K
Initial temperature for the third layer of soil < 50 cm	296.00 K
Soil moisture for the first layer of soil 0 – 20 cm	60%
Soil moisture for the second layer of soil 20 – 50 cm	70%
Soil moisture for the third layer of soil < 50 cm	75%
Calculation of stomata resistance (1=Deardorff, 2=A-gs)	2
CO_2 concentration	400 ppm

The soil parameter adopted was developed by Gusson (2016) and Shinzato (2016) considering Brazilian conditions, and adding to ENVI-met data bank asphalt used on the road and sandy-clay-brick used under the vegetation (Fig. 4).

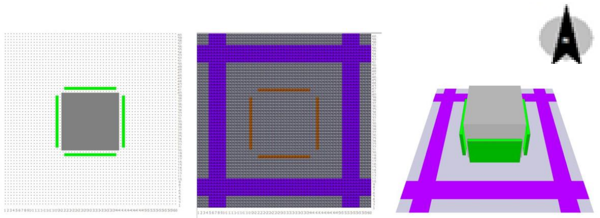


Figure 4 - Modeling for parametric scenarios of a general building and its immediate sur-roundings.

Seven parametric simulations were carried out based on the greenery presence or absence, soil moisture 50% or 60%, and LAI variations, by comparing the variables air temperature (°C), surface temperature (°C), average radiant temperature (°C) and specific humidity (g/Kg) (Table 2).

Table 2 – Parameterization of the simulation scenarios

Soil Moisture	Leaf area index (LAI)
Without Greenery (Soil moisture disregarded due to the pavement)	-
50%	0.5
50%	1.0
50%	2.0
60%	0.5
60%	1.0
60%	2.0

5. Simulation Results

The increase in soil moisture from 50% to 60% without varying LAI showed a maximum decrease of 0.60°C in the air temperature at 30 cm height and 1 m from the green wall; also a maximum decrease of 0.36°C in the air temperature at 1.5 m height.

When comparing the scenarios without and with green walls varying the LAI to soil moisture 50% at 6 a.m., shortly before sunrise, we observed a maximum air temperature decrease by 0.12°C, 0.25°C and 0.55°C, relative to the increment of LAI from 0.5 to 2.0 m²/m.

During the day, the stomata evapotranspiration effect on air humidity can increase 1.0 g/kg, at 26°C air temperature, as air temperature can decrease when comparing to the scenario without vegetation. The successive increases in LAI, to soil moisture 50% at 2 p.m., presented a respective air temperature decrease of 0.17°C, 0.36°C and 0.68°C, particularly leeward. Confirming the influence of soil moisture on evaporative cooling (Fig. 5), a 60% soil moisture reduces the air temperature at 0.44°C, 0.66°C and 0.99°C,.

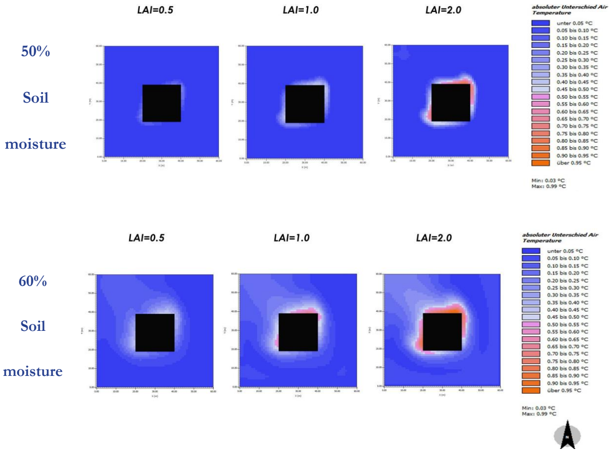


Figure 5 - Air temperature difference with LAI=0.5 m²/m², LAI=1.0 m²/m² and LAI=2.0 m²/m², 50% and 60% soil moisture at 2 p.m., h=1.50 m.

Without the greenery evapotranspiration effect at 10 p.m., we observed a more significant wind effect on cooling, and lower air temperatures on the windward side (Fig. 6 and 7).

