EVAPOTRANSPIRATION OF ROOFTOP GARDENING PLANTS AND THEIR EFFECT ON THE THERMAL ENVIRONMENT OF BUILDING

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Summary

In recent years, heat island phenomenon has been increasingly affecting urban environment. Rooftop gardening is considered as one of the options to realize sustainable urban living by mitigating environmental load due to dissipation of latent heat by evapotranspiration and thermal insulation effect. In this study, we measured evapotranspiration of several rooftop gardening plants and thermal environment of an existing building with rooftop garden in order to obtain basic data to quantify the effects of rooftop gardening on thermal environment of the building. We set up rooftop gardens with 2 kinds of soils, natural soil (Andisol) and artificial potting soil (Perlite-based commercial product), in 3 different thicknesses (7cm, 14cm and 21cm). Thermal data of soil and slab were recorded by means of thermocouples. There is limited knowledge on the amount of evapotranspiration from gardening plants. Three species each of common gardening plants that are suitable to each soil thickness were selected for the evapotranspiration study and grown in stainless steel Lysimeters buried in the experimental plots. The decrease in weight of Lysimeters was measured as evapotranspiration. The results showed that the effectiveness of the Perlite-based artificial soil used in this study might be lower than Andisol, although its original ability of heat insulation is greater than Andisol. Unhealthy plantings would suppress evapotranspiration in comparison with the bare ground. The amount of evapotranspiration of *Sedum mexicanum* was almost the same as that of bare ground. When plants are growing healthily, plantings with thicker soil might be able to make the amount of evaporation larger.

1. Background

Contributing factors to the recent progress of heat island phenomenon include the increase in exhaust heat sources such as air conditioning systems, electric devices, combustion appliances and automobiles, as well as decrease in planted areas and water surfaces due to construction of artificial ground surfaces such as buildings and pavements. The increase in installations of air conditioning due to the high temperature and humidity has been accelerating further elevation of ambient temperature during summer time, which becomes a vicious circle. The influences of heat island phenomenon range from public sanitation, such as increase in heat prostration and risks of expansion of epidemics, to many other environmental factors.

Greening is regarded as one of the options to realize sustainable urban living by mitigating environmental load because of its thermal diffusion and insulation effects as well as dissipation of heat in the form of latent heat in evapotranspiration. Rooftop gardening is getting increased attention in urban area, where it is often difficult to create open spaces because of the intensive land use. Tokyo and a few other city governments in Japan have issued an ordinance that requires rooftop gardening for construction of building of a certain scale. There are subsidy systems, provided by the Ministry of Land, Infrastructure and Transport, to promote rooftop gardening. These ordinances and subsidy systems have helped the spread of rooftop gardening. Rooftop gardening is often built with thin soil layer due to load limits of the roof and construction cost. *Sedum* spp., drought-resistant perennials, are especially in wide use because the plants require little maintenance. It has been recently pointed out, however, that the effect of *Sedum* garden to mitigate heat island phenomenon is limited because its latent heat dissipation is quite low and sensible heat dissipation is high (Yokoyama et al., 2004). Even though the difference in the effectiveness of various types of rooftop gardening on thermal environment is recently attracting our attention, almost all of the simulations dealing with the rooftop gardening in Japan are based on the data of the evapotranspiration of turf (Horiguchi et al., 1996). The evapotranspiration effects of gardening plants, especially when they are used in rooftop gardens, are not well known.

In this study, we measured evapotranspiration of several rooftop gardening plants and thermal environment of building with rooftop garden as the basic data to quantify the effects of rooftop gardening on thermal environment of the building.

2. Materials and Methods

2.1 Site Preparation

The experiment site was located at Ikuta Campus of Meiji University in Kawasaki, Kanagawa that is a typical urban region of Japan as it is a neighboring city of Tokyo. We set up rooftop gardens on two-story part of the building with 2 kinds of soils, natural soil (Andisol) and artificial potting soil (Perlite-based commercial product), in 3 different thicknesses (7cm, 14cm and 21cm). Figure 1 shows the layout of the experimental plot. Each plot was a 2m×2m square and subdivided into 4 subsections. Three species each of common gardening plants that are suitable to each soil thickness were selected and planted separately in each subsections. Nothing was planted in the remaining subsection as reference (bare ground). Three species of perennial ground cover plants, Mexican stonecrop 'Mexico mannengusa (in Japanese)' (*Sedum mexicanum*), rosemary (*Rosmarinus officinalis*) and mascarene grass 'Kourai shiba' (*Zoysia tenuifolia*) were planted in the plots of 7cm-depth soil. Garden Petunia (*Petunia × hybrida*), annual plant, verbena (*Verbena × hybrida*), half-hardy perennial, and hypericum (*Hypericum carisinum*), hardy perennial, were planted in the plots of 14cm- depth soil. Two species of evergreen broad-leaved trees, Rhododendron 'Oomurasaki tsutsuji' (*Rhododendron pulchrum* cv. Oomurasaki) and camellia 'Sazanka' *(Camellia sasanqua*), and one species of evergreen coniferous tree, yew plum pine 'Inumaki' (*Podocarpus macrophyllus*), were planted in the plots of 21cm-depth soil (Figure 2).

