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Optical evaluation of the shading properties of climbing fern *Lygodium japonicum* used as a thermal buffering green wall plant

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Abstract: Recently, thermal properties of the landscaped rooftops and walls have attracted the interest of researchers because of the potential to minimize energy consumption in urban areas and to aid summer-time thermal control. For this reason the creation of a plant-based shade for walls or above buildings is highly important. In this paper we evaluate using *Lygodium japonicum,* one of the many ferns and fern allies traditionally used in Japanese gardening, as a component of thermal-buffering green walls. *Lygodium japonicum*, the only climbing fern species in Japan, is fast-growing, adheres easily to walls and has a climbing nature. A simple thermal analysis of the sun-shading effect of *Lygodium* canopy suggested that local surface temperature above the ceramic tiles placed on the rooftop of a building can be buffered (lowered in daytime and maintained relatively warm at night) by the presence of leafy climbing ferns covering the tiles, possibly due to the reflection and absorbance of solar radiation. Furthermore, the presence of the plants may also slow the night-time release of heat from the building surface. Because plants installed on tall walls or on the tops of buildings are not easily accessed for manual care, we performed a real-time routine monitoring and control of plant growth status using various optical sensors that could be automated and monitored remotely for large-scale applications. For this purpose, the optical properties of a *L. japonicum* canopy under solar incident light have been determined. In order to evaluate the natural shading and growing properties of a green canopy, the incident solar radiation spectrum (*J*), leaf canopy-filtered light spectrum (transmittance, *T*) and leaf-reflectivity spectrum (*R*) were measured. By reading the reflectivity spectrum, concomitant chlorophyll fluorescence signals (*F*) from *Lygodium* leaves were also detected at 760 nm, which corresponds to the O_2-A Fraunhofer line. Our data suggests that the daily change in photosynthetic status (*P*) can be traced by monitoring the change in relative *F* in relation to the estimated heat loss (*H*) and measured *J*, *R*, and *T* using a series of practical equations designed to roughly estimate the gross photosynthetic response within the plant canopy. Using our equations, the photosynthetic capacity in the plant canopy structure could be simply simulated and predictable by optical sensors.

1. Introduction

To aid summer-time thermal control in urban areas, the creation of shade above buildings and/or streets is highly important for a number of reasons. First, shade can provide protection for residents and passersby by buffering the changes in housing thermal conditions inside the building and/or local climate on the streets during heat wave attacks, a serious concern as discovered in the case of the historic, heat-related disaster in Paris in 2003 (Keller, 2013). Second, minimizing energy consumption within buildings has become an important goal of architecture and urban planning in recent years. As a result, several guidelines have been developed depending on the climatic zones, aimed at increasing solar exposure for buildings in cold climates and reducing solar exposure for buildings in warm climates (Okeil, 2010).

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The thermal properties of greened rooftops and walls have recently been extensively documented. A study was performed to compare greened and non-greened walls with and without additional covering shade cloths using model buildings with thermal thin walls (Yamasaki *et al*., 2009). By quantitatively evaluating the cooling load reduction effect under/inside the greened roof/walls, the room temperature of the green-covered building was shown to be significantly lower due to the sun-shielding effect of plants covering the building, and electrical power consumption for air conditioning was also lower in the green building. According to this model, around 40 to 45% of energy could be saved in the greened building compared to the non-greened building. It is natural to conclude that lowering total temperature inside the model buildings is the consequence of the local temperature controls on the surface of the walls or roofs.

As a lack of or excess water could drastically alter the growth status of the plants installed, water consumption by the plants needs to be understood. In addition, the rate of water consumption and air-cooling properties of plants have a close relationship since transpiration by plant leaves plays a key role in local heat removal. Therefore, quantitative evaluation of water consumption by a model wall-greening system is of great importance. Toward this purpose, simple models with net-supported vine plants (such as ivy and morning glory) have reportedly been conducted (Takayama *et al*., 2014).

