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ScienceDirect
Energy and Buildings 40 (2008) 1048–1052
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

Evaluating the thermal reduction effect of plant layers on rooftops

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Received 20 March 2007; received in revised form 13 June 2007; accepted 19 June 2007

Abstract

This study examines the thermal reduction effect of plant layers on rooftops through experiments performed in a controlled environment. The relevant parameters are coverage ratio (CR) and total leaf thickness (TLT). Both parameters are positively correlated with thermal reduction ratio (TRR). The TRR data of all experiments were plotted on a grid system with CR on the *x*-axis and TLT on the *y*-axis. A TRR map was then drawn using the curve fitting process. The applicability of the TRR map drawn for *Codiaeum variegatum* (1) was further confirmed by performing experiments with *Cordyline terminalis* (1) and *Ixora duffii* (1) and by results of experiments on *C. variegatum* (2), *C. terminalis* (2), *Duranta repens*, and *I. duffii* (2) in outdoor environments. The TRR map provides quantitative and straightforward guidance on thermal reduction planting arrangements for green roofs.

Keywords: Cooling; Green roof; Heat insulation; Shading

1. Introduction

Intense solar radiation in the tropics and subtropics amplifies the thermal load of buildings, and thereby increases the costs of air conditioning. Researchers have proposed planting trees [1], green roofs [2] or ivy walls [3] around buildings to reduce the thermal load of buildings and urban heat islands by exploiting the biological and physical functions of plants.

Researchers confer that leaf area [4–6] and foliage height thickness (vertical thickness of canopy) [6] are the important factors governing the thermal reduction effect of plant layers on rooftops. Wong et al. [4] mentioned that the thermal reduction effect of green roofs increases with the leaf area index (LAI). However, that investigation did not quantify the relationship between LAI and the thermal reduction effect. Del Barrio [5] presented a mathematical model of the cooling effect of canopies. Barrio's work reveals that LAI is negatively correlated with transmitted solar flux. However, this model comprises 18 parameters that cannot be easily determined by environmental designers. The model was too complicated and could not be applied on a large scale by laymen. Kumar and Kaushik [6] examined an energy balance model for green roofs and confirmed their experiments in the field. They demonstrated that the LAI and foliage height thickness are negatively correlated with heat flux. However, the energy balance model employs 20 parameters, and is therefore too complex. The model includes foliage height thickness as a parameter. While tree canopies may have similar vertical thickness, the number and thickness of leaves of different plant species can vary. Consequently, the thermal reduction effects of various species are not necessarily similar. In conclusion, a model of thermal reduction effect from plant layers on rooftops has been proposed, but the canopy form parameter requires further clarification. It is thus very important to explain the parameter of the canopy form for thermal reduction, and construct a simple and convenient model for thermal reduction by plant layers on rooftops.

This study examines the thermal reduction effect of plant layers on rooftops. The parameters are coverage ratio and total leaf thickness. Maps showing thermal reduction ratio were constructed based on coverage ratio and total leaf thickness. The maps provide a tool to quantitatively and plainly elucidate the thermal reduction effect of plant layers on rooftops.

2. Materials and methods

2.1. Materials

The plants employed in this study are commonly used as ornamentals in the tropics and subtropics. Ornamental species

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doi:10.1016/j.enbuild.2007.06.007

Nomenclature

CR	coverage ratio of leaf (%)
LAI	leaf area index
T_A	the atmospheric temperature (°C)
T_P	the temperature of P% coverage ratio (°C)
T_0	the temperature of 0% coverage ratio (°C)
TLT	total leaf thickness, plant layer multiplied by average leaf thickness
TRR	thermal reduction rate (%)

must be vigorous, with many leaves and a large coverage ratio, such that they can exhibit the potential thermal reduction effect on green roofs. First, the plant *Codiaeum variegatum* (1) was tested in a controlled experimental chamber in the lab for the purpose of plotting a thermal reduction map of this plant species. Second, the same experiment was conducted with *Cordyline terminalis* (1) and *Ixora duffii* (1) to verify the map. At last, four plant species *C. variegatum* (2), *C. terminalis* (2), *Duranta repens* and *I. duffii* (2) were tested in outdoor settings to verify the applicability of the TRR map. Table 1 presents the species and characteristics of the experiment.