2.2 Measurement of Evapotranspiration

Two small Lysimeters made of stainless steel mesh were prepared for each plot. The dimensions of Lysimeters (without handle) were L15cm×W15cm×H7cm, L15cm×W15cm×D14cm and L20cm×W20cm ×H21cm for 7cm depth, 14cm depth and 21cm depth, respectively. The mesh size was 20m/s, which was

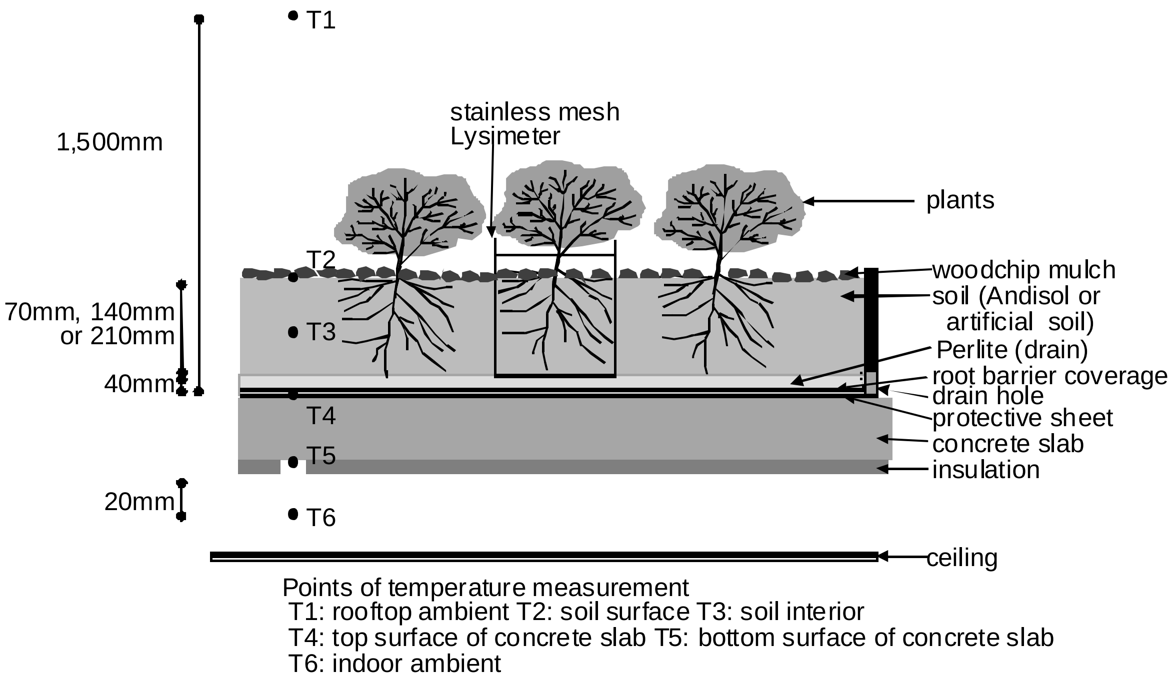

Figure 1 Layout of experimental plot.

expected to be small enough to prevent loss of soil. One plant was planted in each Lysimeter except for the Lysimeters for *Z. tenuifolia* subsections and the bare ground subsections. *Z. tenuifolia* was cut to fit the size of Lysimeter and laid on the top surface of soil in the Lysimeters. All the Lysimeters were buried in soil and nursed before the experiment. All the plots were watered two days prior to the 2-day experiment until the soil was saturated. No rainfall was observed during the experimental period. The roots running out of the mesh of Lysimeters were cut with knife. The decrease in weight of Lysimeter was measured as evapotranspiration. Some researchers carried out the evapotranspiration studies with small non-meshed pots (Dou et al., 2001, Nakayama et al., 1997). This type of Lysimeter, however, tends to have a problem to limit the transfer of heat and water and can hardly reflect the effects of plants in the garden. The mesh type small-scale Lysimeters is expected to permit the transfer of heat and water as naturally as possible.

