Evaluation of CO_2 reduction effects of buildings with green roofs by using a coupled urban-canopy and building-energy model

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1. Introduction

In recent years, global warming has become a more serious problem, and it is now an urgent priority to reduce energy consumption and CO_2 emissions. In particular, energy consumption for cooling buildings in the summer continues to grow every year, and thus, reductions in the cooling demand for residential and living spaces represent a potentially important countermeasure to global warming. Moreover, efficient cooling technology will be critically important in the years ahead given that increases in air temperature due to urbanization (i.e., the urban heat island phenomenon) can contribute to losses of comfort in urban spaces and further increase cooling demands (Ichinose, 2005; Ichinose, 2008; Hirano and Fujita, 2012).

Rooftop greening is one measure that can be used to improve the urban thermal environment. Although vegetation is known to be effective for reducing temperatures via evapotranspiration processes, there is only limited room for large ground-greening projects in urban areas. This has lead to the increased popularity of rooftop greening projects.

Many previous studies have been conducted on rooftop greening to evaluate its effectiveness at mitigating the thermal environment, and several of these studies were based on urban-scale meteorological simulations. In particular, simulations linking local weather and air-conditioning load calculations have been conducted, as well as evaluations of heat island mitigation and reductions in cooling energy consumption due to rooftop greening (Tanimoto et al., 2004; Kikegawa et al., 2006).

However, in cases of those simulation-based evaluations at the district scale, surface wetness was parameterized as fixed values (e.g., evaporation efficiency, vegetation community conductance) and calculations were performed without considering the amount of water used. If watering is performed to maintain rooftop greening, then attention must be paid to the fact that other environmental loads arise because of factors such as powering pumps. Therefore, when conducting future evaluations of the effects of thermal environment mitigation in connection with rooftop greening, it will be necessary to accumulate detailed data on the surface heat balance, surface temperature, and the supplied amount of water.

The objective of this research was to evaluate the effectiveness of rooftop greening in urban districts for the purpose of heat island mitigation and CO_2 emission reductions, and the analyses were based on simulations of the urban thermal environment in Tokyo, Japan. In particular, we calculated the amount of evapotranspiration from the latent heat flux and evaluated CO_2 emission reductions by taking into account the amount of water and needed for watering.

2. Calculation conditions

In this research, we used a coupled urban-canopy and building-energy model (Kikegawa et al., 2003; Kondo et al., 2005; Kikegawa et al., 2006; Ohashi et al., 2007). In this model, a vertical one-dimensional local meteorological model is coupled with an air-conditioning load calculation model for buildings, and this makes it possible to forecast the heat load of buildings in a district, energy consumption due to air-conditioning, and temperature variation.

We set the rooftop greening assumptions to three levels of 0%, 50%, and 100% (i.e., a no-greening case, a 50% greening case, and a 100% greening case, respectively). The evaporation efficiency at the rooftop greening surface was set to 0.2 according to observations by Hirano and Ichinose (2006). Calculation conditions for buildings such as the wall surface structure, heat source equipment composition, air-conditioning operation schedule, bodily heat production pattern, and heat production pattern by equipment other than air-conditioning were all set to the same values used for a typical office district in Kikegawa et al. (2006).

The days subject to calculation were August 8-10, 2002, which was a period of continuous fair summer weather in Tokyo. Of these days, the results from the third day of study were used for the evaluation, whereas the data for the first two days provided a time period for preliminary calculations to be run.

3. Evaluation of the heat island mitigation effect

Fig. 1 shows the rooftop surface temperatures calculated under the aforementioned calculation conditions for the no-greening case and 100% greening case. For comparison, the average air temperatures for three cases at the rooftop level were also added to the illustration. Fig. 1 shows that a temperature difference of approximately 10°C occurs during the day between the vegetated surface and the concrete surface; hence, there is a major surface temperature reduction effect due to rooftop greening. At night, the temperature of the concrete surface always exceeded the air temperature, except for a very short period in the early morning. Conversely, the vegetation surface consistently had a lower temperature than the air temperature, and this is thought to be due to differences in the radiative cooling effect and the amount of heat accumulated during the day.

