Estimating the Untapped Cooling Power of Green Walls as Evaporative Coolers for Buildings

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Abstract

Limited studies have been conducted on the impact of green walls on the energy performance of buildings. A majority of studies have focused on green walls as shading systems and few studies have considered the free cooling provided by green wall transpiration. In this study we have combined the *εNTU* and FAO-56 models to estimate the performance of vining green walls as evaporative coolers in six different climates. The proposed model provides a methodology to design and size the system as a function of canopy geometry, plant biophysical traits, and environmental variables. The results show that the plant biophysical traits and the design of the support structure of green walls are crucial factors in produced cooling power. The largest cooling power of 190 W/m^2 and the lowest cooling power of 30 W/m^2 were estimated for the hot and dry, and cool and dry climates, respectively.

Introduction

Green walls are vertical vegetative surfaces and can be broadly categorized as direct, indirect, and living walls. Direct green walls consist of climber and clinging vines that grow along a building facade. By contrast, indirect green walls are comprised of a separate support structure affixed to the building facade. In both direct and indirect green walls, vines are planted either on the grade level or in elevated pots. Living walls are self sufficient in that they contain substrate for the plants to grow. They are normally irrigated via hydroponic systems. As a result, they are more expensive, have short life spans, and require continuous maintenance (Hunter et al., 2014).

Direct and indirect green walls are cost effective and, if designed properly, require minimal human intervention and maintenance over their lifespan (Hunter et al., 2014; Mitsch & Jorgensen, 2003; Mitsch, 2012). It takes 5 to 15 years for a tree to grow large enough to contribute to energy savings (McPherson & Rowntree, 1993), whereas vines provide a faster return as they can cover large spaces in a couple of growing seasons. Also, they require small footprints in comparison to trees. Thus, they are a perfect solution for dense urban areas. Indirect green walls are highly robust, customizable systems, since the vines can be easily trained to take the design of their support structure.

In contrast to green roofs, the impact of green walls on the energy performance of buildings has received limited attention. The majority of published studies have evaluated green walls solely as a shading device. Only a few studies have considered the cooling power produced from the transpiration of green walls, and almost all evaluate this cooling power as a reduction of heat flow into the building façade (Alexandri & Jones, 2008; Koyama, Yoshinaga, Maeda, & Yamauchi, 2015; Stec, van Paassen, & Maziarz, 2005; Šuklje, Medved, & Arkar, 2016; Susorova, Angulo, Bahrami, & Stephens, 2013). This approach fails to fully harvest the available free cooling power. For example, Koyama et al. (2015) found that the air surrounding a green wall that was installed against a closed shed was 6 ℃ lower than the ambient temperature. However, they concluded that this potential cooling power lowered the interior temperature of the closed shed by only 0.23 ℃. The 6 ℃ cooler air could have been used to directly cool the interior if the air were allowed to enter the shed.

The objective of this research is to develop a mathematical model to estimate the performance of green walls as an evaporative cooling system for buildings. To this end, a theoretical model of heat and mass transfer for direct evaporative coolers has been used and modified to estimate the cooling performance of green walls. The proposed model accounts for such performative variables of green walls as i) the transpiration rate of the canopy as a function of plant biophysical traits and environment, ii) canopy geometry, and iii) frontal air velocity.

Theoretical Considerations

Penman-Monteith Model

The Penman-Monteith (P-M) model is the most prevalent method to estimate the transpiration rate of a vegetative canopy. The model has been adopted by the Food and Agriculture Organization of the United Nations (FAO 56 Method) to estimate the transpiration rates of various crop fields (Allen, Pereira, Raes, & Smith, 1998). The model accounts for the environment variables, plant biophysical traits, and various time scales (1).

$$TR_c = \frac{\Delta \,.\, R_n + K_{time} \,.\, \frac{\rho_a . C_p . VPD}{r_a}}{\lambda[\Delta + \gamma(1 + {}^{r_c}/_{r_a})]} \tag{1}$$

A few studies have demonstrated that the model can be used to estimate the tranpiration rates of green walls. Stec et al. (2005) did not modify the P-M model since their experiments were conducted in controlled lab conditions with a light source parrallel to the canopy. Davis and Hirmer (2015) adjusted the model to the experimental conditions by eliminating the solar radiation term and introducing a new method to calculate the r_a variable to represent the unique design conditions of their green wall design.

For this investigation the P-M model has been modified to estimate the transpiration rates of typical indirect green walls affixed to the exterior envelope of buildings.