Like other forms of green infrastructure, green façades in which climbing plants are grown either directly against, or on support structures affixed to external building walls, have recently been gaining the attention of architects as a design feature aimed at reducing internal building temperatures, reducing building energy consumption, and facilitating urban adaptation to a warming climate (Hunter *et al*., 2014). Today, such vertical greenery systems (VGS) are viewed as passive tools for energy savings in buildings (Pérez *et al*., 2014). Accordingly, not only the lowering of building temperature, but also many economic, environmental and social benefits are associated with the use of VGS (Safikhani *et al*., 2014). Furthermore, various new green wall construction methods have been developed to date, although many of these technologies have yet to be evaluated and even to be amended, mainly due to the difficulty of maintaining the active growth and development of plants under stressful conditions such as forced adhesion by artificial supports, exposure to thermal stresses, lack of or excess irrigation and/or fertilization on site and on time (Tachibana *et al*., 2011).

Reports on approaches for the greening of buildings using self-growing plants are increasing day-by-day. For an instance, a Canadian team has designed a prefabricated piece to be used on building envelopes, interior partitions, façades or landscape enclosures, in which the vegetation is integrated within the wall construction instead of being adhered to it (Ardila *et al*., 2009). Accordingly, the designed system by an incorporated conduit system included the self-supporting, self-irrigating and self-fertilizing performance for the growing plants. An urban geographer, Gandy (2010), has explored the work of French botanist Patrick Blanc, who applies his knowledge of botany and related sciences to urban wall design with inspiration from the *mur végetal* (green wall) first made in 1988. Blanc intended to transform the urban sceneries into ravines or rainforests by covering the streets and buildings with ferns and mosses.

It is well known in Japan that, second to mosses, many members of Pteridophytes (encompassing ferns and fern allies) have been traditionally used in Japanese garden design (Kawano, 2015). As encouraged by a French botanist, one of the authors (TK) recently propounded that the use of Japanese fern species on green walls and/or roofs is worth pursuing (Kawano, 2015). For this reason, we would like to discuss the criteria for the plant components of heat buffering green walls which should also be applied to the fern species.

The first criterion is the plants' adhesion to the surfaces of walls or roofs. Among the common garden ferns found in Japan, members of Polypodiaceae such as *Lemmaphyllum microphyllum* Presl (Japanese name: *Mamezuta*), *Lepisorus thunbergianus* (Kaulf.) Ching (Japanese name: *Nokishinobu*), and *Pyrrosia lingua* (Thunb.) Farw (Japanese name: *Hitotsuba*) are epiphytic species often attached to trees and rocks. Therefore, these plants can be effectively used to cover walls. However, *Lemmaphyllum microphyllum* is often exposed to competition on the surface of rocks and walls with neighboring epiphytic higher plants such as *Ficus pumila* L. (Moraceae; Japanese name: *Ōitabi*). Therefore, we would like to emphasize that the second criterion for plant components of thermal buffering green walls is that they should be fast growing. The third criterion for green wall ferns must be an ability to not only adhere, but also climb up the poles and nets, and cover irregular walls of the greening structures. The last criterion is the heat-buffering property of the greenery components.

However, to date, studies on the influence of climbing plant characteristics are still very limited, and even fewer works have investigated the impact of green façade design components on thermal performance (Hunter *et al*., 2014).

As a candidate fern species to be listed as a green wall component, *Lygodium japonicum* (Thunb.) Sw. (Lygodiaceae; Japanese name: *Kanikusa*), the only climbing fern species in Japan, is of great interest since this plant species has a fast-growing, wall adhesive, and climbing nature. The sun-tracking and rotating movements associated with the climbing growth in two *Lygodium* members (*L. articulatum* and *L. scandens*) were briefly described by Charles Darwin (1875). In his book, he concluded that "*As ferns differ so much in structure from phanerogamic plants, it may be worthwhile here to show that twining ferns do not differ in their habits from other twining plants*".