The measurement of evapotranspiration was started at 5:00pm on August 18, 2004 and ended at 5:00pm on August 20, 2004. The measurements were made at 9:00am, 11:00am, 1:00pm, 3:00pm and 5:00pm on each day. The weather was clear during the experiment. Solar radiation recorded at the nearest local metrological station (Tajima station) from 5:00pm on August 18 to 5:00pm on August 19 was 21.230 MJ/m^2 and that of the following 24 hours was 21.235 MJ/m^2.

2.3 Measurement of Thermal Conditions

Thermal data of soil surface, soil interior and top and bottom surfaces of concrete slab were continuously recorded by means of thermocouples in each experimental plot. Data of top and bottom surfaces of concrete slab without gardening were also recorded for comparison. Ambient temperatures over the rooftop and between the slab and ceiling were recorded at one place each (Figure 1). In this paper, the data taken in August 2003, when there had been no plants or watering, were used as the reference data.

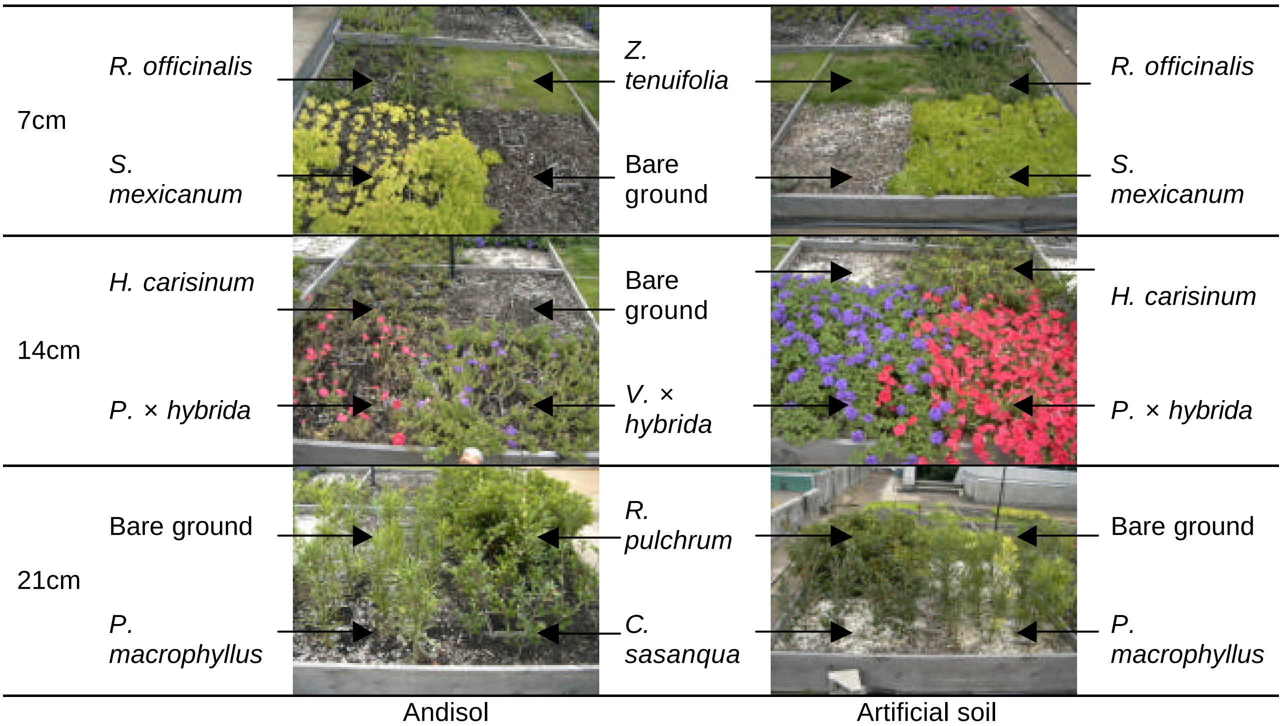

Figure 2 Photographs of experimental plots.

