Leaf Coverage Quantification for the Design of Vegetated Shading Geometries Using Algorithmic Modeling, Coupled with Imaging Software

Débora Mela, Andressa Carmo Pena Martinez, Affonso Henrique Lima Zuin

Federal University of Viçosa, Brazil
debora.mela@ufv.br
andressamartinez@gmail.com
zuin@ufv.br

Abstract. One of the most significant parameters for obtaining positive benefits from vegetation is the leaf area index. This parameter influences the shading of the plant, acting as a solar control device in the architecture. In this sense, this work aims to collect average parameters of the percentage of leaf cover of climbing species, in a high tropical climate, through digital mapping and pixel counting, using the image software ImageJ for digital image processing and analysis. With these parameters, it will be possible to simulate the shading of the vines and predict their growth. This simulation can help designers make decisions such as mesh configurations, planting spacing, and regular maintenance. The research hopes to fill a gap in the literature on specific data on leaf cover of climbing species, which can serve as an input to the algorithmic modeling of green facades in architecture.

Keywords: Digital image processing, Algorithmic design, Green shading devices, Leaf area index, Pixel counting.

1 Introduction

A constructive strategy for passively shading buildings is integrating vegetation into roofs or facades. Thus, one of the ways of applying this vegetation on building envelopes is using vertical gardens, a system that encompasses two main types: green facades and green walls. For green façade, this typology uses creepers or shrubs fixed to the façade or supported by wire trellises. In this option, we usually plant the seedling at the base of the structure directly on the ground or in pots placed at different heights of the façade.

In the last twenty years, green façades have been much investigated and explored through different methodologies. However, although previous studies (SCHERER; FEDRIZZI, 2015; DAVIS et al., 2017; RILEY, 2017) attest these systems have several benefits for the building and the urban area (ASCIONE et al., al., 2020), there are still some gaps and limitations related to computational simulation methods to explore the behavior of this system.

One way to represent and simulate vegetation cover in algorithmic-parametric modeling software (LI et al., 2014) and parametric simulation (LARSEN et al., 2015) is to create a surface using the percentage of leaf coverage of the species, better known as the leaf area index (LAI). This parameter is the most important mechanism of a species, resulting in the vegetation's ability to provide shade, acting as a solar control device in architecture (KOYAMA et al., 2013; PÉREZ et al., 2017; KOKOGIANNAKIS et al., 2019).

However, modeling and simulating vegetated shading in digital environments involves a large amount of data, which is not static due to factors such as constant vegetation growth. In addition, each species has distinct characteristics that will influence its development, such as the greater or lesser degree of closure of the foliage, its growth speed, its size, perennial or deciduous leaves. In this sense, one of the main limitations for modeling customized green façades is the lack of digital database parameters for vegetated materials, which allows the designer to analyze, predict, and simulate the vegetation behavior and growth. Until then, predefined configurations are more often for traditional architectural components such as concrete, masonry, or wood materials.

Most of the works have used experimental methods to extract parameters on the thermal effect of vegetation (OLIVIERI et al. 2017; ARENGHI et al. 2021), but there is a lack of data for the physical and visual conditions of plant growth, such as type of growth, leaf coverage and the permanence of leaves. Therefore, determining the leaf area parameter before modeling the green facade is essential to predict the long run of the vegetation and modeling the conditions for adapting the plant to the environment.

Among the ways to estimate leaf coverage, we can use specific software that helps define the LAI through digital image processing. With this procedure, we can obtain the leaf coverage without using expensive electronic devices such as the LI-COR model LAI 2000 canopy analyzer. The software enables calculating the LAI through two options: mathematical relationships between the dimensions of the leaves and the total leaf area (RIBEIRO et al., 2020) or an image pixel count. In the second option, it is necessary to carry out a photographic survey of the species during their development period to record the closing of the foliage. This procedure is an indirect (non-destructive) method indicated for research that needs to keep up the integrity of the plants, being able to test them over time.