Finally, the heat buffering property under solar radiation must be determined with *L. japonicum.* Through the minimal model tests described here, we attempt to demonstrate that local surface temperature above ceramic roof tiles of a building can be effectively buffered, thus lowering daytime temperature and maintaining relative warmth during the night, by the presence over the tiles of leafy climbing ferns, possibly due to reflection and absorbance of solar rays and prevention of the release of heat from the building surface. However, once plants are installed on tall walls or the top of buildings which are far from accessible for manual daily care, real-time routine monitoring and controls of plant growth status should be automated using various optical sensors. For this purpose, background data for optical properties of a *Lygodium* canopy under solar incident light, reflecting the thermal and growing status, have been investigated.

2. Materials and Methods

Plant materials and experimental set up

Lygodium japonicum is commonly known as "Japanese climbing fern". This native fern grows very rapidly and thus often covers neighboring living trees, rocks and walls in gardens (Fig. 1). For ornamental purposes, *L. japonicum* has been exported out of the country. For instance, this plant was introduced in 1932 in Florida, USA (Gordon and Thomas, 1997). In the Hibikino campus of the University of Kitakyushu (Wakamatsu-ku, Kitakyushu, Japan; 33˚ 53'24'' North latitude, 130˚ 42' 49'' East longitude), semi-wildly propagating *L. japonicum* plants (Fig. 1A-E) directly exposed to sunlight were sampled, replanted in pots, and kept in the greenhouse for three days under fluorescent light to recover prior to experiments.

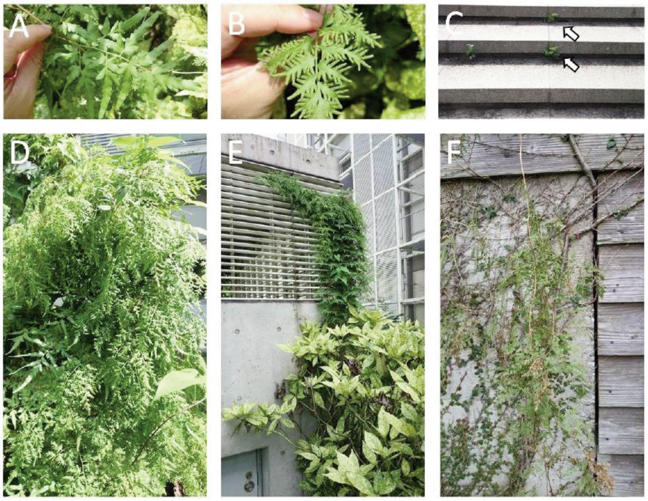

Fig. 1 - The semi-wildly propagating Japanese climbing fern, *Lygodium japonicum,* used in this study. (A) Vegetative leaflet. (B) Reproductive leaflet. (C) Semi-wild plants surviving in the gaps between stones (as indicated by arrows). (D) Aggressive growth of *L. japonicum* winning the competition with other standing plants. (E) Climbing growth of *L. japonicum* on the concrete and aluminum walls, thus naturally greening the building. (F) Even though it came after, *L. japonicum* plants are growing on the concrete wall by rapidly covering over the pre-existing vines of *Ficus pumila* L. Plants were found on Hibikino campus of the University of Kitakyushu, Wakamatsu-ward, Kitakyushu, Japan (A-E), and a private garden in Miyazaki Prefecture, Japan (F).

Model set-up on building roof to measure daytime roof tile temperature with and without Lygodium leaf canopy

The experimental was set up on the rooftop of a building to assess the shading properties of the *Lygodium* canopy (Fig. 2A). *Lygodium* plants were potted and placed on the building roof-top, with bunches of leaflets covering ceramic tiles on which pairs of fine thermocouples (thermal sensors) were set.

We previously reported the real-time measurement of rapid and accurate temperature changes in the micro-environments within a plant cell culturing system (Lin *et al*., 2006). The real-time thermo-sensing units employed here have similar set-ups. The units consist of fine thermocouples (KFT-25-200-100, ANBE SMT Co., Japan), an AD/DA 8 channel converter (MR-500, Keyence, Japan), and a PC with a display (Fig. 2 B-D). Each sensory unit, calibrated immediately before the experiment, possesses small heat capacity, thus enabling immediate and accurate measurements.