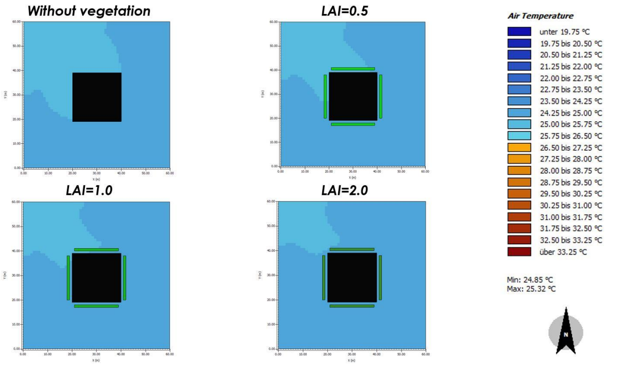


Figure 6 - Air temperature with relative soil moisture of 50% in the scenarios without vegeta-tion and with vegetation for LAI=0.5 m²/m², LAI=1.0 m²/m² and LAI=2.0 m²/m² at 10 p.m.

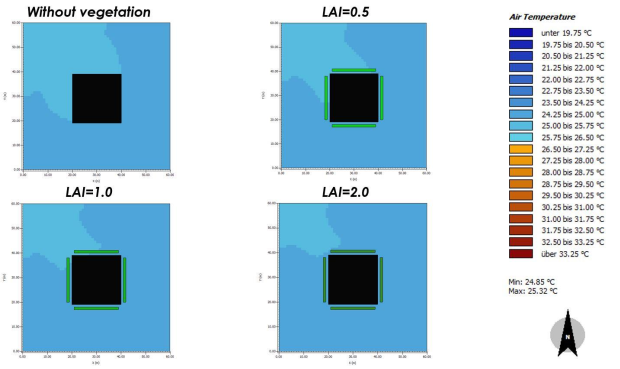


Figure 7 - Air temperature with relative soil moisture of 60% in the scenarios without vegeta-tion and with vegetation for LAI=0.5 m²/m², LAI=1.0 m²/m² and LAI=2.0 m²/m² at 10 p.m.

We also analysed the LAI influence on the specific air humidity, considering the 50 % soil moisture at 2 p.m. Although we observed effects from evapotranspiration up to 4 m far from the building leeward, the maximum variation in specific humidity observed was 1.0 g/kg, for 26 °C air temperature in the first grid of cells close to the vegetation.

Figure 8 shows an average result of LAI and soil humidity variation impact on the specific air humidity, between 4 a.m. and 11 p.m., in which an increase in LAI is responsible for an increase in specific humidity from 8 a.m. to 6 p.m. The increment on soil moisture was irrelevant to the specific air humidity. However, from 6 p.m., as the model considers stomata closed, the increment on soil moisture results in a decrease in specific humidity.

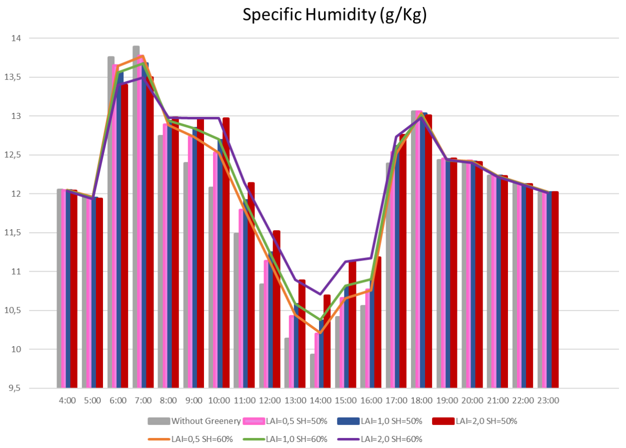


Figure 8 - Specific humidity variation, LAI=0.5 m²/m², LAI=1.0 m²/m² and LAI=2.0 m²/m², 50% and 60% soil moisture.

The effects of green walls on MRT are almost imperceptible in outdoor microclimate under solar radiation effect, despite the LAI increment. The vegetation shadow effect results in small MRT decrease, whereas the soil moisture increase to the same LAI value. An increase in relative soil moisture decreased 0.01°C of the greenery MRT and 0.03°C in MRT between greenery and the building wall. However, the effect on human thermal comfort on the pedestrian level depends on how close the greenery is, as corroborated by Morakinyo et al. (2019).