εNTU Method for Direct Evaporative Coolers

The Effectiveness - Number of Transfer Units (*ϵNTU*) method is used to design and size heat exchangers with different flow configurations (Nellis, 2009). The *εNTU* equation is expressed in terms of the maximum possible cooling power, $\dot{q}_{max}$, and the effectiveness, ε, which is the dimensionless performance of a heat exchanger (2).

$$\dot{q} = \varepsilon \times \dot{q}_{max} \tag{2}$$

For such single fluid heat exchangers as evaporative coolers, ε depends on the *NTU*, where *NTU* is defined as ratio between total conductance of the heat exchanger, *UA,* and the minimum capacitance, $\dot{c}_{min}$ (3) (Gregory Nellis, 2008).

$$NTU = \frac{UA}{\dot{C}_{min}} \tag{3}$$

In direct evaporative coolers, the air temperature is reduced by passing through a padding that is continuously saturated with water. Neglecting the heat flux transferred from the surroundings, the air is cooled with constant enthalpy.

A few studies have used the *ϵNTU* method to analyze the heat and mass transfer of evaporative coolers (Bougleux, Saboya, Marques, & Parised, 2007; Stabat, Marchio, & Orphelin, 2001; Wu, Huang, & Zhang, 2009). Accordingly, the ε of a direct evaporative cooler is defined as:

$$\varepsilon = 1 - e^{-NTU} \tag{4}$$

The effectiveness, ε, is a function of the padding material, geometry, and frontal air velocity. Normally, ε for heat exchangers is a constant number. However, for evaporative coolers the effectiveness continuously changes since the saturation efficiency varies with the airflow rate of the immediate environment. Wu et al. (2009) defined the *NTU* term as a function of pad geometry, frontal air speed, and air thermal properties (5).

$$\varepsilon = 1 - e^{-\frac{h_c \cdot \xi . \delta}{V . \rho_a . C_p}} \tag{5}$$

The convective heat transfer coefficient, h_c, can be obtained from field data from the padding of the evaporative cooler. *A* and *n* are factors changing with material and configuration (Wu et al., 2009).

$$h_c = A.V^n \tag{6}$$

The *ϵNTU* method is an effective solution for analyzing the performance of evaporative coolers since it reduces system variables to only the frontal air speed. This method has been adopted to evaluate the design and analyze the performance of green walls as evaporative coolers.

Proposed model for green walls

Modified P-M Model

The P-M model treats a canopy as a large, continuous, horizontal leaf with no water limitations (Allen et al., 1998). Therefore, it is rather successful when applied to large crop fields that mimic these conditions. However, studies of isolated plants such as those in vineyards, orchards, and isolated trees report that the model lacks precision as isolated plants are more coupled with their surrounding environments (Dragoni, Lakso, Piccioni, & Tarara, 2006; Lu, Yunusa, Walker, & Müller, 2003; Thom & Oliver, 1977; Yunusa, Walker, Loveys, & Blackmore, 2000).

In this investigation the P-M model has been used to estimate the transpiration rate, and ultimately cooling power, of green walls. Similar to plants in vineyards, green walls are isolated plants, which are more coupled with their surrounding environments. Therefore, the P-M model must be adjusted to account for these variations.

The modified variables are highlighted below. All other variables have been calculated following the FAO 56 instructions (Allen et al., 1998).

Time Scale

The FAO 56 method offers both daily and hourly time step calculations. The goal of this research is to estimate the average monthly cooling power produced from the transpiration rate of a canopy. The monthly estimation can be particularly advantageous when using the P-M model, as some studies have reported that the model can predict the water use of canopies within 1% accuracy. The accuracy of the model is reduced for smaller time steps, such as daily or hourly (Dragoni et al., 2006).

Since night-time transpiration is negligible, only transpiration during daylight hours was considered. To do so, the daylight hours of the 15th of each month were calculated and converted to the number of seconds in a month (7).

$$K = N_h \,.3600 \tag{7}$$

The Daylight Hours, N_h, was calculated using FAO 56 field methods (Allen et al., 1998). Note that all environmental variables have been adjusted to the monthly time scale.

Absorbed Net Radiation (R_n)

Solar radiation has the largest impact on the transpiration rate of plants. It is essential to adjust the P-M model to reflect the appropriate net radiation that is absorbed by a vertical surface against a building facade. FAO 56 considers the absorbed net radiation, R_n, of one large, uniform, horizontal leaf (8).

$$R_n = R_{ns} - R_{nl} \quad (8)$$

The net shortwave radiation, R_{ns}, is calculated as a fraction of the total received shortwave radiation, R_s, where α represents the albedo of the canopy (9). The FAO 56 model considers the albedo value of a grass field to be 0.23. This value has been used throughout this investigation.

$$R_{ns} = (1-\propto)R_s \quad (9)$$

A vertical surface only collects a fraction of the total radiation received by a horizontal surface. The received shortwave radiation on a vertical surface depends not only on the geographical location and the time of the day, but also on the orientation of the wall.

The monthly R_s values were estimated using a solar simulation software, *Diva for Rhino* (http://diva4rhino.com/). Six climate scenarios corresponding with summer conditions in six U.S. cities were selected (Table 1). The monthly R_s values of a black south facing vertical unit surface were simulated for each climate condition using TMY30 weather files for each location.