3. Results and Discussions

3.1 Thermal Conditions

Figure 3 shows the daily changes in temperatures at each plot. Average thermal data recorded on clear days (August 2-4, 11, 21-25, 29-30) are shown in the first graph, and the data of August 21 and 24 are shown in the middle and the bottom graphs, respectively. As clear days continued from August 21 to 25, it is expected that soil water content was abundant on August 21 but much less on August 24.

Subscripts used in the expressions for temperature denote as follows;

T (Soil thickness) (Soil type) – ("Soil" or "Slab") – (Position)
Soil thickness: 0 (bare ground), 7, 14 or 21
Soil type: And (Andisol) or Art (artificial soil)

Position: Surf (soil surface), In (soil interior), Top (top surface of slab) or Bot (bottom surface of slab)

T_{Roof} : rooftop ambient

T_{Room} : ambient under concrete slab

Ex. $T_{7And\text{-}Soil\text{-}Surf}$: Temperature of soil surface at 7cm-depth Andisol plot

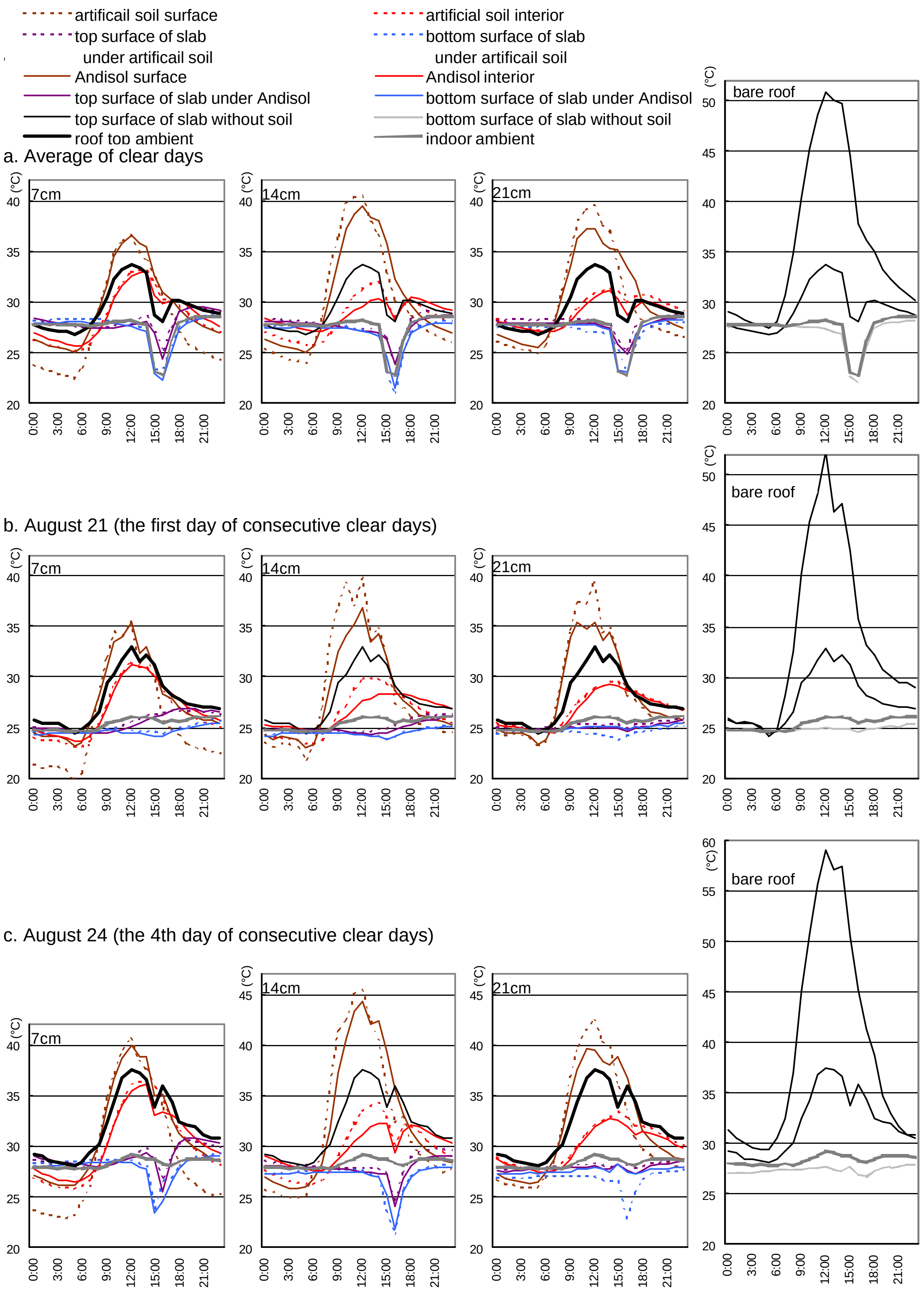

Figure 3 Changes in temperatures in August 2003.