Currently, there are some software options to perform digital image processing, some in the public domain such as ImageJ® and R-package® and others paid as ArcGis® and MATLAB®. Although the use of this software is already a standard procedure among some areas of scientific knowledge, such as Meteorology (SILVA et al., 2009), Medicine (WEBER; SANTOS, 2019), Biology (HOOPER et al., 2020) and Agricultural Sciences (RIBEIRO et al., 2020), in the field of Architecture, it is still rarely used. Generally, the researches that quantified the LAI in green facades used the Adobe Photoshop© software as a tool, as seen in some works (KOYAMA et al., 2013; SCHERER and FEDRIZZI, 2015; and Soon, ALLAN and KIM, 2016).

In this sense, this work aims to collect average parameters as a percentage of leaf coverage of climbing species, in the high-altitude tropical climate, through digital mapping and pixel counting, as input for algorithmic-parametric modeling in Grasshopper©. For this purpose, this research brings together professionals and researchers from Architecture and Plant Science in collaborative work.

Then, this research consists of five stages of non-destructive testing for plant assessment: (1) the construction of five prototypes in an open ground, where we planted five species of creepers, evaluated monthly. Each panel supports two seedlings, cropped in the soil and in pots, to measure the behavior in both situations; (2) data extraction through photographs and field observation; (3) digital mapping and pixel counting, using ImageJ® for digital image processing, analysis, and collecting the percentage of leaf coverage; (4) the use of LAI as input for the algorithmic modeling in Grasshopper©; and (5) vegetation development simulation processes. However, in this paper, we discuss steps 02, 03, and part of step 04.

The results of this research intend not only to fill a gap in the literature about data on leaf coverage of climbing species but also predict the development of the green façade through time. In addition, it will also allow further studies using algorithmic simulation software.

2 Materials and methods

This investigation used two methods: the first for data extraction using an indirect (non-destructive) method from image capture, digital processing, and quantitative analysis with ImageJ© software; another for validating the collected data through algorithmic-parametric modeling in Grasshopper©.

2.1 Prototype definition

We built the green façades in the city of Viçosa in the Teaching Research and Extension Unit (UEPE) Floriculture-Belvedere, at the Federal University of Viçosa, in Brazil. We built five independent panels (2.00m wide by 2.40m high) and positioned with the length axis in the North-South direction and the screen faces facing the East and West orientations. We use treated eucalyptus posts as a frame, and an internal grid of 0.40 meters by 0.40 meters, composed of wire lines extended vertically and horizontally, to hold the vegetation. For a comparative analysis with two different vegetated systems, each panel has two seedlings of each species, one planted in a 10-liter pot and the other in the soil.

We distributed the seedlings along the panel keeping 0.80 meters between them and 0.15 meters away from the panel screen. We drive the vines to scale the wire mesh and place it on the west side of each panel. We planted the species in January 2020 and monitored them until May 2021 to check their growth and adaptation. The monitoring of this period included regular visits for irrigation, fertilization, fixation of new branches, pruning, and photographic record. We chose the following species of vines: *Tumbergia-blue (Tumbérgia-azul); Clitoria ternatea (Butterfly Beans); Mikania glomerata Spreng (Guaco); Congea tomentosa (Congea) e; Potatoes cavanillesii G. Don. (Viola string).*

2.2 Extraction of empirical data

Once the species reached the height of the panel mesh, we recorded the evolution of the species with photographs every month, for 12 months, passing through all seasons of the year and climatic changes. These photographic records started in June 2020 and ended in May 2021. We recorded the images between the 5th and 10th day of each month, so that the intervals were close to 30 days.

For the analysis, we separated the samples of seedlings in pot and soil (Fig. 1). The colored spots represent the area accounted for the leaf coverage of each seedling, and the dashed lines in red represent the distribution of the mesh to support the vegetation. In all, we captured and treated 60 images of seedlings both in pots and in soil, totaling 120 images for the database. The pictures referring to the area of the vessel have dimensions of 0.40 meters wide (950 pixels horizontally) and 2.40 meters high (4330 pixels vertically) in a total amount of 4.113.500 pixels per image, with 600 dpi resolution and size 676 KB. The images referring to the area projected for the soil seedlings have dimensions of 1.00 meters in width (2363 pixels horizontally) and 2.40 meters in height (4318 pixels vertically) in a total amount of 10.203.434 pixels per image, with 600 dpi resolution and 1.55 MB size.