Table 1: summer month climate conditions and average r_l

Climate Types	**City, State**	**Monthly Ave. Max. Temp. Range (°C), and Rain (mm)**	**Average r_l *(s/m)***
Cool & Humid	Bemidji Muni, MN	20 to 27, > 50	115
Cool & Dry	Cut Bank, MN	20 to 27, < 50	256
Warm & Humid	New York, NY	27 to 32, > 50	128
Warm & Dry	Denver, CO	27 to 32, < 50	152
Hot & Humid	Miami, FL	32 to 40, > 50	91
Hot & Dry	Phoenix, AZ	32 to 40, < 50	125

To calculate R_{nl}, the FAO 56 accounts for the longwave radiation leaving the surface of the canopy multiplied by a correction factor for air humidity and cloudiness. The monthly R_{nl} was calculated following the FAO 56 equations, but a factor of 0.5 was introduced to adjust for the vertical surface sky view.

Canopy Resistance (r_c)

The canopy resistance describes the resistance of vapor flow through the transpiring crop (Allen et al., 1998). In FAO 56, the r_c value is given by:

$$r_c = \frac{r_l}{LAI_{Slit}} \quad (10)$$

The Leaf Area Index (LAI) is a dimensionless value describing the ratio of one-sided leaf area to unit ground/wall area. The sunlit LAI, LAI_{Slit}, is the amount of leaf area that receives sunlight and contributes to the transpiration rates of green walls. LAI_{Slit} is a function of LAI, solar elevation, and leaf angle. Note that for this study a vertically oriented canopy was assumed.

Although the FAO 56 method for estimating canopy resistance is simple, the r_l values can be challenging to obtain, as there are limited studies on urban vine species. Due to this problem, the studies on transpiration of green walls consider a generic r_c value of woody plants.

This assumption is not correct because the r_l value varies between species and climates. To address this problem, this research recorded the stomatal resistances of various vine species (agricultural and non-agricultural) in six different climates. To that end, the r_l field-measured values of 89 vine species from 11 geographical locations were compiled from 27 studies.

For example, the largest r_l library is for grapevines in the warm and dry climates. The largest group of r_l values (25 reports) was between 100 and 200 s/m with an average of 151.63 s/m. Six studies reported r_l values less than 100 s/m (average of 79.43 s/m), three reported of r_l values between 200 and 300 s/m (average of 250.16 s/m), and three studies found r_l values larger than 300 s/m (average of 352.52 s/m). We disregarded the small groups corresponding with extreme low and highs of r_l values as they might represent water-stressed conditions or particular environmental anomalies. Instead we considered the r_l average value of 152 for our calculations. Accordingly, the maximum, minimum, and average values of r_l per climate were recorded and used for P-M model calculations and analysis (Table 1).

Aerodynamic Resistance (r_a)

Aerodynamic resistance, r_a, defines the water vapor and heat transfer from the plant into the air above the canopy. The proposed r_a equation in the FAO 56 works well for large, short, dense crop fields. However, studies on grapevines have reported poor correlation for tall, isolated plants, which are highly coupled to their surrounding environments.

To address this problem, several studies have successfully used the r_a model developed by Thom and Oliver for tall, isolated plants (Thom & Oliver, 1977):

$$r_a = \frac{4.72[In\left(\frac{Z}{Z_0}\right)]^2}{(1 + 0.54U)} \tag{11}$$

These studies showed a reasonable agreement with the data from the field measurements in both "hot and dry" and "cool and humid" climates (Dragoni et al., 2006; Lu et al., 2003; Yunusa et al., 2000). Similarly, we have used Eq. 11 to estimate the r_a values of green walls.

Modified Effectiveness

To account for the ε of green walls, Eq. 5 was modified to reflect the geometry and h_c of the canopy. The geometry of the padding is defined by ξ, the ratio of evaporative surface to the total volume of a padding, and δ, the padding thickness. Similarly, the geometry of green walls can be described as the Leaf Area Density (*LAD*, the total leaf surface area within a volume of canopy), and the canopy thickness, δ.

In reality, due to the nonlinear response of stomata to sunlight, not all leaves in a canopy transpire at the same rate. Only leaves receiving direct sunlight transpire at maximum rates. Depending on the plant species, shaded leaves transpire at a fraction of the rate of sunlit ones (Gates, 1980; Jones, 1992; Monteith & Unsworth, 2013).

To avoid overestimation of canopy transpiration,, only the sunlit leaves are considered . Thus the *NTU* of a green wall canopy can be defined as:

$$NTU_{gr} = \frac{h_c.LAD.LAI_{Slit}.\delta}{V.\rho.C_p} \tag{12}$$

In the following section the possible range of each variable as it relates to vine species and methods of h_c calculations will be discussed.

Canopy Leaf Area Denisty (LAD)

LAD is a "three dimensional measurement that accounts for differences in canopy volume among systems varying in architecture" (Gladstone & Dokoozlian, 2015). The architecture of a vine canopy, and hence its interaction with fluxes of energy, is determined by its support/training system.