2.2. Parameters

The parameters adopted herein are the coverage ratio and the total leaf thickness. Methods of estimation are explained below.

Measuring leaf coverage ratio (*CR*). This research used 8 white nylon threads to divide the growing areas into 25 grids 8 cm × 8 cm. The tested plant was later put into a grid and was held straight by the nylon threads. The leaf coverage ratio (%) was calculated by dividing the total number of grids covered by the tested plants by the total number of grids (25).

Measuring total leaf thickness (*TLT*). First, 10 leaves were randomly chosen and their thicknesses were measured using a micrometer to determine average leaf thickness. Second, the mean number of plant layers was estimated, and the average leaf thickness was multiplied by the average number of layers to yield TLT.

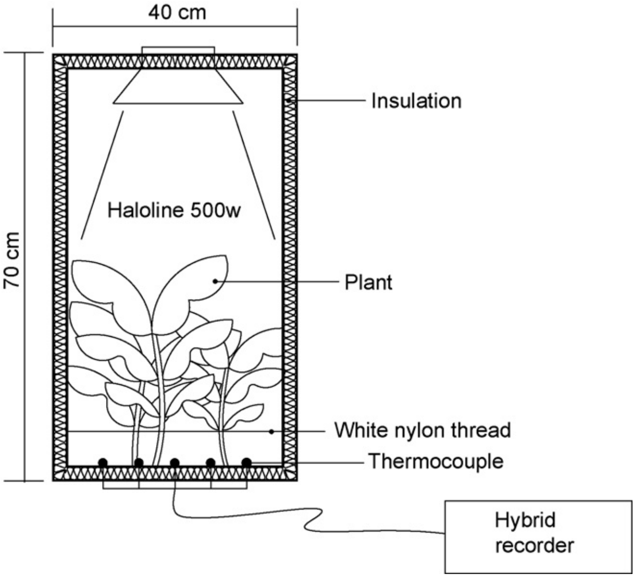

Fig. 1. Indoor measuring system.

2.3. Experimental system

This study comprises two experiments. The first experiment was set up indoors in a chamber with a stable light source. The plants were placed in the chamber and their thermal reduction effect was measured. The atmosphere was controlled so that the influence of background temperature, moisture and wind velocity could be excluded, simplifying the factors involved and supporting a discussion of the main factors. The second experiment was performed outdoors. Four species of plants were planted in pots on rooftops to confirm the data from the first experiment.

2.3.1. Indoor experiment

The chamber ($L \times W \times H$: 40 cm × 40 cm × 70 cm) was established and covered with heat insulation to prevent interference from atmospheric temperature and light (Fig. 1). The indoor temperature was maintained at 28 ± 0.5 °C. A light (OSRAM HALOPIN: 500 W) was placed on the top of the chamber to provide thermal energy. A black plastic board lay on the bottom of the chamber. Five thermocouples (K-type) were placed on the plastic board and connected to a hybrid recorder.

Table 1
Characteristics of plants used in the experiment

Experiment type	Characteristics of plants			Experimental status		
	Species of plant	Average thickness per leaf (mm)	Plant height (cm)	Coverage ratio of plant (%)	Layer of plant	Background temperature (°C)
Indoor experiment	*Codiaeum variegatum* cv. 'Indian Blanket' (1)	0.45 ± 0.04S.E.	60	100, 80, 60, 40, 20	1–7	28
	Cordyline terminalis cv. 'Aichiaka' (1)	0.23 ± 0.005S.E.	75	100, 80, 60, 20	5, 8	28.2
	Ixora duffii cv. 'Super King' (1)	0.35 ± 0.011S.E.	65	100, 80, 40, 20	1, 4, 6, 8	28.5
Outdoor experiment	*C. variegatum* cv. 'Indian Blanket' (2)	0.45 ± 0.04S.E.	60	70	6	25.6
	C. terminalis cv. 'Aichiaka' (2)	0.23 ± 0.005S.E.	70	50	6	26
	Duranta repens cv. 'Golden Leaves'	0.27 ± 0.014S.E.	50	100	5	24.1
	I. duffii cv. 'Super King' (2)	0.35 ± 0.011S.E.	70	90	8	29.6