Rapid drop in temperature bottoming at 3:00pm or 4:00pm was observed in all the plots almost everyday, although there was no obstacle shading the experimental area. It seemed unlikely that the air conditioning running in the building below the rooftop influenced the thermal environment on the roof, because the rooftop ambient temperature recorded at 150cm above the roof floor decreased simultaneously. The relationship with wind speed and radiation was not very clear as well. The affecting factor of this decline in temperature is still under investigation.

$T_{0\text{-Slab-Surf}}$ rose up to 50.8 °C on the average, while the highest temperatures recorded were between 28.5 °C ($T_{21\text{And-Slab-Top}}$) and 29.5 °C ($T_{14\text{And-Slab-Top}}$) when concrete slab was covered by soils, either Andisol or artificial soil. The maximum of $T_{0\text{-slab-surf}}$ reached 59.1 °C on August 24, the hottest day in this month, and the maximum temperature recorded in the plots with soil was 30.8 °C ($T_{7\text{And-Slab-T}}$). The minimum of daily maximum temperature was only 28.5 °C ($T_{21\text{And-Slab-Top}}$).

$T_{21\text{And-Slab-Top}}$ was always higher than $T_{21\text{Art-Slab-Top}}$. $T_{14\text{And-Slab-Top}}$ was either higher than $T_{14\text{Art-Slab-Top}}$ or approximately the same. $T_{7\text{Art-Slab-Top}}$ was higher during daytime and lower during the nighttime than $T_{7\text{And-Slab-Top}}$. Both $T_{7\text{And-Slab-Top}}$ and $T_{7\text{Art-Slab-Top}}$ began rising before noon. The time when the temperature began rising was in the following order: $T_{7\text{Art-Slab-Top}}$, $T_{7\text{And-Slab-Top}}$, $T_{14\text{Art-Slab-Top}}$, $T_{14\text{And-Slab-Top}}$and $T_{21\text{Art-Slab-Top}}$, and $T_{21\text{And-Slab-Top}}$, which indicates that the thicker the soil is, the slower the heat conduction, and that the artificial soil conducted heat faster than Andisol. However, the heat conductivity of the water saturated artificial soil was 0.23 W/m/°C and that of water saturated Andisol was 0.56 W/m/°C. When these soils were air-dried, their conductivities were measured to be 0.07 W/m/°C and 0.09 W/m/°C, respectively. The conductivity of Andisol is greater than that of the artificial soil, which major component is Perlite that is sometimes used as a thermal insulating material. The actual heat transfer would be occurring through quite complex mechanisms, involving latent heat effect. Difference in capillary force of Andisol and artificial soil might also affect the results.

3.2 Evapotranspiration

Figure 4 shows the cumulative amounts of evapotranspiration at each subdivision. The amount of evapotranspiration of the artificial soil was more than that of Andisol in 14cm-depth plots without plants, while the opposite was observed in 21cm-depth plots. There was no difference in the evapotranspiration between bare Andisol and artificial soil in 7cm-depth plots. The amounts of evapotranspiration of bare Andisol and artificial soil were greater in 14cm-depth plots than in 7cm- and 21-depth plots. These results imply that evapotranspiration would be limited by the complex factors of heat conductivity, capillary force of soil and other physical factors. The small capillary force of the artificial soil could have resulted in the small amount of its evapotranspiration in 21cm-depth soil. The depth of 14cm might be the most favorable thickness for vaporization of the soil water and transfer of water to the surface of the soil.

The amount of evapotranspiration of *Z. tenuifolia*, whose condition was not good, was lower than that of the bare ground, probably because transpiration of the plants could not compensate for the decrease in evaporation from soil. The amounts of evapotranspiration of *S. mexicanum* planted in Andisol and the artificial soil were about 5,700 g/m^2/day and 7,200 g/m^2/day, respectively, which were almost equivalent to the amount of evapotranspiration in the bare ground. *R. officinalis* evapotranspirated at least 4,600 g/m^2/day. The average amounts were 5,700 g/m^2/day in Andisol plots and 7,200 g/m^2/day in artificial soil plots. The differences would be mainly contributed to the size of plants.