Many studies on grapevine canopy structures have been conducted to evaluate the impact and efficiency of the various commercial training systems (Gladstone & Dokoozlian, 2015; Kliewer & Dokoozlian, 2005; Schultz, 2015). In contrast, there are no studies on the impact of the trellis design on the performance of green walls.

To create a possible range for the *LAD* values of green walls, the *LAD* values of grapevines for various support structures have been used. Only the training systems suitable for green wall design were considered. For example, the Double Curtain and LYR systems are not included since their branching design is not suitable for a green wall affixed to a building envelope. The lowest mean *LAD* value is for the C-System (2.02 m^2/m^3) and the largest is for Vertically Shoot Positioned (10.1 m^2/m^3).

Green Wall Thickness (δ)

The thickness, δ, of a green wall is influenced by the design of its support system. Currently, there is no agreement as to an average δ value. Holm (1989) and Perini et al. (2011) reported 20 cm thickness for a south facing green wall in South Africa and northwest facing green wall in Delf, respectively. These values are close to Hoyano's (1988) observation for a west facing green wall in Tokyo (15 to 35 cm).

However, the reported mean thickness values of 10 various green walls, in the Washington, D.C. metro area, was 64 cm. Also, a canopy of thickness of 70 cm was measured in Southern Maryland, USA (Tilley, Price, Matt, & Marrow, 2012). Schumann (2007) observed minimum and maximum green wall thicknesses of 25 cm and 130 cm, respectively in Southern Maryland, USA (Tilley et al., 2012). For this investigation a range of green wall canopy thicknesses up to 150 cm will be considered.

Canopy Convective Heat Coefficient (h_c)

Much work has been done to determine the leaf scale convective heat transfer coefficient values. All studies agree that h_c values for leaves are approximately 1.5 to 2 times larger than the h_c values of a flat plate with a similar characteristic length (Gates, 1980; Jones, 1992; Monteith & Unsworth, 2013).

Gates (1980) recommended using Eq. 13 to estimate h_c values of leaves with characteristic length, d, larger than 0.05 m, and Eq. 14 for leaves with d equal to or smaller than 0.05 m.

$$Nu = 1.18\, Pr^{0.33} Re^{0.5} \tag{13}$$

$$Nu = 1.86\, Pr^{0.33} Re^{0.5} \tag{14}$$

Because it is difficult to scale up the experimental results from a leaf scale to the canopy scale, there are no agreed upon methods nor studies for calculating h_c at the canopy scale (Jarvis & McNaughton, 1986; Jones, 1992; Monteith & Unsworth, 2013). The canopy boundary layer conductance is a function of "canopy structure, leaf area density, and the resulting wind speed distribution" (Stokes, Morecroft, & Morison, 2006). As such, the conductances vary according to design conditions of green walls. For this investigation, the leaf scale h_c will be used to estimate the ε of the evaporative system. The limits of this approach will be considered in the discussion section.

Implementation

Both the modified P-M and *εNTU* models were written in Engineering Equation Software (EES) (http://www.fchart.com/ees/) . The impact of each variable has been tested through studying their possible ranges, which were defined in the previous sections.

Results and Analysis

Penman-Monteith Model Analysis

The P-M model accounts for the maximum possible transpiration rates of canopies in specific climatic conditions without water limitations. In other words, the P-M model predicts the maximum possible cooling power ($\dot{q}_{max}$) produced by a canopy.

The modified P-M model was verified in two steps. First, the general trends of each variable and their impact on transpiration rates (R_n, *VPD*, u, r_a, and r_c) were compared to Jones (1992). Second, the predicted TR_c for grapevines in each climate condition was compared to their reported field measured counterparts (Braun & Schmid, 1999; Bucks, Erie, Nakavama, & French, 1974; Dragoni et al., 2006; Eastham & Gray, 1998; Erie, French, & Harris, 1965; Evans, Spayd, Wample, Kroeger, & Mahan, 1993; Forseth & Teramura, 1987; Intrigliolo, Lakso, & Piccioni, 2009; Lascano, Baumhardt, & Lipe, 1992; Moutinho-Pereira, Correia, Gonçalves, Bacelar, & Torres-Pereira, 2004; Padgett-Johnson, Williams, & Walker, 2003; Patakas, Noitsakis, & Chouzouri, 2005; Poblete-Echeverría & Ortega-Farias, 2013; Yunusa et al., 2000).

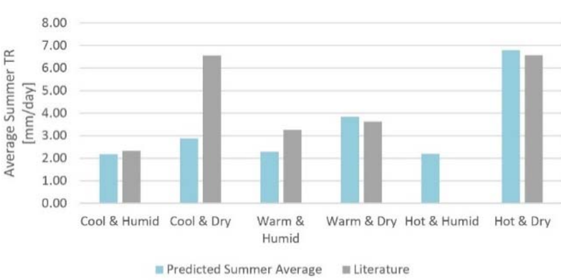

Figure 1: Comparative study of average summer day TR_c from modified P-M model and literature on grapevine canopies (LAI= 5, U=2 m/s, h=1.5 m, r_c= 150 s/m).