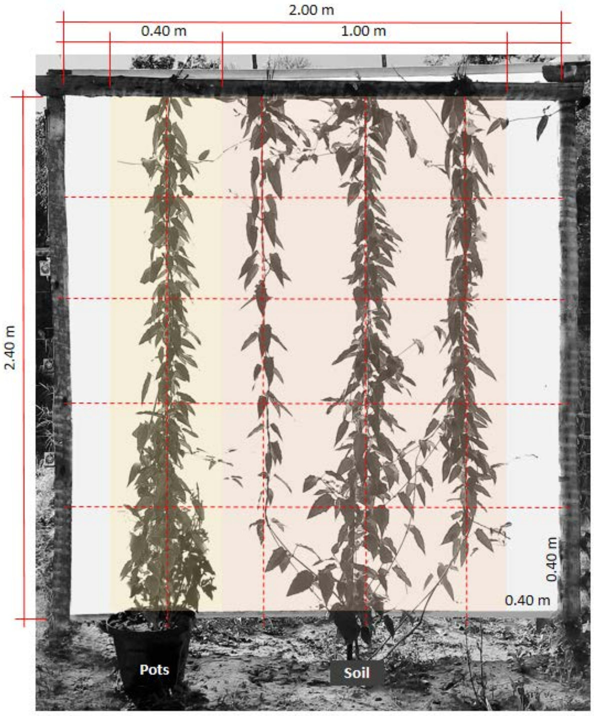

Figure 1. Structure of the prototype with the location of species on the panel. The yellow sample represents the seedling in the pot, while the orange one is for the soil). Source: The authors. Pictures collected in 2020.

We captured the images of the panel from the side where the sun shines (West) in the afternoon, always at the same time (2 pm), with a Sony digital camera model DSC-W120, supported by a tripod always at the same reference point to keep an alignment and pattern of images. To highlight the foliage from the context, we placed a white panel behind the prototype as a background.

2.3 Image processing with ImageJ

First, we use Adobe Photoshop© software for processing and framing the digital image captured on-site. In this step, we resize the image and cut it to the exact dimensions of the panel (2.00mX2.40m). Then, we delimited the cutting area of the region for the analysis of the vessel (in yellow) and the soil (in orange). After that, we processed and analyzed the images quantitatively with ImageJ software. This processing involved three steps:

a) Pre-processing: Initially, it was necessary to convert the original 32-bit images to 8-bit (gray levels between 0-255), then the images underwent a brightness level correction and foliage enhancement. The function of this step was to improve the quality and sharpness of the images.

b) Segmentation: in this step, we have the image segmentation to highlight the foliage from the white background. We call this technique image binarization or Threshold image. In binarization, we consider a gray level as a separation threshold between the pixels that make up the objects and the background. Thus, we get a binary image (Fig. 2) with only two luminance levels: black and white.

c) Data extraction: as a final step, we extract the quantitative information from the image. The purpose of this step is to automatically recognize the total area and the percentage of segmented objects in the image (occupied by the white and black colors of the binary image). For this, selecting the function Analyze - Measure, we find the percentage of the area in black and white, representing how much the plant has developed each month.

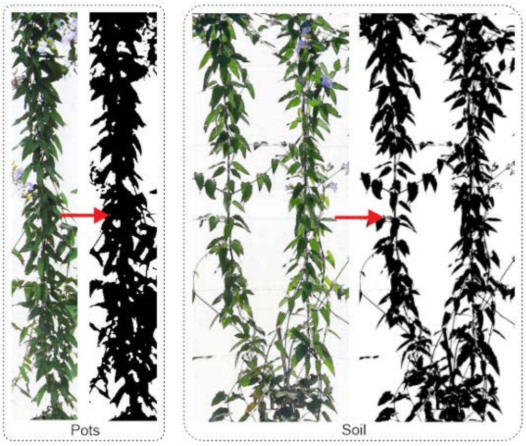

Figure 2. Conversion of the original image into a binary image using the “Threshold” technique. From left to right: seedlings in pot and soil transformed into binary. Source: The authors. Pictures collected in 2020.

2.4 Algorithmic-parametric modeling

Based on field observation and the extraction of empirical data about the shading of vines, this work presents a practical method for 3D modeling and simulation of vine leaf cover. In this step, we use the Rhinoceros® modeling software with Grasshopper®, and the process involves five main stages: (1) surface definition; (2) surface subdivision; (3) image mapping; (4) calibration; (5) and validation.