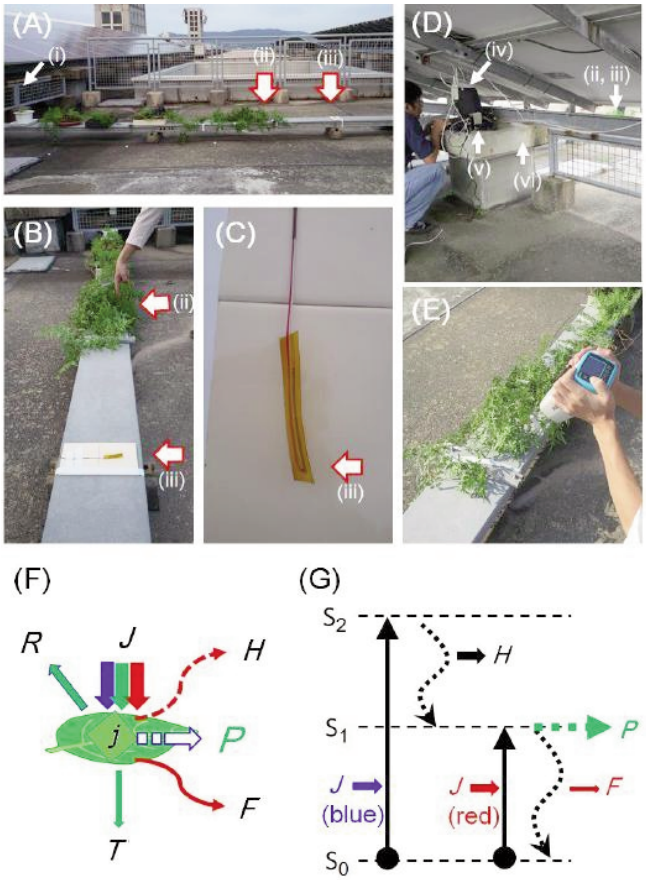

Fig. 2 - Experimental set up to assess the shading properties of the *Lygodium japonicum* canopy on the roof of a building. (A, B) *L. japonicum* plants set up on the roof. (C) One of the fine thermocouples placed on the ceramic tiles. (D) Composition of the monitoring units. (E) Measurement of reflection spectra on the surface of plant leaves using a portable NIR field spectro-radiometer. (i) PC control booth beneath the solar panels. Arrows (ii) and (iii) indicate the positions of the thermocouples. (iv) A note PC, (v) an AD/DA 8-channel converter, (vi) connecting cables. (F) Fate of incident solar light illuminating plant leaves. *J*, incident light; *R*, reflection; *T*, transmittance; *j*, captured light energy; *H*, local heat loss; *F*, fluorescence; and *P*, photosynthesis. Optically, *J*, *R*, *T*, *j* and *F* can be determined. (G) Energy transfer by short wavelength (blue) light and long wavelength (red) light after illumination of chlorophylls.

Solar spectra, canopy-filtered light spectra and leaf-reflectivity spectra

To measure solar and leaf canopy light spectra, a CL-500A Illuminance Spectrophotometer (Konika Minolta, Tokyo, Japan), which covers the range between 360 nm and 780 nm, was used. Spectroscopic analyses of reflectivity on the surface of leaves were carried out using a portable near-infrared (NIR) field spectro-radiometer, FieldSpec HandHeld 2 (ASD Inc., Atlanta, GA, USA), designed for spectral measurements (ranging from 325 nm to 1075 nm) on site (Fig. 2E). In figure 2F and G, the fate of incident solar light illuminating plant leaves and generalized modes of energy transfer by short wavelength (blue) light and long wavelength (red) light after illumination of chlorophylls are illustrated. Based on the experimental design described here, spectroscopic data on incident light (*J*), reflection by leaves (*R*), transmittance through leaves (*T*), light energy captured by leaves (*j*) and chlorophyll fluorescence (*F*) can be non-invasively and remotely monitored.