6. Discussion

Despite diverse benefits of green walls to indoor spaces, as the reduction of indoor temperatures and the consequent need for air-conditioning systems (Wong et al., 2010; Safikhani et al., 2014), the results confirm the localized microclimatic effects of the climbing green wall and a distinct behavior between daytime and night time, as previously observed by Wong et al. (2010) in Singapore. According to Wong's study, the most important temperature difference was measured 15 cm away from the surface. Whereas differences were insignificant 60 cm away from the green wall, the results observed by this work are also supported by other studies that found significant measured benefits only close to the vegetation (Daemei et al., 2018; Pan, Wei, & Chu, 2018; Zhang et al., 2019).

During the day, the evapotranspiration effect is clearly observed, and at night convec-tive changes influence more the cooling, indicating a different performance of the green walls between day and night time, as also evidenced by Acero et al. (2019) in their study for Singa-pore.

Considering the variable specific air humidity, the results suggest that LAI is directly responsible for the increase in specific humidity, due to leaf evapotranspiration, in which the effect of soil moisture increase is slight, between 0.1% and 0.3%.

We also observed the model sensitivity to the wind direction; determined as 135°, and responsible for extending the greenery impacts in the same direction, except for the MRT vari-able.

The localized microclimatic effect of green walls contrasts with the trees performance due to the shading area provided by the canopy, as demonstrated by Zölch et al. (2016) and Coutts et al. (2016).

Regarding the carbon storage between green walls and urban trees, the trunk is the main element to store the carbon. This is different on green walls, since they only leaves com-posed of circa 98% water, which store low carbon. Moreover, the tree environmental services to the human quality of life are: shade, increasing of air moisture; reduction of particulate ma-terial in the air; groundwater recharge; among others (Buckeridge et al., 2018).

The high implementation and maintenance costs (Buckeridge et al., 2018), associated to the minor impact on outdoor microclimates demonstrate that the Sao Paulo environmental compensation policy, which establishes the possibility to replace urban vegetation loss using green walls, was mistaken and non-evidence-based regarding urban microclimate benefits.

Green walls technologies adopted by the Sao Paulo municipality are dependent on support, nutrition and irrigation technology systems, which are essential to undergo continuous maintenance. Sao Paulo is a city that historically neglects attention to the necessary greenery, causing accidents every summer due to the lack of maintenance of the urban trees and the increment of rainfalls in the summer season, raising the question regarding the durability of the environmental compensation proposed.

The analysis of the public policies on environmental compensation reported herein and the inherent needs of the adopted green systems, hypothesized that the environmental agreements would not be honored and the installed green walls would not have an adequate maintenance. The environmental compensation using green walls had as a result legal claims made by the buildings residents requesting the structure removal (R7, 2019). In September, 2020, a contracted cost of circa US$200.000,00 payed by the municipality initiated the removal of the green walls, reducing the useful life and ecosystem services of these green walls to less than four years (Folha de S.Paulo, 2020). Considering that the compensation policies using trees establish that an accepted tree to be used in environmental compensations has to meet some requirements as a minimum 2.5 m high, a four-year old compensated tree is in full force, normally without needing expensive maintenance (Buckeridge et al., 2018).

7. Conclusion

This study aimed to understand the outdoor thermal benefit of green walls at the pedestrian level, to investigate the environmental compensation policy made by the Sao Paulo municipality from a microclimate point of view. Despite the proven green walls benefits to indoor microclimates addressed by the literature, by studying existent typologies of green walls, the simulation for the Sao Paulo climate conditions, and factual and documentation analysis of public policies, we found that their impact on outdoor microclimates on pedestrian level is minor. Once the environmental compensation of the Sao Paulo municipality disregards the loss of the green wall for vegetation loss compensation, the green walls and their environmental services were lost; with them, the environmental services of the previous trees that will be uncompensated for causing environmental damage and financial loss to the people of Sao Paulo.

Studies that compare trees' and green walls' environmental services as similar were not found. The lack of contradictory findings reinforces this study results. The compensation of trees by green walls is highly questionable; green walls can be adopted considering other potential benefits, as an increment to other strategies, but not as environmental compensation for the trees suppression. This study presented a comparison of the benefits between urban trees and green façades in urban microclimate at the pedestrian level, although we only considered the variables air temperature, air humidity, and mean radiant temperature. Further analyses are recommended to improve the consistency of results regarding the ecosystem services of trees and green façades, and their combined effects.

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