The results showed a good agreement except for the cool and dry climate where our TR_c estimation was almost half of the reported value (Figure 1). Most likely this discrepancy is due to the limited data available for the cool and dry climate (3 grapevines), since such a climate is relatively unsuitable for grape production. Note that since grapevines do not thrive in humid climates, the TR_c value of a Kudzu vine was used for the warm and humid climate. We could not find a comparable vine for the hot and humid climate.

The verified model was then used to find the best possible green wall design for $\dot{q}_{max}$. Figure 2 shows $\dot{q}_{max}$ as a function of r_c for various r_a values in a hot and dry climate. The largest value (250 s/m) and the smallest value (5 s/m) correspond with short grass and forest, respectively. The r_a of 10 s/m represents a typical canopy aerodynamic resistance value for a grapevine in a vineyard (h=1.5 m, z= 0.13h, and u=2 m/s).

Accordingly, the $\dot{q}_{max}$ increases as both r_c and r_a decrease. Low r_a values occurs when a canopy is highly coupled with its environment, such as in the case of tall plants or high wind velocities. Theoretically, transpiration rates increase when the height of the canopy increases and wind speed decreases.

However, in reality, transpiration is restricted by the biophysical resistance of canopies, r_l. For example, forest transpiration is often less than field transpiration since most forest species (especially in coniferous forests) have relatively high r_l values (Jones, 1992). The dotted reference lines represent the biophysical restrictions imposed by the vine species on the transpiration rates of the canopy.

Similar parametric studies were conducted for all six climate conditions. The results show that the greatest transpiration rate occurs in the hot and dry climate followed by the warm and dry, and cool and dry, climates. The humid regions with hot, warm, or cool summers correspond to the lowest ranges of canopy cooling power.

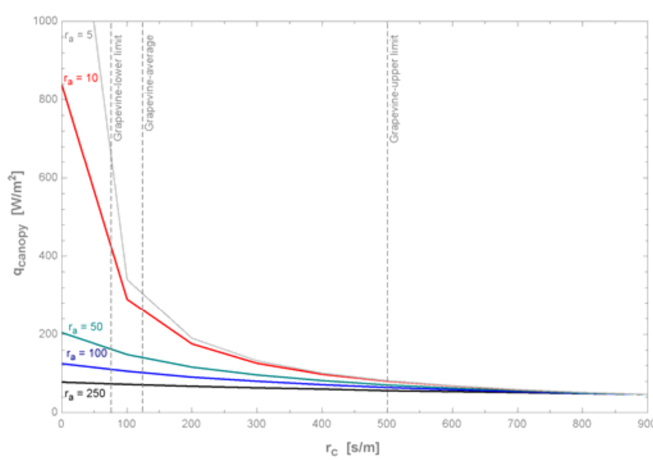

Figure 2: $\dot{q}_{max}$ as a function of r_c for various r_a.

Since r_c has a direct relationship with the leaf surface resistance, r_l, and an inverse relationship with *LAI*, canopies with low r_l and high *LAI* values should produce the largest transpiration rates (10). Figure 3 illustrates r_c as a function of r_l and LAI. The dotted lines represent the r_c values corresponding with the cooling power of 100 W/m^2 and average r_c values of grapevines in the hot and dry climate.

Out of the six climate conditions, only three vine canopies have the potential to produce 100 W/m^2 or more of cooling power. As expected, the hot and dry climate provides the most robust conditions (designated by the pink box). In this scenario, r_c and r_l can reach values as large as 400 s/m and 370 s/m, respectively. Within this boundary, most sun-loving vine species can produce significant cooling power.

The warm and dry climate provides the second largest boundary. In this environment, vines' r_c and r_l values of 200 s/m and less can produce 100 W/m^2 or more of cooling power. Most Vitis (grapevine) species can meet this requirement easily. Finally, the r_c and r_l values of approximately 100 s/m can produce 100 W/m^2 or more of cooling power in hot and humid climates. In these environments, most urban vines thrive.

The 100 W/m^2 cutoff point eliminated warm and humid, cool and dry, and cool and humid scenarios. However, a green wall canopy still produces cooling power in those climatic conditions. The average cooling power values during summer months are approximately 80 W/m^2 for the cool and dry climate followed by 60 W/m^2 for both the warm and humid, and cool and humid, climates.

Furthermore, for low values of LAI, the impact of r_l on r_c is significant. As LAI increases the influence of r_l on r_c diminishes, since there are more leaves within the canopy to transpire. Note that during summer months, LAI values of 3, 4 and 5 are fairly common for green walls.

