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Characteristics of Thermal Performance on the Different Ambient Air Temperatures of Green Roof Plants

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Abstract - **Changes in land use and increase in urban energy consumption influence urban life. This study analyzed the characteristics and patterns of urban heat and presents management schemes to generate a comfortable and sustainable urban environment. The study aimed to demonstrate the positive effects of artificial ground greening on improving the microclimate through evapotranspiration using perennial herbs. We have designed a chamber that could control constant temperature and humidity, measure temperature reductions in each plant and changes in sensible heat and latent heat. This study identified *Sedum kamtschaticum* as the most effective plant in controlling temperature. At 22°C, 3.2°C temperature reduction was observed, whereas four other plants showed a 1.5°C reduction. At 25°C, 2.0°C temperature reduction was observed. On the other hand, the use of *Sedum sarmentosum* resulted in the lowest effect. *Zoysia japonica* is the most commonly used ground covering plant, although the temperature reduction of *Lysimachia nummularia* was more effective at high temperature conditions. Sensible heat and latent heat were calculated to evaluate the thermal performance of energy. At a temperature >30°C, *L. nummularia* and *S. sarmentosum* emitted high latent heat. In this study, we analyzed the thermal performance of green roof perennial plants; in particular, we analyzed the evapotranspiration and temperature reduction of each plant. Since the substrate depth and types, plant species, and seasonal change may influence temperature reduction and latent heat of green roofs, further studies are necessary.**

Key words : green roofs, urban green system, biotop

INTRODUCTION

Urban green space, which consists of trees, herbs, and soil within the city, serves to lower the ambient temperature by blocking or absorbing solar radiation on buildings and acting as an evapotranspirator. In cities where land value is high and the use of land as green space is unfeasible, greening of structures that utilizes the three-dimensional aspect of buildings, without incurring the additional costs associated with land acquisition and maintenance of open land or parks has emerged as an economical and practical solution.

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The need for the development of a structure greening method that does not put stress on the weight load and is applicable to currently standing buildings, minimizes maintenance costs following its implementation, and controls the microclimate as well as improves the urban environment. In light of the increased interest in the perpendicular wall greening system, much research is underway regarding systemization methods that incorporate plants, plant foundations, and irrigation. However, while development regarding soil material and mixture, construction method, and module system has seen progress, investigation of plants that are appropriate for a low-maintenance, lightweight greening system, but nonetheless maximizes the environmental effects that a green space provides, has been lacking.

The evapotranspiration rate is higher in herbaceous plants than in trees. Perennial plants of Korea survive the harsh climates of summer monsoons and cold winters, grow and flower in the spring and autumn months, and stay throughout autumn and winter as an evergreen or die and return the following spring from their surviving rootstock. Such plants have high water content as well as high rainwater storage capacity to weight ratio, which makes them effective urban microclimate controllers. In addition, roof greening can suppress the influx of conductive heat into the building, as well as impart temperature cooling effects with latent heat caused by evapotranspiration from plants and soil, which not only reduces the air conditioning load with its insulating capability, but on a broader scale, can also alleviate the urban heat island effect as well as improve the urban environment.

Thus, further development of the green structure system should involve the creation of an ecological building envelope that can effectively perform environmental and ecological functions, including the optimal growth of plants. Furthermore, the effects of these efforts should be predictable.

The purpose of this study was to calculate the energy functions of a green system structure and to describe the optimal properties of each green roof plant through heat analysis of a layer of vegetation, focusing on factors that can be applied to a building energy simulation program.

MATERIALS AND PROCEDURES

Through literature reviews, the heat balance movement model of a vegetation layer required in a building energy simulation tool was analyzed. Based on this, the thermal performance of major green roof plants in a given unit of space were analyzed and compared to obtain the material properties of input elements. The study procedures were as follows:

(1) The input elements of vegetation layer and soil layer applicable to the building energy simulation tool, EnergyPlus' Ecoroof module, were obtained. The evapotranspiration model of plants was reviewed to explain the basis of Ecoroof module's calculations.
(2) For the analysis of Ecoroof module's plant heat balance, the thermal performances of plants in a given unit of space at different temperature settings were measured.
(3) For the analysis of the dynamic thermal performance of a vegetation layer, the change in sensible heat and latent heat of the plant space was measured, and the differences among the plant species were examined. The thickness of the soil layer and the leaf area index (LAI) of the vegetation layer was kept constant.