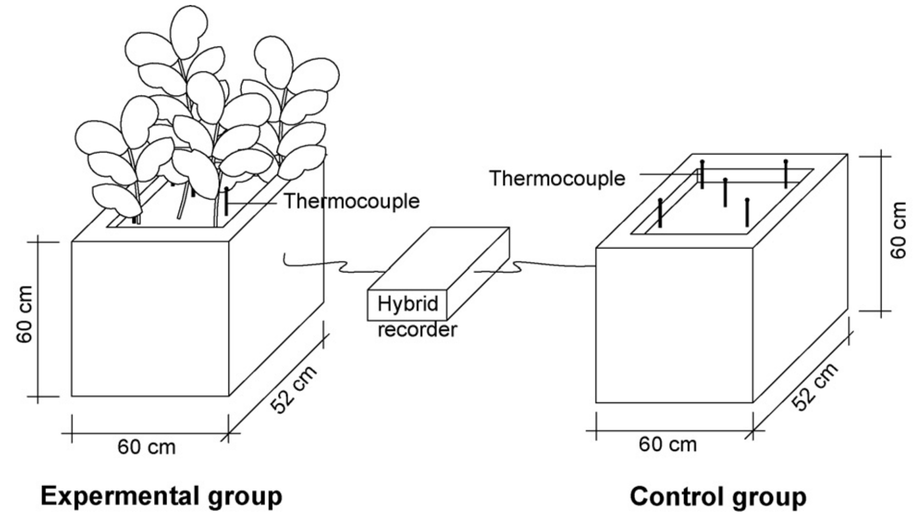

Fig. 2. Outdoor measuring system.

The thermocouple was calibrated with an error margin of ±0.2 °C. The white nylon threads were netted (forming squares 8 cm × 8 cm) to fix the plants and assist in estimating coverage ratio. A limiting duration of 30 s was allocated per measurement.

The soil block around plant roots was removed to eliminate the thermal conductive effect of soil when determining the thermal reduction effect of plants. The parameters in this study were CR and TLT. Various planting arrangements with measured CR and TLT values were placed in this chamber, and the temperature measured (T_P). The control set (CR = 0%) was established by removing all plants out of the experimental chamber, and measuring the temperature (T_0). The thermal reduction rate (TRR, %) was derived from atmospheric temperature (T_A), T_P and T_0:

$$\mathrm{TRR} = \left(\frac{T_0 - T_P}{T_0 - T_A}\right) \times 100\% \tag{1}$$

The temperature data of *C. variegatum* (1) from various CR and TLT settings were recorded by hybrid recorder and then transformed into TRR data. A map was constructed with axes x and y representing CR and TLT. TRR was plotted for various CR and TLT and a thermal reduction ratio map (TRR map) was finalized through the curve fitting process.

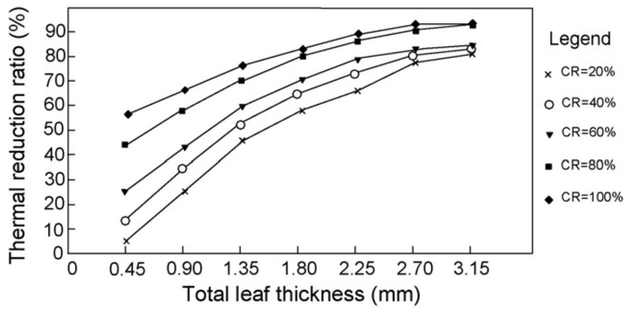

Fig. 3. Temperature and TRR for various CR and TLTs of *Codiaeum variegatum* (1).