3. Results and Discussion

Effects of Lygodium japonicum *canopy on ceramic roof tile surface temperature*

The heat-blocking or buffering action by the leafy canopy of *L. japonicum* was assessed by monitoring the changes in local temperature on the surface of model ceramic tiles with and without *L. japonicum* coverage (Fig. 3). Comparisons were made on a cloudy day (2 October 2014) (Fig. 3, top) and a sunny day (3 October 2014) (Fig. 3, bottom). In both cases, daytime temperature was higher on the control tiles without plant canopy. Data clearly suggest that the fluctuation of temperature due to direct exposure to naturally changing solar light intensity could be buffered.

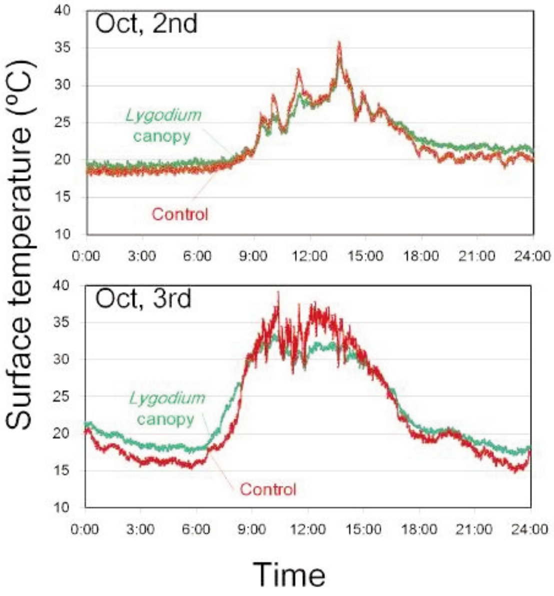

Fig. 3 - Assessment of the sun-shading effect of *L. japonicum* canopy by monitoring of the surface temperature. Typical data, recorded on 2 and 3 October 2014, are shown.

In addition to the action of the plant canopy in the daytime, the nighttime changes in local temperature were also buffered by the presence of the *L. japonicum* leaves, possibly by minimizing the bulk flow of heat-removing air reaching the tile surface, and also by blocking the heat transfer out of ceramic tiles through the highly reflective nature of the leaves in the NIR region. These hypotheses will be the subject of critical experimental examination in future studies.

Filtering of solar rays through Lygodium japonicum *leafy canopy*

Solar radiation above and under the *L. japonicum* leafy canopy were monitored with a hand-held Spectrophotometer (Fig. 4). By subtracting the level of radiation under the canopy from that recorded above the plants, total light filtering performance by *L. japonicum* canopy could be calculated (Fig. 4, bottom). Data from two nearby experimental sites, each with its independent plant, indicated that a majority of solar radiation was filtered by the leaf canopy, possibly through absorption and reflection of light.

Reflection of solar rays by Lygodium japonicum *leaves*

Reflectivity of *L. japonicum* leaflet surface was measured under sunlight (Fig. 5) (3 October 2014). Due to the presence of chlorophylls, there was always a pair of valleys of reflectivity in the blue and red regions (in the range below 450 nm and around 660 nm), which correspond to the absorbance by chlorophyll *a* and its related metabolites (Kawano *et al.*, 1999). In the range of visible light, green-colored light (peaking at around 550 nm) was most highly reflected as expected by the presence of chlorophylls in the leaves. Since green light was also the major light component of the under-canopy radiation (Fig. 4), absorption of green light by plant pigments was shown to be negligible.