LITERATURE REVIEW

1. Green roof model

The current numerical interpretation of vegetation layer thermal flow, from which the algorithm was generated, was based on a basic plant growth model. The two well-known vegetation indices of plant growth model are LAI, the projected leaf area per unit area, and fractional vegetation coverage (FVC), which is the unit area per area shaded by the vegetation (Ministry of Environment 2009).

$$LAI = 1.5 \times \ln(hc) - 1.4 \quad (1)$$

$$FVC = 1 - \exp(-0.75\, LAI) \quad (2)$$

The building energy interpretation program, Energy Plus, calculates the efficiency of green roofs based on LAI values, utilizing conditions such as soil depth, stomatal conductance, and leaf area of a plant, and soil moisture including its watering conditions as input parameters. The greening process is divided into the vegetation layer (F_f) and soil layer (F_g), and the variables associated with the flow of latent and sensible heat are included to produce a calculable equation.

Before the energy flow of the green roof plant area was calculated, it was first divided into the vegetation layer and soil layer using as parameters the amount of sunlight reaching the plantedarea, radiation heat in the surrounding area, and the changes in latent and sensible heat according to the absorption capability of the plant and soil.

The vegetation layer model was interpreted as the amount of long-wave and short-wave sunlight absorbed by the plant leaves above the soil, amount of diffused sunlight that is reflected between the leaves, and the thermal flow of the latent and sensible heat of the vegetation layer. The thermal flow of the vegetation layer was expressed as follows:

$$F_f = \sigma_f\{Is^{\downarrow}(1-\alpha_f) + \varepsilon_f Iir^{\downarrow} - \varepsilon_f \sigma T_f^{\,4}\} + \varepsilon_1 \frac{\sigma_f \varepsilon_\varepsilon \varepsilon_f \sigma}{\varepsilon_1}(T_g^{\,4} - T_f^{\,4}) + H_f + L_f \tag{3}$$

$$H_f = (1.1 \times LAI\rho_{\alpha f} C_{\rho,\alpha} C_f W_{\alpha f}) \times (T_{\alpha f} - T_f) \tag{4}$$

$$L_f = l_f \times LAI\rho_{\alpha f} C_f W_{af\gamma} \times (q_{af} - q_{f,sat}) \tag{5}$$

where F_f represents the net thermal flow of the vegetation layer; H_f is the sensible heat flow of the vegetation layer; L_f is the latent heat flow of the vegetation layer; σ is the Stefan-Boltzmann constant (5.699×10^{-8} W m^{-2} K^{-4}); and σ_f is FVC. $Is^{\downarrow}$ is the total inflow of short-wave radiation (W m^{-2}); $Iir^{\downarrow}$ is the total inflow of long-wave radiation (W m^{-2}); αf is the vegetation canopy albedo; T_g is the surface temperature (K); and T_f is the leaf temperature (K). ε_f is the vegetation canopy emissivity; ε_g is the surface emissivity; and ε_1 is given by the emissivity equation $\varepsilon_1 = \varepsilon_f + \varepsilon_g - \varepsilon_f \cdot \varepsilon_g$.

The main variables in the vegetation layer model were classified as environmental characteristics or vegetation characteristics, and environmental characteristics were inputted using various weather databases. Thus, this study determined the variable vegetation characteristics by calculating the change in latent and sensible heat for each plant using the same soil composition and environmental conditions.

2. Plant evapotranspiration model

In the building energy simulation, changes in heat balance of the green building vegetation layer serve as bases of the plant evapotranspiration model.