First, we create a surface according to the sizes of the “x” and “y” axis of the pictures (Fig. 1). That is 0.40 meters by 2.40 meters for the images for seedlings referring to the pot and 1.00 meter by 2.40 meters for seedlings referring to the ground. We align the measurements with the sizes of the original images so that the pixel reading is without distortion.

In the second step, we subdivide the surface into a grid with 2x2 square meters planes. We estimate this value according to the need for calibration and data processing. These plans will remap the amount of numerical data referring to image pixels. Therefore, depending on the image size, we must readjust to meet the needs of each design project. We use the “Image Sampler” component to remap them (Fig. 3), inserting the binary images processed with ImageJ software.

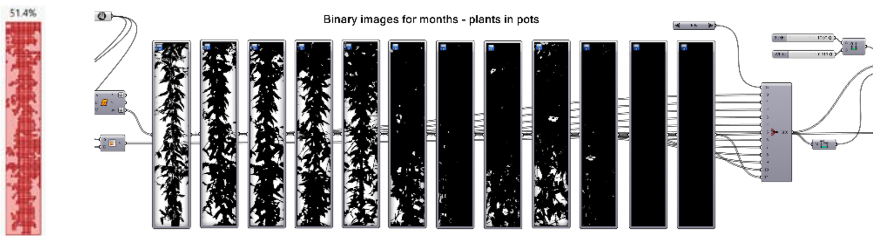

Figure 3. The binary image in Grasshopper® in order to generate shading geometry. Source: The authors, 2021.

Next, we remap the data according to each RGB channel (white and black). For this purpose, we use the Remap Number component that adjusts the amount of black referring to the foliage and thus makes the geometry closer to the original image. After calibrating these numbers and configuring them with a checkered plane to represent the pixels, we use the Dispatch component to select all the black points. Finally, we direct the results to a formula that computes and validates the percentage referring to the image's foliage (Fig. 4).

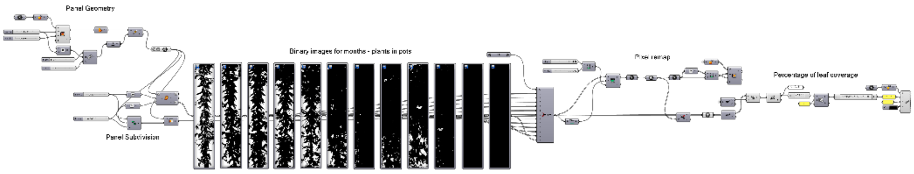

Figure 4. Full code in Grasshopper®. Source: The authors, 2021.

3 Results

3.1 Percentage of climbing species shading

With the above method, we get the percentage of leaf coverage of each vine species after 12 months of observation (Table 1). We organized the table data into monthly results for pot and soil in parallel and after the 12-month sequence, starting in June 2020 and ending in May 2021.

Table 1. Percentage (%) of leaf coverage of species planted in pots and soil in all seasons of the year

Month	Blue Thunbergia		Viola string		Guaco		Congea		Butterfly bean	
	Pots	Soii	Pots	Soii	Pots	Soii	Pots	Soii	Pots	Soii
Jun	13.14	12.95	21.58	20.42	5.23	10.01	*	2.73	6.68	8.25
July	52.35	36.99	35.20	33.82	8.95	19.06	0.72	6.30	14.13	12.12
Agu	62.01	43.84	30.35	31.13	7.56	21.80	4.34	9.02	13.75	11.00
Sep	65.20	52.80	44.30	55.88	11.23	28.75	10.66	15.40	5.21	7.37
Oct	69.07	49.88	50.33	65.74	17.79	32.38	9.30	15.24	7.29	9.59
Nov	69.81	65.86	41.60	60.02	40.02	40.70	41.70	30.01	21.18	20.73
Dec	91.79	82.98	42.80	54.40	55.24	51.65	37.98	34.21	17.10	32.67
Jan	99.03	83.06	50.77	49.76	67.79	57.19	41.81	33.09	11.80	12.15
Feb	95.82	92.70	77.92	67.84	65.07	61.68	41.89	61.83	*	*
Mar	88.17	83.23	91.07	84.75	71.69	45.50	68.54	65.16	*	*
Apr	99.26	90.78	95.16	79.27	81.47	10.01	72.23	69.85	*	*
May	100	100	96.62	99.27	*	19.06	84.52	79.30	*	*

Subtitle: * The seedling had not yet been developed for data collection.
* The seedling died before reaching the expected results.