Fig. 2 shows the air temperature 3 m above the ground and at the rooftop level for each case, as well as the differences between each greening case and the no-greening case. These results show that a greater temperature reduction effect occurs with the 100% greening case than with the 50% greening case. In regards to vertical directions, the temperature reduction effect was almost the same at the rooftop level and 3 m above the ground in all cases. In this research, since we assumed the introduction of greening only on rooftops, it is conjectured that there is roughly uniform diffusion in the vertical direction in the urban canopy. However, the temperature reduction effect was a maximum of 0.13°C during the day, even in the case with 100% greening, and this was relatively small compared to the total variation range of air temperature.

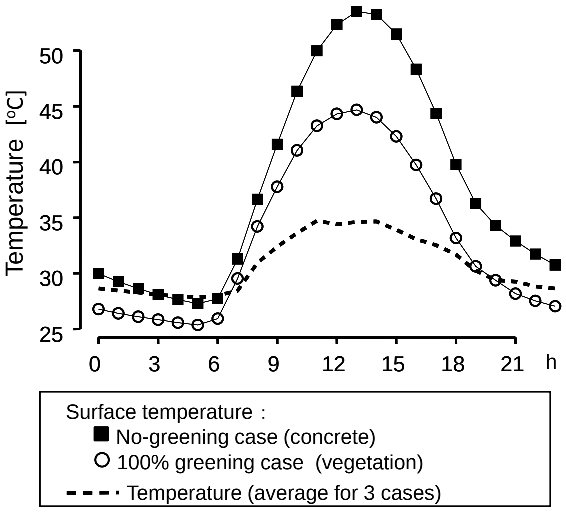

Fig. 1 Surface temperature of concrete and vegetation on a rooftop.

4. Evaluation of the CO_2 reduction effect

We evaluated the CO_2 reduction effect due to rooftop greening. Fig. 3 shows the CO_2 emissions associated with cooling energy consumption in each case, as well as the differences between the cases (each greening case versus the no-greening case). This figure shows that there was a peak in CO_2 emissions and a peak in CO_2 reductions due to greening at the start of operations in the morning when the cooling load was high. In terms of daily cumulative values, the CO_2 reduction effect was 2.93 kg-CO_2/day in the 100% greening case and 1.47 kg-CO_2/day in the 50% greening case. However, since the cases calculated here assume greening only of the rooftops on six-floor buildings, the CO_2 reduction effect for the entire building was only 1.4% in the case of 100% greening.

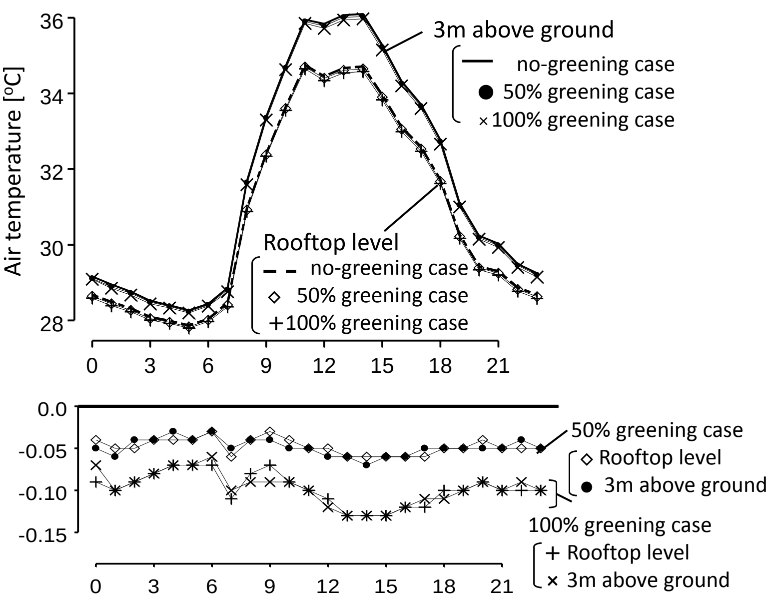

Fig. 2 (top) Temperature in each case scenario, and (bottom) the temperature differences for those cases (i.e., each case with greening - each case without greening).