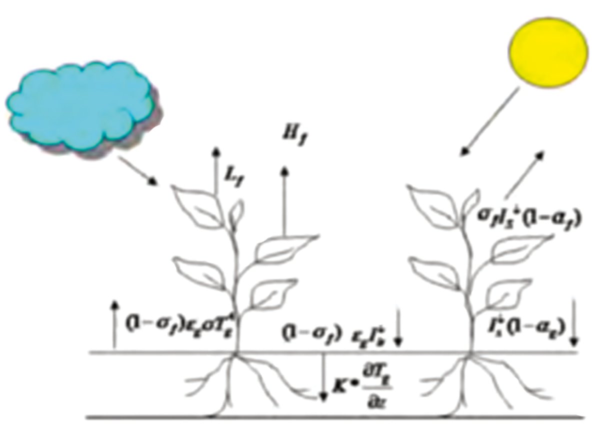

Fig. 1. Thermal performance model of a green roof vegetation layer.

Evapotranspiration from a plant community is influenced by the sun's radiation energy, atmospheric humidity, temperature, and turbulence, the organization of the plant community, and the moisture status of the soil and plant. There are several ways to predict and determine evapotranspiration, but the simplest and the most widely used method is the Penman-Montieth equation (Monteith 1965). This equation was originally used to predict evapotranspiration from a single leaf, although several variants are currently used to explain the interaction between large-scale crops and the atmosphere.

Penmann previously described the evaporation process from an aerodynamic perspective of turbulence motion caused by eddy diffusion, and an energy budget perspective that is related to radiant energy distribution. Montieth (1996) created an equation that can be more universally used by incorporating energy budget, aerodynamic parameters, and surface temperature. Using thermodynamics, he used wet-bulb temperatures and the Clausius-Clapeyron (henceforth written simply as CC) equation to come to Penman's equation. Then, in cases where vapor is not saturated, he used Ohm's Law from electromagnetics to introduce the concept of surface resistance regarding vaporization flux in an equation shown below.

$$\lambda E = \frac{\Delta A + \rho C_p[e_w\{T(z)\} - e(z)]r_{ah}}{\Delta + \gamma(r_{av} + r_{st})/r_{ah}} \tag{6}$$

where r_{st} is the stomatal resistance; r_{ah} and r_{av} are the aerodynamic resistances of heat and vapor, respectively, between the plant and its height; ρ is the air density; γ is the psychometric constant; e is the vapor pressure; e_w is the saturation vapor pressure; Δ is the temperature-dependent change in saturation vapor pressure; c_p is the specific heat at constant pressure; and A is the available energy.

In principle, the PM equation only predicts evapotranspiration from a single leaf. Accordingly, the expansion or conversion of PM equation to a different form must be considered. A parameterization method that applies PM equation under the assumption that a plant community is a one large leaf is known as the big leaf model or the single source model. Under this assumption, the evapotranspiration rate can be calculated using whole stomatal conductance (the reciprocal of stomatal resistance) that represents the plant community and the observed climate data (Equation 7).

$$\frac{\lambda E}{A} = \left(\varepsilon + \frac{g_{ah}}{g_i}\right) / \left(\varepsilon + 1 + \frac{g_{ah}}{g_{st}}\right) \quad (7)$$

where g_{ah} is the aerodynamic conductance of sensible heat; and g_{st} is the stomatal conductance. Here, $\varepsilon = \Delta / r$; and $g_i = rA/\rho C_\rho \delta_e$. It is composed of climate factors such as temperature, humidity, and net radiation and is known as climate conductance.

Equation 7 shows the distribution of energy or how much of the available energy is used in evapotranspiration, according to the relative proportions of the three conductances (g_i, g_{st}, g_{ah}) that are related to climate, stoma, and aerodynamics.

One caveat is that the PM equation is a nonlinear equation, which creates problems when stomatal conductance of each individual leaf is treated in a linear manner, and this is also reflected in the observation results (Kaimal and Finnigan 1994).