Source: The authors, 2021.

Analyzing the variation in the percentage of leaf coverage of the five species, we note that each has distinct and relevant characteristics in its shading capacity. Although these are species of tropical climate, the analyzes showed that some species did not adapt to local conditions, reflecting an irregular percentage with few variations in development over the 12 months.

Among the species, Tumbergia Azul is the only one that kept a constant evolution with high rates of leaf coverage percentage, reaching 100% of coverage in both cases, vase, and soil. Regarding the planting conditions of the five species, we noticed a better adaptation and evolution of the seedlings planted in pots. However, the seedlings planted in the soil developed more stems for branching, which improved the distribution and leaf coverage of the defined sample. We consider this information because this is the most used system to plant vegetation in envelopes of high buildings. Thus, given the monitoring and analysis carried out, we can say that the development of these species is not affected by being planted in a smaller area.

Another relevant result concerns the physical characteristics of the prototype, such as mesh, size, the distance between seedlings, and the site location. For this study, we placed the prototypes in an environment free from shading. For this reason, we left the plants exposed to radiation throughout the day, favoring their development, as it is essential to place these species where they receive more solar radiation during the day. As for the panel mesh, it was clear that it can positively influence the direction and coverage of the species' leaves. Additionally, designing tighter meshes will increase leaf density and affect the visual aesthetics of the species' growth. Finally, the number of seedlings and the distance between them can also accelerate and increase leaf coverage.

3.2 Code validation

As the research is still in progress, this paper presents partial results for modeling a green façade in Grasshopper®. The main result is the Grasshopper® definition for calculating the leaf area index (LAI), a parameter to measure foliage shading. This first approach helped to confirm the empirical data extracted in the field about foliage growth and behavior. It also allows choosing the system (pot or ground), the range period of 12 months of the year, and translate the binary image into geometries mapped on surfaces. Once the surface is modeled, the designer can preview the aesthetic shape of the vegetation. The monthly analyses indicate that vegetation growth changes throughout the year. The foliage shading does not increase linearly over time but depends on the species, as there is some loss of leaves at certain times of the year. This knowledge also aids in design decision-making.

Additionally, this Grasshopper® definition allows inserting other image databases to measure the LAI in other plant species. For future works, we will still collect data about the physical properties of the same species. It will also enable us to carry out some environmental analysis.

4 Conclusion

One of the aims of this work was to give data about the leaf coverage of climbing species, which could serve as input for new simulation studies as a method to analyze green facades. Through this experimental method, we gathered data referring to five species with different physical characteristics. Therefore, we emphasize these data refer to species suitable for the high tropical climate, so the simulations are appropriate for these climatic conditions.

In addition to the percentage of foliage, another contribution is the generative design through parametric modeling for green facades. This model makes it possible to visually predict how these species behave throughout their development and helps to carry out some environmental analyses. Despite the vegetation being a living element, suitable for several transformations, with this method, we can have a preview of how this vegetation will be in its advanced growth stage.

The future steps of this research for improving the Grasshopper® definition are: (1) increasing the geometric complexity of the green facade; (2) predicting the direction of vegetation growth in different geometric meshes, thus expanding the final shape of the leaf closure; (3) estimating the final weight of the plants, according to the LAI, which will help to simulate structural performance.

It is important to emphasize that one of the limitations of this research is the lack of systematic statistical analysis to define the behavior of each species. We know that an experiment more seedlings and several repetitions repetitions to be validated. However, due to the reduced area and low budget for building prototypes, it was necessary to simplify the method and work with few seedlings per panel. Therefore, as a suggestion for future work, it would be interesting to deepen this method with static analysis of each species to overcome the possible variations between species and the collected parameters.

Acknowledgements

We thank the Nó. Lab for the support to develop this research, the Post-Graduate Program in Architecture and Urbanism at the Federal University of Viçosa (PPG.au/UFV) for the financial support to present this work at SIGraDi and the Plant Science Department for supporting the experiment. We also thank the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for the scholarship granted to the authors and to all the volunteers involved who helped to build the prototypes.