Next, we calculated CO_2 emissions for watering when the entire amount of water needed for evapotranspiration was supplied with tap water (Fig. 4). The amount of water needed for evapotranspiration was calculated from the latent heat flux, which in turn was obtained from the results of calculating the roof surface heat balance. In this research, the subjects of the calculations were the CO_2 emissions from the powering pumps that are used to lift water to the rooftop and the CO_2 emissions from the water services that are needed for the supply of tap water. Pump power was calculated by setting the pump efficiency to 0.6 and the rooftop height was used as the lifting height. For the water services, the calculation was done with CO_2 emissions of 0.193 kg-CO_2/m^3 for tasks such as water purification, delivery, and distribution. Fig. 4 shows that CO_2 emissions from the powering pumps were 0.038 kg-CO_2/day in the 100% greening case and 0.020 kg-CO_2/day in the 50% greening case. CO_2 emissions from the water services used were 0.21 kg-CO_2/day in the 100% greening case and 0.11 kg-CO_2/day in the 50% greening case.

These figures are about 8-9% of the CO_2 reduction effect for cooling due to rooftop greening (lower graph in Fig. 3), and thus, under the calculation conditions in this research, the CO_2 reduction effect can be obtained using rooftop greening even when taking into account CO_2 emissions due to watering.

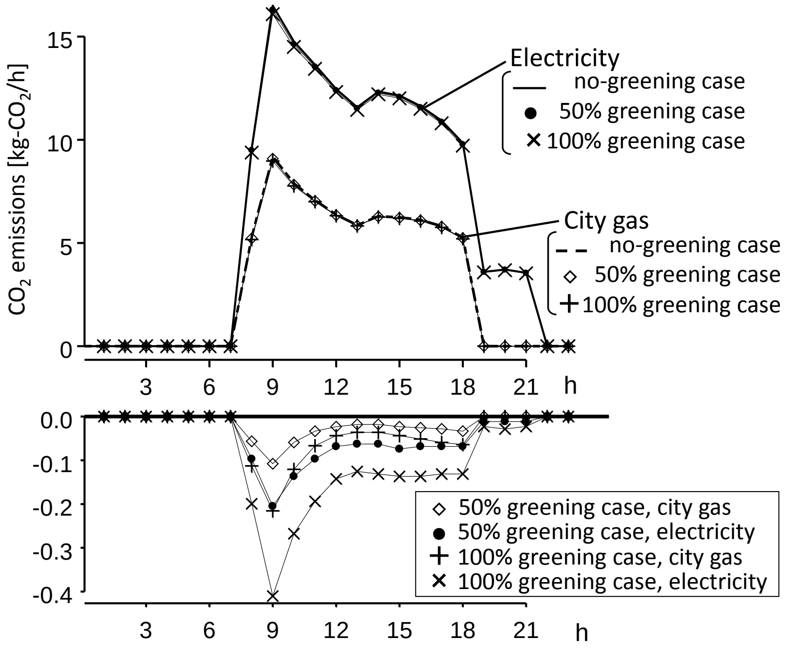

Fig. 3 (top) CO_2 emissions in each case scenario, and (bottom) the emission differences for those cases (i.e., each case with greening - each case without greening).

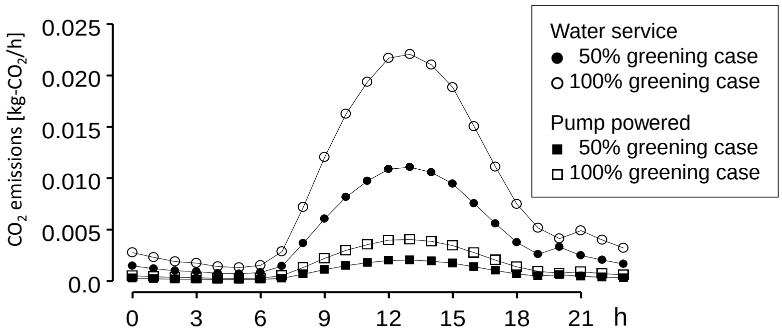

Fig. 4 CO_2 emissions due to watering in each case scenario.

5. Evaluations under various calculation conditions

The relationships between evapotranspiration, the heat island mitigation effect, and the CO_2 reduction effect were examined based on the results in the previous section. We adopted the calculation conditions considered in the previous section as standard conditions here. In addition, the heat insulation performance of the roof and evaporation efficiency at the rooftop greening area were selected as parameters likely to have a large effect on the results, and then, an investigation was carried out in the same way using calculation conditions in which each parameter was varied (high insulation condition and low evaporation efficiency condition, respectively).