In order for the assumption that the whole plant community is one large leaf to be met, Kim and Verma (1996) suggested that the plants must cover the entirety of the soil to nullify evaporation from the soil, a single plant species must exist in the target area under homogeneous conditions, and the temperature within the community must be constant at a given height. As such, this study was conducted under the conditions suggested by Kim and Verma (1996) to determine the differences in performance between vegetation layers under the supposition that the vegetation layer is a single community unit.

CHARACTERISTICS OF THE VEGETATION LAYER TEMPERATURE CHANGES

1. Experimental plot composition and analysis method

Thermal performance efficiency through structure greening is dependent on ambient conditions and components of the vegetation layer. Material properties such as soil density, thermal capacity, thermal conduction, and radiation significantly vary according to soil moisture level, and such moisture transport characteristics of the soil vary according to the evapotranspiration characteristics of each plant.

To measure the temperature change per unit area caused by plants, a 1400 (W) mm × 800 (D) mm × 1200 (H) mm (1344 L) constant-temperature/humidity chamber with temperature and humidity controls were specially created for this study. The specifications of the experimental chamber are shown in Table 1.

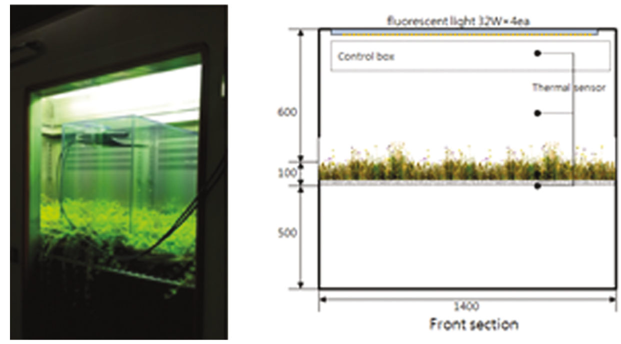

Fig. 2. Experimental constant-temperature/humidity chamber.

Table 1. Experimental Chamber condition

Environment contents	Conditions
Size	1,400 (W) × 800 (D) × 1,200 (H) mm
Flow	800 CMH
Air exchange rate	0.5 m sec^{-1}
Lighting	12,000 lux

The plants used in this study were groundcovers found under trees and shrubs. Ten species were selected from 30 species that are typically used as green roof plants. One year after seeding, each plant was planted in a 53 cm × 35 cm × 8 cm pot and grown for two weeks to promote root growth. The plants preferred in roof greening typically require relatively low amounts of water and are easy to care for. The 10 species used in the experiment and their water requirements are presented in Table 2.

The properties of the artificial soil used in this study in accordance with the standards set by the Artificial Greening Association are shown in Table 3.

To maintain the outdoor illuminance of the unit space, the illuminance was kept at 12,000 lux and the wind speed within the space was kept at 0.5 m s^{-1}.

At a humidity level of 50%, the plant surface temperature and the ambient temperature of the chamber were measured every 10 min at set temperatures from 22°C to 40°C. To calculate the change in latent heat of the vegetation layer, the temperature setting was changed by 2°C every 2 h, and the slope of the room temperature change was analyzed. Five trials of the thermal environment measurements were

Table 2. Growth condition of Experimental plants

Scientific name	Growth conditions		
	Soil depth	Water requirement	Light requirement
Zoysia japonica	20 cm	High	Sunny
Sedum sarmentosum	10 cm	Low	Sunny
Lysimachia nummularia	10 cm	Medium	Semi-sunny
Sedum kamtschaticum	10∼20 cm	Low	Sunny
Liriope platyphylla	20∼30 cm	Medium	Semi-sunny

Table 3. Property of artificial soil

Item	Required performance	Unit
Moisture proportion	0.8∼1.0	
Effective moisture content	0.12	$m^3 m^{-3}$
Porosity	0.6	$m^3 m^{-3}$
Permeability coefficient	1∼3	$cm\ s^{-1}$

carried out for each plant species.

$$q_{SH} = C_p \times G(t_B - t_A) \quad (8)$$

q_{SH}: heating rate (or cooling rate) [$kcal\ h^{-1}$]