In the NIR region, a high rate of solar radiation was reflected upwards (Fig. 5), suggesting that the decrease in NIR radiation below the plant canopy is largely due to reflection. A steep increase in reflectivity spanning from the red region to NIR region represents the so-called "red edge" of reflection. This is a phenomenon commonly observed in various green

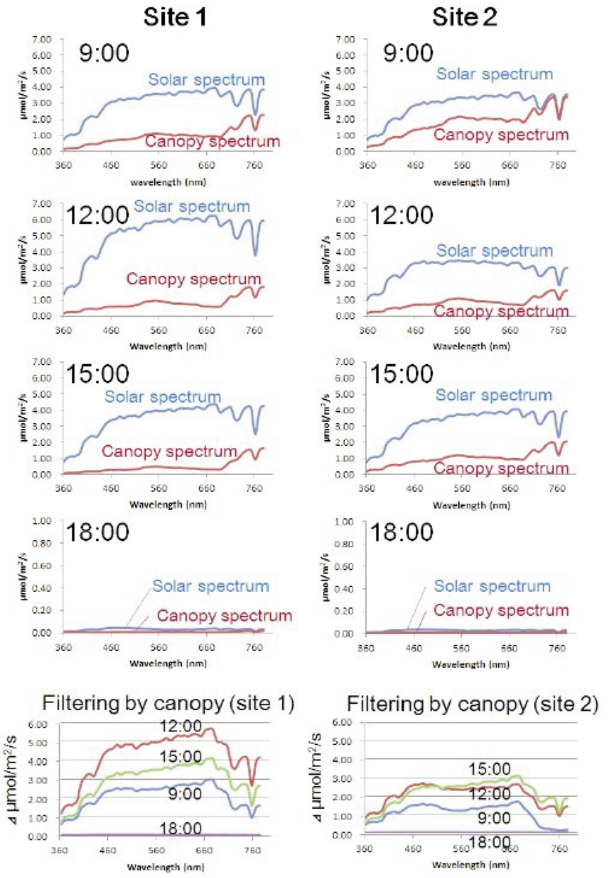

Fig. 4 - Spectrometric analysis of solar radiation and its filtering by *L. japonicum* canopy. Typical data, recorded on 3 October 2014, are shown.

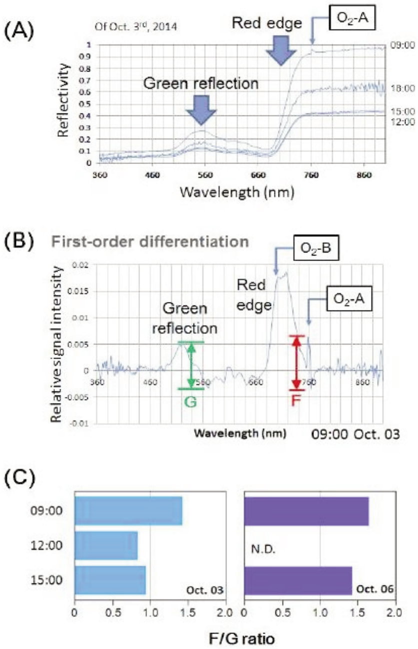

Fig. 5 - Analysis of leaf reflectivity using the leaves of *L. japonicum* plants covering ceramic roof tiles. (A) Typical reflectance spectra from *L. japonicum* leaves recorded at 9:00, 12:00, 15:00 and 18:00 on 3 October 2014 are shown. (B) An example of processed reflectance spectrum. Relative signal intensity was determined after the first order differentiation of the spectral data. (C) Changes in the normalized chlorophyll fluorescence signal. Signals corresponding to reflectance in the green and red-to-NIR regions are labeled as "Green reflection" and "Red edge", respectively. Chlorophyll-dependent fluorescence signals detected at 760 nm and 679 nm, corresponding to O_2-A and O_2-B Fraunhofer lines, respectively, are labeled.

leafy plants, suggesting that most green plant canopies are capable of creating shade, minimizing the NIR radiation allowed to reach ground level, thus blocking the heating radiation to reach beneath the leaves. In this context, a *L. japonicum* canopy fulfills one of the key criteria as a thermal buffering plant canopy.