C. terminalis (1) and *I. duffii* (1) were used in identical experiments to verify the applicability of the TRR map for various plant species.

2.3.2. Outdoor experiment

C. variegatum (2), *C. terminalis* (2), *D. repens* and *I. duffii* (2) were placed on a rooftop to verify the utility of the TRR map in the field. The plants were planted in pots (Fig. 2) and insulation was applied to cover the pot. Five thermocouples were placed below the plant and 10 cm above the soil. A control group was performed without plants.

3. Results

3.1. Relationship between CR, TLT and TRR

The results reveal that as CR and TLT increase, TRR increases (Fig. 3). The TRR of various CRs was logarithmically

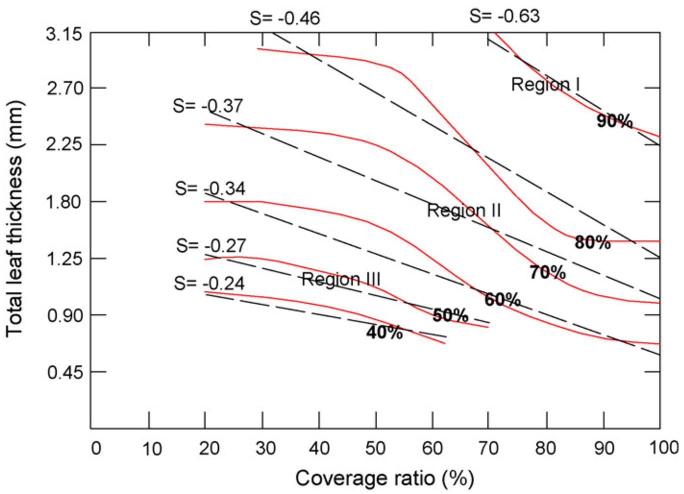

Fig. 4. Map of thermal reduction ratio (TRR map) by plants. The solid lines indicate the curve fitting of TRR and the dotted line indicate the curve fitting of the solid line. The symbol *S* is the slope of the curve fitting line.

and positively related to TLT. TRR increased rapidly with TLT when TLT $\leqq$ 2.25 mm and slowly when TLT > 2.25 mm. TRR increased slowly along with TLT when CR was 100–80% and rapidly when CR was 60–20%.

3.2. *Thermal reduction ratio map (TRR map)*

A map of the effects of CR and TLT on TRR was constructed (Fig. 4). TRR increased with CR and TLT. To facilitate analysis, the entire area was divided into three regions (I, II, III) at the 80% and 60% lines. Region I, where TRR exceeded 80%, was associated with the greatest thermal reduction effect. The slope in this region was $\leqq -0.46$. Region II was associated with the second strongest thermal reduction effect, with TRR values between 80% and 60%. The slope in this region was -0.46 to -0.34. Region III was associated with the smallest thermal reduction effect, with TRR values under 60%. The slope in this region exceeded -0.34. The slope was negative for all TRRs, indicating that CR was negatively correlated with TLT on TRR.

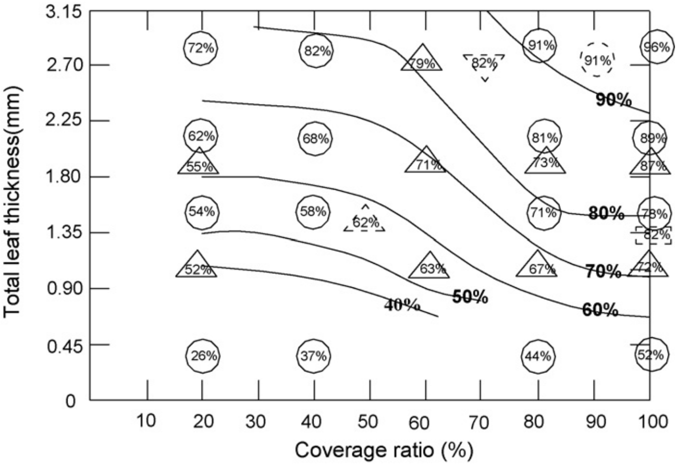

Fig. 5. Verifying the TRR-map with different plant species. Percentages represent TRR. (△) *Cordyline terminalis* cv. 'Aichiaka' (1); (○) *Ixora duffii* cv. 'Super King' (1); (△) *C. terminalis* cv. 'Aichiaka' (2); (○) *I. duffii* cv. 'Super King' (2); (▭) *Duranta repens* cv. 'Golden Leaves'; (▽) *Codiaeum variegatum* cv. 'Indian Blanket' (2).