C_p: specific heat at constant pressure [$kcal\ kg^{-1}\ °C^{-1}$] (C_p of air is 0.24)

G: airflow [$kg\ h^{-1}$]

$t_B - t_A$: dry-bulb temperatures at points A, and B [°C]

$$L = G \times (x_B - x_A) \quad (9)$$

L: humidification or dehumidification rate [$kg\ h^{-1}$]

G: airflow [$kg\ h^{-1}$]

x_B, x_A: absolute humidity at points A, and B [$kg\ kg'^{-1}$]

To determine the thermal performance of a plant on the indoor thermal environment, sensible heat changes, the quantity of heat used to change the temperature of the constant-temperature/humidity growth chamber regardless of change in conditions, and latent heat changes, the quantity of heat transpired from the plant or evaporated from the soil, were investigated. The quantity of heat qSH [$kcal\ h^{-1}$] required for sensible heat changes were calculated using Equation 8, and latent heat changes were calculated using Equation 9.

2. Characteristics of thermal performance of plants by temperature

Plants, which expel moisture through transpiration, can impart climate controlling effects on cities that are often dry due to impermeable pavements by creating an agreeable environment through temperature and humidity control (Eumorfopoulou and Aravations 1998). In effect, the average, high, and low temperatures were shown to be lower in green roofs than normal roofs in most cases, and the degree of difference between the daily high and the daily low were also shown to be smaller in green roofs (e.g. Lee 2003).

Roof greening was shown to stabilize and maintain the temperature, as well as prevent the transfer of heat into the building. The plant surface temperature was shown to be lower than the normal surface temperature, heat transfer was greater in exposed rooftops than a rooftop covered with soil, and the insulating effect of wet soil was greater (Sung and Min 2003). Similarly, plants placed indoors at temperatures higher than the optimum temperature displayed a cooling effect through their physiological activities, and showed a tendency to lower the temperature in a high-temperature indoor environment while keeping the temperature steady in a room-temperature environment.

Measurements of the surface temperatures of greening plants at various temperature settings revealed the following results:

The temperature of the control group that contained no plants, the no-plant group, was on average 1.5°C higher than the temperature setting.

The *Z. japonica* vegetation group maintained a stable temperature at a temperature setting of 22°C. At 25°C and 28°C, the temperature decreased by 0.5°C and 0.9°C, respectively. The cooling effect was greatest at 34°C and 37°C, with a temperature decrease of 1.4°C and 1.6°C, respectively. *S. sarmentosum* maintained a level within 0.1°C of the temperature setting of 22°C, but the temperature was progressively cooled by 0.1°C each at 25°C, 28°C, and 31°C. The degree of temperature reduction was smaller in *S. sarmen-*