Detection of chlorophyll fluorescence signals in the reflectivity spectra

At 760 nm, the wavelength corresponding to the O_2-A solar Fraunhofer line (telluric absorption band) near 760 nm, a spike of signal corresponding to chlorophyll fluorescence was observed especially under morning solar radiation (Fig. 5A) (labelled as O_2-A). However, chlorophyll signal at O_2-B near 687 nm solar Fraunhofer line could hardly be detected since 687 nm coincides with the steep increase in "red edge" reflectance by leaves (Fig. 5A). After first-order differentiation of the reflectance spectra, the red edge reflectance signal no longer interferes with the reading of chlorophyll fluorescence at 687 nm (Fig. 5B) (labelled as O_2-B). In this way, quantification of chlorophylls and estimation of the spread and density of vegetative plant tissue can be non-invasively and even remotely monitored as plant vegetation performance mapped by remote-sensing satellites (Meroni *et al*., 2009; Guanter *et al*., 2010; Mazzoni *et al*., 2012). However, we have to be cautious about the handling of fluorescence data to assess the area of leaf coverage since fluorescence signals can potentially report the status of gross photosynthesis (without considering the rate of respiration) and therefore, it may be altered over the course of the day. The fate of light energy reaching the plant leaf surface can be expressed as follows:

$$J= R+T+H+F+P \qquad [1]$$

$$j= J-R-T \qquad [2]$$

where *J*, *R*, *T*, *H*, *F*, *P*, and *j* stand for incident light, reflection, transmittance, heat loss, fluorescence, photosynthesis, and captured light energy, respectively. Then, the fate of *j* can be traced as follows:

$$j= H+F+P \qquad [3]$$

$$P= j-H-F \qquad [4]$$

In this study, we directly and fully monitored *J* (Fig. 4) (solar spectrum), *R* (Fig. 5A), and *T* (Fig. 4) (canopy spectrum), and partial *F*, the intensity of which is proportional to the total *F* (Fig. 5A, B). By definition, *j* can be readily estimated from recorded *J*, *R* and *T*. Therefore, the rate of gross photosynthesis (*P*) under constant or known *j* should be negatively proportional to the rate of heat loss (*H*) + fluorescence (*F*). Assuming that *H* is constant (actual changes in local heat loss in the leaves should be determined in future experiments), changes in *F* indicate the photosynthetic status of the plants. In fact, quantification of fluorescence signal and monitoring of its temporal changes can be readily performed after normalization with green reflection (Fig. 5B, C). Taken together, the data in figure 5C suggest that *L. japonicum* plants are fully ready for photosynthesis only after midday.

Need for the evaluation of photosynthesis

We have recently proposed a series of practical equations designed to describe the collective gross photosynthetic response within the plant canopy (Okamoto *et al*., 2016). Using our equations, the photosynthetic capacity in the plant canopy structure can be simply simulated based on minimal sampling of a single top-positioned leaf through measurement of (i) PI-curve in a horizontally placed single leaf, (ii) state of dark respiration in a single leaf, and (iii) transmittance through a single leaf.

As pointed out by Monsi and Saeki (2005), *T* through layer of leaves can be expressed according to the definition by Beer-Lambert law as follows:

$$T=e^{-ax} \qquad [5]$$

where *a* and *x* are absorption coefficient and length of the path within the leaf layer, respectively. For simplification of the model, we assume that the canopy structure consists of uniform leaves. By experimentally determining the value for *T* in a single leaf, we can approximate the total light used for photosynthesis within the canopy structure as follows:

$$\sum_{i=0}^{\infty} JT^i = \lim_{k\to\infty} \sum_{i=0}^{k} JT^i = \frac{J}{1-T} \qquad [6]$$

where *i* is the number of leaves (*i*=0 is initial light intensity above the leaves). Today, Michaelis-Menten-type photosynthetic equation proposed by Platt and Jasby (1976) is widely accepted by the plant research community to describe the nature of gross photosynthesis as below:

$$P = \frac{P_{max} J}{K_j + J} \qquad [7]$$

Recently, we proposed that photosynthetic light response curves can be generated based on a limited number of experimental data points through application of Platt-Jasby equation by determining $P_{\max}$ values and K_j values from least-sized experiments (Nagasawa *et al*., 2015).