Among 14cm-depth plots, the quite vigorous growth of *V. × hybrida* and *P. × hybrida* led to the large amount of the evapotranspirations of 12,100 g/m^2/day and 9,200 g/m^2/day, respectively. *H. carisinum* planted in Andisol and artificial soil and *V. × hybrida* planted in Andisol were growing in medium condition, and the average amounts of the evapotranspiration were 6,100 g/m^2/day, 5,600 g/m^2/day and 7,200 g/m^2/day, respectively. The growth of *P. × hybrida* planted in Andisol were fairly bad, and the amount of evapotranspiration was only 4,500 g/m$_2$/day, which was about 13% of the amount of evaporation in the bare ground (5,200 g/m^2/day).

R. pulchrum evapotranspirated quite large amounts, 13,500 g/m^2/day in Andisol plots and 10,300 g/m^2/day in artificial soil plots. The amount of evapotranspiration of *C. sasanqua*, whose cuticular layer is thick, was 6,300 g/m^2/day both in Andisol plot and artificial soil plots. *P. macrophyllus* , needle-leaved tree, gave the lowest amount of evapotranspiration among the trees investigated; 4,600 g/m^2/day in Andisol and 6,000 g/m^2/day in artificial soil.

The following were the major findings in this study.

1. The Perlite-based artificial soil used in this study might be less effective than Andisol with respect to the effect on mitigating thermal environment. The result could have been caused by a set of complex factors, as the heat insulation capability of Perlite is very high.

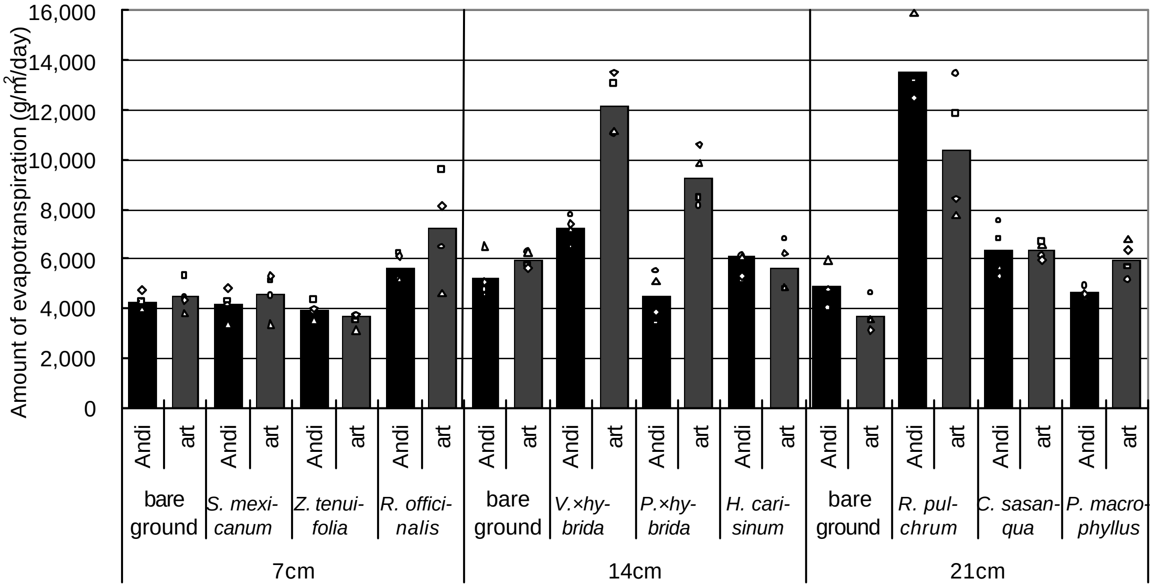

Figure 4 Cumulative amounts of evapotranspiration.

2. Unhealthy plants would suppress evapotranspiration comparing to the bare ground. The amount of evapotranspiration of *S. maxicanum* was almost the same as that of the bare ground, even though its condition was not bad. But, it is noteworthy that bare ground itself has the functionalities such as heat insulation and latent heat effect.
3. When plants are growing healthily, plantings with thicker soil might be enable greater evapotranspiration.

The amount of evapotranspiration was measured under the conditions where the soil was initially water-saturated. It is necessary to conduct investigations on the effects of initial water contents, as Yokoyama et al. (2004) pointed out. The influences of wind speed and solar radiation should also be investigated. Furthermore, the effects of the seasonal changes in plant activities on the efficacy of rooftop gardening for thermal environment need to be studied and evaluated.

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