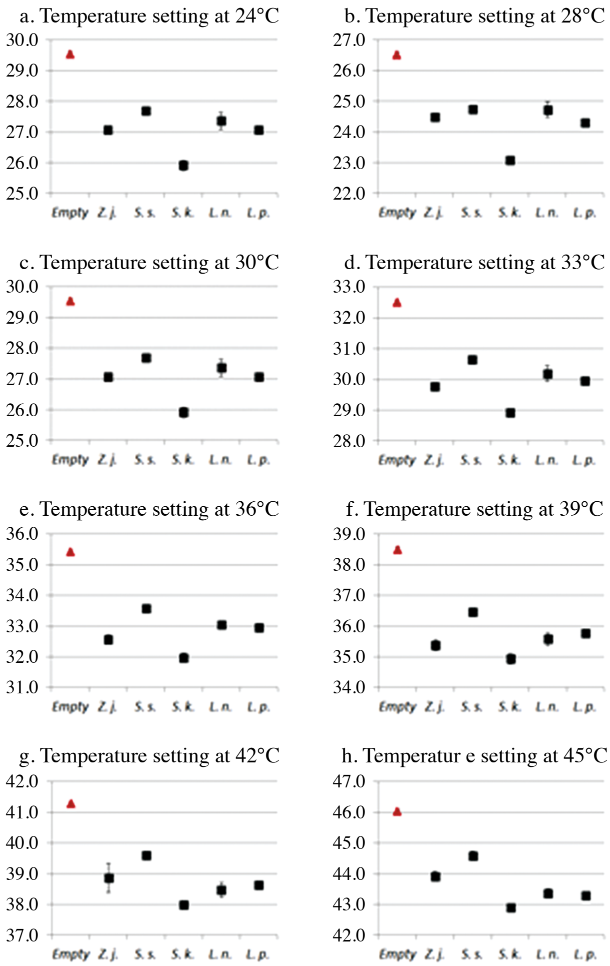

Fig. 3. Characteristics of plant-induced temperature change at various temperature settings.

tosum than other plants.

S. kamtschaticum displayed a minimum temperature cooling effect of 1.5°C and a maximum of 2.1°C. In particular, the temperature consistently measured approximately 2°C lower even at high temperature settings.

L. nummularia did not show much difference at a temperature setting of 22°C, but displayed stable cooling effects as the temperature increased. At 37°C, 40°C, and 45°C, the temperature measured on average 1.5°C lower. *L. platyphylla* at 22°C and 25°C showed a reduction of 0.2°C and 0.7°C, respectively. At 37°C, 40°C and 45°C, the temperature was cooled by 1.2°C, 1.4°C, and 1.7°C, respectively, displaying the greatest cooling effect at the high temperature setting of 45°C.

S. kamtschaticum showed the greatest difference compared to the no-plant group. Its cooling effect was 1.0°C~2.0°C lower than other plants, indicating that *S. kamtschaticum* is the most suitable greening plant for improving the thermal environment.

Z. japonica, which is commonly used for large-scale greening, displayed the best cooling effect around 35°C, whereas *L. nummularia* and *L. platyphylla* displayed better cooling effects than *Z. japonica* at high temperatures >40°C.

At a temperature setting of 22°C, *S. kamtschaticum* maintained a temperature lower than the no-plant group by 3.2°C, whereas other plants displayed a cooling effect of approximately 1.5°C.

At 25°C, *S. kamtschaticum* again showed the greatest cooling effect. The temperature of the no-plant group was 26.5°C, and *S. kamtschaticum* lowered the temperature by 3.4°C, whereas the other plants lowered the temperature by approximately 2.0°C.

The ability of the plants to improve the thermal environment was greater as temperatures exceeded 27°C, and the pattern of change was similar for all plants.

3. Change in quantity of sensible heat for each plant caused by temperature change

The results of sensible heat changes caused by temperature changes of greening plants are presented in Table 4.

When the temperature setting was increased from 22°C to 45°C in the chamber containing no plants, the ambient temperature increased at a slope of 0.15 ± 0.02°C min^{-1}. The changes in the thermal environment caused by transpiration of plants were compared between plant species, and *L. nummularia* displayed the slowest increase in temperature at 0.05 ± 0.00°C min^{-1}.

S. kamtschaticum, which is frequently used as a green roof plant and is effective in temperature cooling due to its high quantity of evapotranspiration, showed a temperature change rate of 0.22 ± 0.01°C min^{-1} at 25°C, which was similar to the humidity change rate, but was calculated as 0.22 ± 0.01°C min^{-1} above 31°C. However, at conditions above 34°C, the humidity change rate relative to the temperature change rate sharply decreased, with evapotranspiration reaching negative values. This contrasts the results discussed above that showed that *S. kamtschaticum* showed the greatest temperature cooling effect. Thus, it is believed that fur-