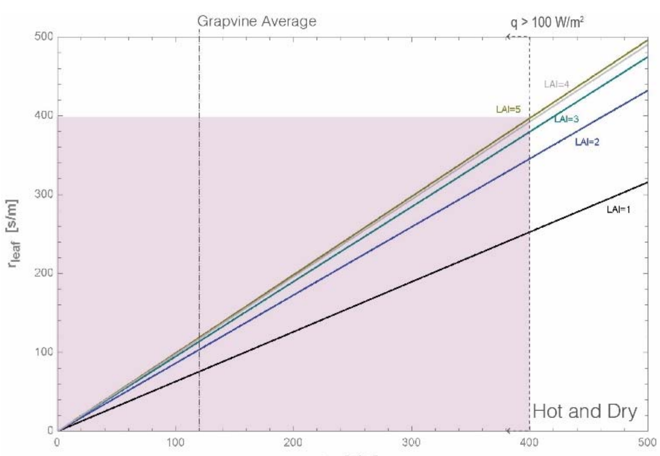

Figure 3: r_c as a function of r_l and various LAI.

When provided with a strong support structure, most vines can climb up to 20 m. Although in most cases wind speed cannot be controlled, the height, h, of the canopy can be adjusted to reduce r_a. Our parametric study of r_a as a function of u and h illustrates that as h increases, r_a decreases. However, the impact of h on r_a becomes negligible as h reaches 10 m. As expected, an increase in wind speed, u, reduces r_a as long as r_c does not impose restrictions on water vapor loss from stomatal.

Figure 4 illustrates the best design options for maximizing the cooling power of a south-facing green wall in the month of June in a hot and dry climate. The average r_c values, accounting for the possibility of 10% variability, and the corresponding maximum cooling power values, are highlighted with a pink bar and text, respectively. The cooling power values of three green walls with different heights (3 m, 6 m, and 9 m) for both no wind (0.1 m/s) and a wind speed of 2 m/s are considered.

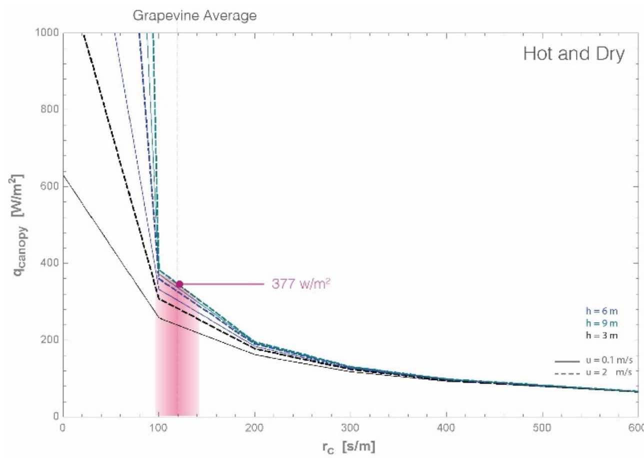

Figure 4: Month of June $\dot{q}_{max}$ of a south facing canopy as a function of r_c and r_a for various h (3, 6 and 9 m) and u (0.1 and 2 m/s). The pink bar represents the average r_c with 10% possible changes.

Our study shows that the largest cooling power is produced in the hot and dry climate (377 W/m^2) followed by the warm and dry (155 W/m^2) and hot and humid (120 W/m^2) climates.

Except for the cold and dry climate, the tallest canopy (9 m) with a wind speed of 2 m/s produces the largest cooling power. The least cooling power (60 W/m^2) is produced in the cold and dry climate where the cooling is mostly provided through convection and not transpiration. This is due to high average r_c values (255 s/m). The r_c values of 100 s/m or smaller can significantly improve the cooling power of the canopy. For all climates, the positive impact of the wind on cooling power decreases as the height of the canopy increases. The largest impact of wind on cooling power is when the canopy is 3 m tall. This study suggests that in all climates, wind only slightly improves the cooling power of canopies taller than 6 m.

Furthermore, in all climates, r_c values of 100 s/m or less greatly improve canopy cooling power. However, the influence of canopy height must be further investigated, as some studies on forests suggest that r_l increases as height increases. This would result in lower transpiration rates and cooling power rates at higher canopy elevations (Jones, 1992).

Effectiveness analysis

The study of the exponential relationship between ε and *NTU* showed that the *NTU* of about 3 produces an acceptably large value of ε, 0.95. Therefore, a green wall reaches its optimal ε when it is physically large while processing the lowest possible air frontal velocity rates (3). To that end, both the impact of *V* and green wall geometry on *NTU* and ε were further analyzed. As expected, the lowest air speeds produce the largest *NTU* values. As the wind speed increases to 0.5 m/s, the *NTU* value is reduced from 1.5 to 0.4. The *NTU* value is further decreased to 0.2 approaching *V*= 1 m/s.