By substituting *J* in equation [7] with the total light used for photosynthesis within the canopy as shown in equation [6], we can obtain the following equation:

$$\sum_{n=1}^{k} P_n = \frac{P_{max}\frac{J}{1-T}}{K_j+\frac{J}{1-T}} \quad [8]$$

where P_n stands for P in the n^{th} leaf in the canopy. Since the collective light yield rapidly converges, k can be replaced with ∞ in a practical sense. This equation can be rewritten to modify the apparent Michaelis constant as follows:

$$\sum_{n=1}^{k} P_n = \frac{P_{max}J}{K_j(1-T)+J} \quad [9]$$

By accurately determining P or total P in the canopy through a model experiment, we can more accurately estimate the local heat loss (H) on the leaf as:

$$H= j-F-P \quad [10]$$

Climbing plants

It is well known that climbing plants, as represented by the tendril-bearing plant families, chiefly belong to higher flowering plant families such as Vitaceae, Bignoniaceae, Passifloraceae and Cucurbitaceae (Fabre, 1855; Darwin, 1875; Gerrath *et al*., 2008), many of which are agriculturally and economically important (Kawano *et al*., 2012). Interestingly, only a few climbing species can be found among the seedless vascular plant lineages, including ferns (Darwin, 1875). Many more climbing fern species may have been lost in the course of evolution, since it is believed that there was a dramatic drop in the diversity and abundance of most fern species, inversely-proportional to the burst of diversification in angiosperms during the Cretaceous period (Schneider *et al*., 2004).

Timing of model experiments

We planned to examine the slowing effects of *L. japonicum* canopy on both local heating during daytime and local cooling during nighttime; for this purpose, early October (2014) was chosen as the timing for model experiments. Although the attempt presented here provides preliminary data in support of the thermal buffering capacity of *L. japonicum* canopy, further model experiments taking place under two extreme conditions, namely in mid-summer and mid-winter, are required in order to fully assess the thermal buffering capacity of this species. Finally, there is great interest in assessing the quantitative heat balance and the radiation balance on the surface of walls or roofs based on the larger scale experiment with special reference to the thermal buffering effect of *L. japonicum* in all seasons in Japan.

Future environmental studies

Green components covering buildings and walls in urban areas are exposed not only to natural environmental stresses but also to artificial stressful conditions, chiefly exposure to polluted air containing ozone (Kadono *et al*., 2006; Tran *et al*., 2013) and related oxidants (Yukihiro *et al*., 2012). Most plants exposed to such oxidative stress readily develop visible symptoms on the leaves reflecting the onset of programmed cell death (Kadono *et al*., 2010). The sensitivity and/or tolerance of *L. japonicum* to such stressful conditions must be studied prior to its wider application in urban greening projects.

4. Conclusions

The minimal thermal analysis of the sun-shading effect of *L. japonicum* canopy was performed by monitoring changes in tile surface temperature. In order to optically monitor the natural shading and growth properties of a green canopy consisting of the leaves of a climbing fern, the following optical approaches have been performed for the first time: here, optical properties of *L. japonicum* under solar incident light, namely, the natural shading and growing properties of green canopy were studied. The incident solar radiation spectrum (J), leaf transmittance (T) spectrum, and leaf-reflectivity spectrum (R) were measured. In the reflectivity spectrum, concomitant chlorophyll fluorescence signal (F) was detected at 760 nm, corresponding to the O_2-A Fraunhofer line. Data suggests that the daily change in photosynthetic status (P) can potentially be traced by monitoring the change in relative F in relation to the estimated heat loss (H) and measured J, R, and T.

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