Table 4. Temperature change rate of the vegetation layer by temperature change

Plant	22°C~25°C	25°C~28°C	28°C~31°C	31°C~34°C	34°C~37°C	37°C~40°C	40°C~45°C
Empty	0.08±0.64	0.10±0.21	0.10±0.42	0.09±0.07	0.10±0.14	0.09±0.07	0.10±0.07
Z. japonica	0.10±0.15	0.09±0.15	0.10±0.32	0.10±0.15	0.08±0.75	0.10±0.12	0.14±1.01
S. sarmentosum	0.10±0.06	0.09±0.15	0.08±0.49	0.10±0.10	0.10±0.12	0.10±0.00	0.15±0.06
S. kamtschaticum	0.10±0.21	0.09±0.06	0.07±0.46	0.10±0.06	0.09±0.06	0.09±0.06	0.15±0.23
L. nummularia	0.09±0.21	0.10±0.06	0.10±0.46	0.10±0.06	0.09±0.06	0.09±0.06	0.16±0.23
L. platyphylla	0.08±0.17	0.08±0.20	0.09±0.06	0.09±0.15	0.09±0.15	0.09±0.15	0.14±0.12

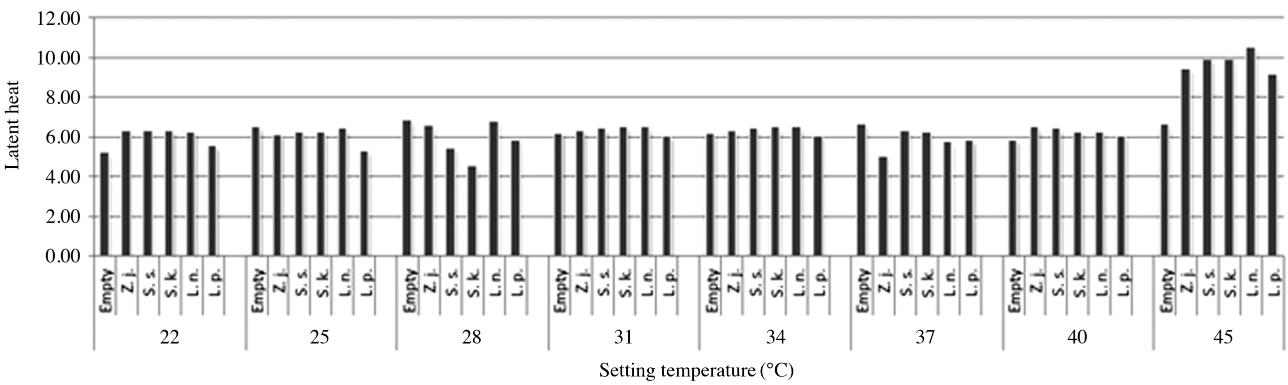

Fig. 4. Temperature change rate of the vegetation layer by temperature change (°C min^{-1}).

ther research regarding the correlation between latent heat quantity and condition-dependent evapotranspiration of the genus Sedum will be required.

Quantity of latent heat was calculated for *S. sarmentosum* and *Z. japonica*, which grows relatively easily at high temperatures, at change conditions from 28°C to 31°C because the temperature change rate was constant while the humidity change rate was high. *Z. japonica* displayed constant temperature and humidity change rates at 25°C, but the humidity change rate slightly increased relative to the temperature change rate at 28°C. At higher temperature settings above 31°C, the humidity change rate showed a similar change pattern to the temperature change rate, and the quantity of latent heat could not be calculated at temperature settings of 34°C, 37°C, 40°C, and 45°C.

S. sarmentosum displayed a somewhat limited temperature cooling effect compared to other plants, but results of its evapotranspiration performance on the temperature and humidity change curve showed that a large quantity of latent heat was released at change conditions from 28°C to 31°C. At high temperature settings 37°C, 40°C, and 45°C, the humidity change rate increased slightly, or stayed level relative to the temperature change rate, and latent heat was continuously released.

The amount of evapotranspiration of *L. nummularia* slightly decreased at a temperature setting of 25°C, but showed an increasing trend past 28°C. In fact, between temperatures 31°C and 40°C, the humidity change rate was high, indicating that a large quantity of latent heat was released. Thus it was revealed that the evapotranspiration performance of *L. nummularia* is better at high temperatures than at low temperatures.