3.3. *Verifying results with different plant species*

C. terminalis (1) and *I. duffii* (1) were used in the indoor experiment. Results show that most TRRs of *C. terminalis* (1) and *I. duffii* (1) were consistent with the TRR map (Fig. 5) with an error margin of 3–20%.

C. terminalis (2), *C. variegatum* (2), *D. repens* and *I. duffii* (2) were employed in the outdoor experiment. The results (Fig. 5) indicate that the TRR map was consistent with field conditions, and the error margin was less than 10%. Restated, the applicability of the TRR map for various species of plants in the field was confirmed.

4. Discussion

4.1. *CR and TLT*

CR is positively related to TRR (Fig. 3). The area of shadow increases with CR, reducing the transmission of solar radiation and increasing the thermal reduction effect. TRR increased slowly with TLT when CR was between 100% and 80%, indicating that the effect of CR on thermal reduction exceeded that of TLT. Restated, the thermal reduction effect of increasing CR was stronger than that of increasing TLT, at CR values of over 80%. When CR was under 80%, TRR increased or decreased rapidly along with increases or decreases in TLT, revealing that the effect of TLT on thermal reduction exceeded that of CR. Restated, when the CR of tested plants was less than 80%, thermal reduction was more effectively achieved by increasing TLT.

TRR was positively related to TLT (Fig. 3), since a higher TLT is associated with greater thermal resistance, and better thermal reduction effect. When TLT was under 2.25 mm, TRR varied rapidly, suggesting that increasing TLT effectively reduced the thermal energy. Plants can reduce the thermal energy of solar radiation by 70–90%. When the measures of TLT exceeded 2.25 mm, TRR measurements for all coverage ratios increased slowly. This is because 70–90% of thermal energy was eliminated by leaves, leaving only 10–30% of thermal energy remaining. Accordingly, plants should be used

Table 2
CR, TLT and layers[a] of various plants required to reach a target TRR of 80%

Species	Average thickness per leaf (mm)	40%[b] (TLT[c]: 2.93 mm)	50%[b] (TLT[c]: 2.7 mm)	60%[b] (TLT[c]: 2.46 mm)	70%[b] (TLT[c]: 2.03 mm)	80%[b] (TLT[c]: 1.89 mm)
Hymenocallis speciosa	0.68	4	4	4	3	3
Garcinia subelliptica	0.49	6	6	5	4	4
C. variegatum cv. 'Indian Blanket'	0.45	7	6	5	5	4
D. repens cv. 'Golden Leaves'	0.35	8	8	7	6	5
Schefflera arboricola cv. 'Hong Kong'	0.34	9	8	7	6	6
C. terminalis cv. 'Aichiaka'	0.23	13	12	11	9	8
Acalypha wilkesiana	0.20	15	14	12	10	9
Rhapis excelsa	0.16	18	17	15	13	12
D. repens cv. 'Golden Leaves'	0.27	11	10	9	8	7

[a] Number of layers of plants required to achieve 80% TRR.

[b] Coverage.

[c] The TRR map suggests the TLT and CR of the plant to produce 80% TRR.

to reduce solar energy only if TLT exceeds 2.25 mm, yielding a TRR of over 70–90%.

4.2. TRR map

This study converted the TRR of CR and TLT into a concise TRR map (Fig. 4). The slope of TRR in the TRR map was negative, indicating that as CR increases, less leaf thickness is required to reduce thermal energy. Conversely, as CR decreases, TLT must be increased to maintain equivalent thermal reduction rates. Briefly, CR and TLT have a complementary effect in reducing thermal energy.