References

Arenghi, A.; Perra, C., & Caffi, M. (2021). Simulating and comparing different vertical greenery systems grouped into categories using energyplus. *Applied Sciences* (Switzerland), v. 11, n. 11.

Ascione, F.; De Masi, R, F; Mastellone, M; Ruggiero, S & Vanoli, G, P. (2020). Green walls, a critical review: Knowledge gaps, design parameters, thermal performances and multi-criteria design approaches. *Energies*, v. 13, n. 9.

Davis, M. J. M.; Tenpierik, M J; Ramírez, F R., & Pérez, M, E. (2017). More than just a Green Facade: The sound absorption properties of a vertical garden with and without plants. *Building and Environment*, v. 116, p. 64–72.

Hooper, S. E.; Weller, H., & Amelon, S. K. (2020). Countcolors, an R package for quantification of the fluorescence emitted by pseudogymnoascus destructans lesions on the wing membranes of hibernating bats. *Journal of Wildlife Diseases*, v. 56, n. 4, p. 759–767.

Kokogiannakis, G.; Darkwa, J.; Badeka, S., & Li, Y. (2019). Experimental comparison of green facades with outdoor test cells during a hot humid season. *Energy and Buildings*, v. 185, n. 1, p. 196–209.

Koyama, T.; YoshinagA, M.; Hayashi, H.; Maeda, K. Ichiro, & Yamauchi, A. (2013). Identification of key plant traits contributing to the cooling effects ofgreen façades using freestanding walls. *Building and Environment*, v. 66, p. 96–103.

Larsen, F, S.; Filippín, C., & Lesino, G. (2015). Modeling double skin green façades with traditional thermal simulation software. *Solar Energy*, v. 121, p. 56–67.

Li, X. S.; Byrne, U., & Kesik, T. (2014). Experimental design of energy performance simulation for building envelopes integrated with vegetation. In A. *Symposium on Simulation for Architecture and Urban Design*. Tampa, Florida, USA.

Olivieri, F.; Grifoni, R. C.; Redondas, D.; Sánchez, R, J. A., & Tascini, S. (2017). An experimental method to quantitatively analyse the effect of thermal insulation thickness on the summer performance of a vertical green wall. *Energy and Buildings*, v. 150, p. 132–148.

Pérez, G.; Coma, J.; Sol, S., & Cabeza, L. F. (2017). Green facade for energy savings in buildings: The influence of leaf area index and facade orientation on the shadow effect. *Applied Energy*, v. 187, p. 424–437.

Ribeiro, J, E, D, S; Nóbrega, J, S; Figueiredo, F, R, A; Ferreira, J, T, A; Pereira, W, E; Bruno, R, D, L, A., & Albuquerque, M, B, D. (2020). Estimativa da área foliar de Mesosphaerum suaveolens a partir de relações alométricas. *Rodriguésia*, v. 71, p. 1–9.

Riley, B. (2017). The state of the art of living walls: Lessons learned. *Building and Environment*, v. 114, p. 219–232.

Scherer, M. J., & Fedrizzi, B. M. (2015). Desempenho das cortinas verdes no controle solar de edificações: um estudo experimental. *Cadernos do PROARQ*, v. 25, p. 179–195.

Silva, C. A. V. Da; Silva, H. A. Da; Oliveira, T. H. De., & Galvíncio, J. D. (2009). Uso do Sensoriamento Remoto através de Índices de Vegetação NDVI, SAVI e IAF na microrregião de Itamaracá - PE. In A. *1° Simpósio de Cadeias Produtivas e Desenvolvimento Sustentável na Amazônia*, p. 3079–3085.

Soon, S.; Allan, T., & Kim, H.-I. (2016) A Study of Workflow for Simulations of Vertical Greenery Systems. *Architecture Research*, v. 6, n. 6, p. 142–153.

Weber, J. F., & Santos, A. L. F. Dos. (2019) Utilização do software ImageJ para avaliar área de lesão dermonecrótica. R*evista de Saúde Digital e Tecnologias Educacionais*, v. 4, n. 1, p. 120–130.