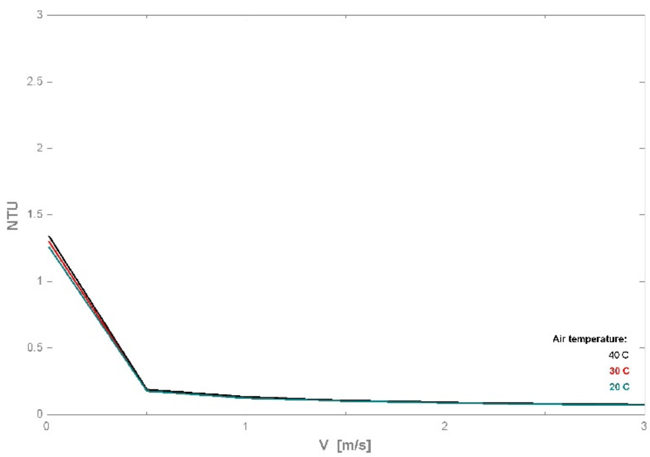

Figure 5: NTU as a function of V for various ambient temperatures, T. (LAD=10 m^2/m^3, LAI_{slit}= 0.99, d= 0.05m, δ=0.5 m, p= 1 atm).

As a result, for green walls, as wind speed increases, the h_c value, in the numerator, does not reach large enough values to counteract the increased *V* parameter in the denominator (12). This leads to a decrease in *NTU* as *V* increases. Also, Figure 5 shows that the impact of air temperature on *NTU* is negligible.

The *d*, *LAD*, and δ define the physical properties of a green wall. The most significant impact of *d* on ε occurs when *d* is larger than 0.05 m. When *LAD*= 15, the ε is reduced from 45% to 25% as *d* is doubled from 0.05 m to 0.1 m. This is due to a significant reduction in the h_c value for leaves with $d > 0.05$ m (13 and 14).

In practice, most small leaves ($d < 0.05$ m) transpire less than large leaves as they have evolved to conserve water. Therefore, it is imperative to only consider leaves with *d* either equal to or larger than 0.05 m.

As the physical size of a green wall increases, the *NTU* value increases. However, δ impacts *NTU* at a faster rate compared to the *LAD*. Figure 6 illustrates ε as a function of *LAD* for various green wall thicknesses. All other variables are set to produce the optimal efficiency for the green wall system. The green wall with the greatest thickness (0.7 m) corresponds to the highest ε value of 0.5 for *V*=0.5 m/s. The ε is reduced to approximately 0.4 and 0.25 for *V* of 1 and 2 m/s, respectively.

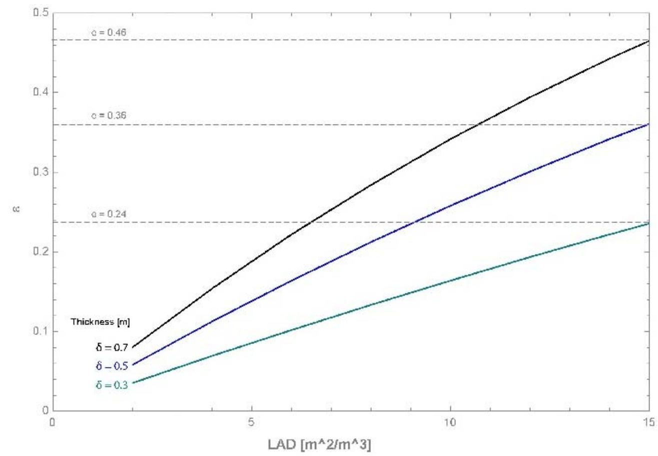

Figure 6: ε as a function of LAD for various δ (V= 0.5 m/s, LAI_{slit}= 0.99, T= 40 °C, p= 1 atm).

Discussion & Conclusion

The predicted evaporative cooling performance of green walls for various ε corresponding with the δ values is shown in Table 2. The largest *q* corresponds with the hot and dry climate followed by warm and dry. The *q* for the cool and humid climate is slightly larger than the *q* for the hot and humid climate. This can be attributed to the impacts of r_l and R_n. Due to the solar angle, a vertical surface in a cool climate (further from the equator) will receive more solar radiation, R_n, than its counterpart in a hot climate. However, in a cool and humid climate, r_l is larger than in the hot and humid climate (115 vs. 91 m/s). Similarly, the *q* is reduced in warm and humid climates as the average r_l is increased to approximately 130 s/m. This highlights the importance of the biophysical traits of the selected plant species in producing *q*.

To better contextualize these findings, let us consider a simplified example of an infill room and address its internal cooling loads. In this scenario, only the southern façade is exposed to a dense green wall (LAI = 5, negligible solar gains). The height, width, and length are 3 m each and the total internal load is 200 W, accounting for a person (100 W), a laptop (60 W), and lighting (40 W). Let's imagine that 50% of the southern façade of the room (4.5 m^2) is open to a green wall. Table 3 shows the entering *q* for various green wall designs (δ = 0.7, 0.5, and 0.3 m).