The TRR map reveals that when CR was 20–50% and TLT was more than 2.7 mm, a TRR of 70–80% can still be achieved. In other words, even when 80–50% of an area is exposed to sunlight, a 70–80% TRR can still be attained by adding more plant layers. The research suggests that as the plant layers or number of leaves increase, the total leaf edge also increases. Diffusion occurs when light passes around leaf edges, thus reducing solar radiation. In conclusion, when TLT increases, the total length of leaf edge also increases, thereby enhancing light diffusion and TRR.

The TRR map provides quantitative guidelines for environmental designers to choose heat-reducing plants for green roofs. If a designer aims to reduce TRR by 80%, he/she may refer to Region I of the TRR map to select a combination of different CR and TLT values such as 60% CR and 2.7 mm TLT, or 85% CR and 1.8 mm TLT. A TRR map represents the complementary relationships between TRR and both CR and TLT, and provides a recommended range for a more flexible use of plants to produce thermal reduction effects.

Numerous works have used LAI as an important parameter in predicting models of thermal behavior of green roofs [5,6]. LAI stands for leaf area per unit ground area. However, the apparatus for measuring LAI is expensive and LAI cannot easily be determined by environmental designers. This investigation employs CR as a parameter, representing the ratio of leaf coverage area to ground area. The meaning of CR is similar to that of LAI. Additionally, the TLT parameter used in this study has employed the thermal resistance concept into the TRR map. Both CR and TLT can be measured by eye and micrometer, and are thus easily obtained. Consequently, the TRR map that consists of CR and TLT is simple and easy for a planting designer to use.

4.3. Selection of plant species for thermal reduction effect

Environmental designers can design plant layers on rooftops to have a desired thermal reduction effect according to the TRR map. For example, 70% CR and 2.25 mm TLT (Table 2) were chosen to produce 80% TRR using *Schefflera arboricola*. The individual leaf thickness of *S. arboricola* was estimated to be 0.34 mm. Hence, seven layers of leaves are required to obtain a TLT of 2.25 mm. In conclusion, *S. arboricola* should be planted to yield 70% CR and seven layers are required to produce a TRR of 80%.

This study provides a novel and straightforward method to evaluate the thermal reduction effect of plant layers on rooftops. This method can be used to construct TRR maps for each plant species. TRR maps can be used to propose planting arrangements that can attain, to a certain degree of accuracy, thermal reduction objectives for green roofs.

5. Conclusion

The study considers the thermal reduction effect of plant layers on roof gardens. The parameters herein were the coverage ratio (CR) and the total leaf thickness (TLT) of plants. The plants were employed in an indoor experiment with controlled environmental conditions. A thermal reduction ratio map (TRR map) with two parameters was constructed. The adaptability of the TRR map was confirmed using various species of plants on an actual roof. The results were summarized as follows:

1. CR was positively related to TRR. When CR exceeded 80%, the slope of TRR against TLT was shallow, revealing that the impact of CR was prominent. Therefore, altering CR has a greater influence on TRR. When CR was under 80%, the slope of TRR against TLT was high, indicating that the impact of TLT was significant, and that increasing TLT may have a greater effect on thermal reduction.
2. TLT was positively correlated with TRR. The thermal reduction was effective when TLT exceeded 2.25 mm.
3. The TRR map showing the relationship with CR together with TLT was plotted. It showed that the relationship of CR and TLT was complementary on thermal reduction effect. That is, a greater coverage ratio means a smaller total leaf thickness is required; conversely, a smaller CR means a greater TLT is required in planting designs for thermal reduction. The TRR map was confirmed using various plant species in both a controlled indoor environment and on the roof. The TRR map is appropriate for different plant species on rooftops.
4. The TRR map (Fig. 4) and Table 2 provide quantitative information on thermal reduction by plant layers of green roofs. This study offers simple and easily implemented suggestions for heat insulation using green roofs.

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