L. platyphylla, which prefers the shade and grows easily in semi-shaded conditions, displayed a steady trend of temperature and humidity change rates. The temperature and humidity change rates at given temperature settings showed similar patterns up to 40°C, when the humidity change rate began to decrease sharply. At high temperature settings above 40°C, almost no evapotranspiration occurred due to high temperature stress.

With these results in mind, changes in temperature and humidity of the vegetation layer for each species can in general be associated to growth conditions unique to plants. Analyzing the temperature and humidity change curve revealed that at the optimum plant growth temperature range of 25°C~31°C, the humidity change rate relative to the temperature change rate was in most cases constant or increased, with the evapotranspiration process constantly occurring. In particular, at high temperature settings (37°C∼40°C), the evapotranspiration performance of *L. nummularia* and *S. sarmentosum* was determined as excellent. On the other hand, the evapotranspiration rate decreased for *L. platyphylla*, *S. kamtschaticum*, and *Z. japonica* at the high temperature setting of 37°C, and latent heat was not calculated.

4. Change in quantity of latent heat for each plant caused by temperature change

Increase in latent heat is related to a change in entropy, and thus it is important to measure the amount of latent heat released by each plant.

The temperature and humidity change caused by varying the temperature settings remained constant in the chamber containing no plants, and latent heat was not calculated. Temperature change rate-dependent humidity change rate showed similar patterns at all temperature settings.

For vegetation layers in chambers containing plants, it was determined that the characteristics of each plant correlates to the changes in latent and sensible heat.

CONCLUSIONS

This research was a preliminary study that quantified the thermal environment functionality of green structure systems, and the characteristics of temperature change in the plant space were analyzed to calculate the sensible heat, latent heat, and thermal performance of five plant species commonly used in structure greening. To measure the change in temperature per unit area caused by plants, a 1400 (W) mm × 800 (D) mm × 1200 (H) mm (1344 L) constant-temperature/humidity chamber was specially designed to control for temperature and humidity. Each plant's temperature cooling effects, as well as its latent heat and sensible heat quantities during increases in temperature, was investigated.

Analysis of the differences in plant and ambient temperatures at various temperature settings revealed that the greatest difference occurred in genus Sedum, which is the most commonly used green roof plant. At a temperature setting of 22°C, *S. kamtschaticum* showed the greatest cooling effect, maintaining a temperature 3.2°C lower than the no-plant group, whereas the other four plants cooled the room temperature by approximately 1.5°C. At a temperature setting of 25°C, *S. kamtschaticum* again showed the greatest cooling effect, lowering the temperature by 3.4°C, whereas the other plants lowered the temperature by approximately 2.0°C.

The temperature of the no-plant group was 26.5°C. *S. sarmentosum*, which belongs in the same genus as *S. kamtschaticum*, displayed the weakest cooling effects.

Compared to *Z. japonica*, the most commonly used ground cover species, *L. nummularia* showed the greater cooling effect at higher temperatures.

The change in temperature was measured for each plant in temperature-changing conditions. Analysis of the difference in slopes of temperature change, and the difference in temperature between plants yielded the expected result in that most plants displayed a greater cooling effect at higher temperature settings.

In addition, an accurate calculation of latent heat and sensible heat quantities of the vegetation layer was required for energy performance evaluation, and these characteristics differed according to plant species. In particular, *L. nummularia* and *S. sarmentosum* have high latent heat quantities at conditions above 30°C. One limitation of this study is that the experiment was not conducted at an actual outdoor locale, but rather in a specially designed chamber that controlled for external variables. Further studies conducted in an outdoor locale that augments the sensible heat and latent heat quantity measurement data and allows for the formation of a database regarding the thermal performance of plant materials for green roof systems will largely contribute to the establishment of green roof systems as a viable and ecological building envelope.

The significance of this study lies in the analysis and quantification of thermal performance characteristics and cooling effects of roof/wall greening systems. However, the cooling effects and the thermal performance of a green roof or green wall are not only affected by plant type, but also by other factors such as soil type, soil depth, and seasonal variances, which prompts the need for additional investigations using long-term monitoring studies.

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