Except in warm and humid, and cool and dry climates, green wall designs with 50% and 40% efficiency are easily capable of meeting the 200 W internal load requirement. As ε is reduced to 0.25 (δ=0.3 m) the q is reduced below 200W. However, except in the cool and dry, and warm and humid climates, the green wall can meet more than 50% of the total required cooling power.

Table 2: Cooling power, q, of green walls for various ε (δ=0.7, 0.5, and 0.3, LAD=15, d=0.5, h=6, V=0.5, r_l=average value per climate, LAI=5)

	$\dot{q}_{max}$ W.m^{-2}	q (ε: 0.5) W.m^{-2}	q (ε: 0.4) W.m^{-2}	q (ε: 0.25) W.m^{-2}
Hot & Dry	380	190	152	95
Hot & Humid	120	60	48	30
Warm & Dry	155	78	62	39
Warm & Humid	80	40	32	20
Cool & Dry	60	30	24	15
Cool & Humid	130	65	52	33

These estimations can be further refined by including the impact of the sheltering effect and transpiration of the shaded leaves. Depending on the design of a green wall, the sheltering effect from the surrounding leaves and stems can reduce the leaf boundary layer, and in turn, the canopy boundary layer, conductances (Stokes et al., 2006). The amount and method of transference of the produced cooling power into the building is highly dependent on the overall design of a system, which can be the subject of further design investigations and system developments.

Table 3: Produced q from various southern facing green wall designs against 4.5 m^2 window opening (δ=0.7, 0.5, and 0.3, LAD=15, d=0.5, h=6, V=0.5, r_l=average value per climate, LAI=5)

	q (ε: 0.5) W	q (ε: 0.4) W	q (ε: 0.25) W
Hot & Dry	855	684	428
Hot & Humid	270	216	135
Warm & Dry	349	279	174
Warm & Humid	180	144	90
Cool & Dry	135	108	68
Cool & Humid	293	234	146

In reality, the shaded leaves also contribute to the TR_c (Ding, Kang, Du, Hao, & Zhang, 2014). The significance of this contribution depends on both the design of a green wall and plant biophysical traits. For example, the shaded leaves of Pueraria lobata (Kudzu) vines transpire only 50% less than their sunlit leaves (Forseth & Teramura, 1987).

The sheltering effect and the contribution to TR_c of the shaded leaves are highly dependent on the selected plant and design of the support system of green walls. Thus, the next steps of this investigation must involve testing green wall system designs and verifying results through field experiments.

Finally, similar to evaporative coolers, the q produced from green walls can be used only within the range of occupancy comfort levels. However, in contrast to evaporative coolers, this design takes advantage of natural ventilation, which allows for the expansion of the occupant comfort boundary.

Furthermore, in the cases where humidity in the cooled air would exceed the occupancy thermal comfort and cannot be brought into the interior of buildings, green walls still contribute to the cooling of buildings by both shading the façade and reducing the exterior ambient temperature.

This investigation establishes a methodology to define the potential and limits of green wall designs as evaporative coolers. By doing so it opens up a new avenue for further design exploration of green walls as a performative façade.

Nomenclature

C_p	Specific heat of dry air at constant pressure	MJ/kg°C
d	Leaf characteristic length	m
h	Canopy height	m
h_c	Convective heat transfer coefficient	W/m^2.K
K_{time}	Unit time conversion	s/month
LAD	Leaf Area Density, total leaf area to canopy volume	m^2/m^3
LAI	Leaf Area Index	m^2/m^2
LAI_{Slit}	Sunlit Leaf Area Index	m^2/m^2
N_h	Daylight hours in the 15th day of a month	hr
NTU	Number of transfer units	Dimensionless
q	Actual cooling power	W/m^2
q_{max}	Maximum cooling power	W/m^2
r_a	Canopy aerodynamic resistance	s/m
r_c	Canopy bulk/surface resistance	s/m
r_l	Bulk stomatal resistance of the well-illuminated leaf	s/m
R_n	Net radiation absorbed by the canopy	MJ/m^2.month
R_{nl}	Net isothermal long wave radiation	MJ/m^2.month
R_{ns}	Net short wave radiation	MJ/m^2.month
TR_c	Canopy transpiration rate	mm/month
U	Wind speed	m/s
V	Air frontal velocity	m/s
VPD	Vapor pressure deficit of air	kPa

Z	Height of measurement of wind speed (taken at 2 m)	m
Z_0	Roughness height taken as 0.13 of the canopy height	m
γ	Psychrometric constant	kPa/°C
Δ	Slope of saturation vapor pressure vs. temperature	kPa/°C
δ	Thickness	m
ε	Effectiveness of evaporative cooler	Dimensionless
λ	Latent heat of vaporization of water	MJ/kg
ξ	Pore surface coefficient per unit padding volume	m^2/m^3
ρ_a	Density of dry air	kg/m^3
ϵNTU	Effectiveness Number of Transfer Unit	Dimensionless

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