For the high insulation condition, the rooftop insulation material was assumed to be equivalent to the energy-saving standard, just like the high insulation cases in Kikegawa et al. (2006). In addition, just like in standard conditions, rooftop greening was varied between 0%, 50%, and 100%. In this research, only rooftops were changed, and values other than rooftop insulation performance were all set to be the same as standard conditions. For the low evaporation efficiency condition, evaporation efficiency at greening areas, which was set to 0.20 in standard conditions, was changed in steps in the range of 0-0.2 without changing the green coverage ratio. In this calculation, settings other than evaporation efficiency were all set to be the same as the 100% greening case under standard conditions.

Fig. 5 shows the relationship between evapotranspiration and the temperature reduction effect, and Fig. 6 shows the CO_2 reduction effect under the various calculation conditions. Differences between the greening cases and the no-greening case were graphed for the standard condition and the high insulation condition. For the low evaporation efficiency condition, a graph was plotted of the differences for calculation results in the case when the evaporation efficiency was 0. Fig. 5 shows that, regarding the temperature reduction effect, the differences were small under the three calculation conditions and the data roughly formed a straight line. It is likely that the temperature reduction effect in response to evapotranspiration depends almost entirely on the field of atmospheric diffusion. Fig. 6 shows the net CO_2 reduction when taking into account both the reduction in cooling energy and CO_2 emissions due to watering. This figure indicates that there were no large differences between the standard condition and low evaporation efficiency condition. For the high insulation condition, the CO_2 reduction effect in response to evapotranspiration was about half that of the other conditions. Thus, the effectiveness of rooftop greening strongly depends on building structure and insulation performance.

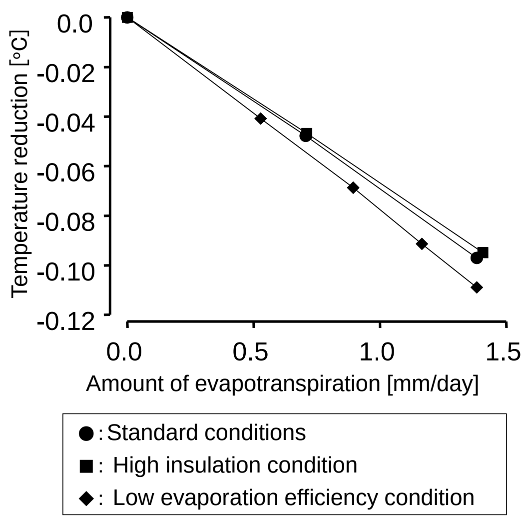

Fig. 5 Relationship between the amount of evapotranspiration and the temperature reduction effect.

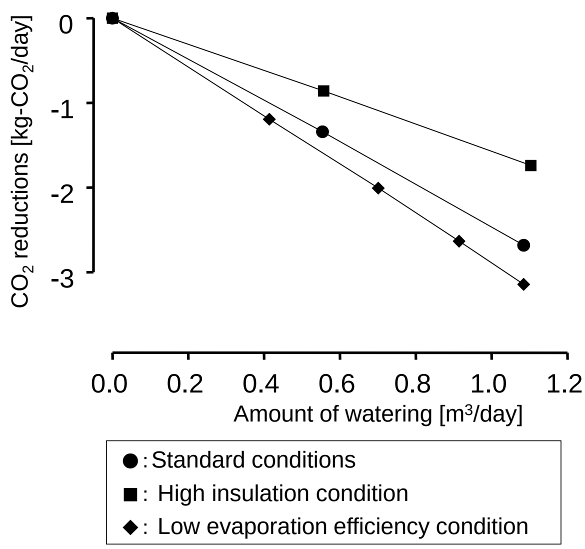

Fig. 6 Relationship between the amount of watering and CO_2 reductions.

6. Conclusion

This research evaluated the effectiveness of rooftop greening for mitigating urban heat island conditions and reducing CO_2 emissions while taking into account the amount of water needed for evapotranspiration. CO_2 emissions should be decreased with rooftop greening because there will be less of a need for cooling energy. In this research, a coupled urban-canopy and building-energy model was used to carry out simulations. The main results of this research were as follows.

(1) The heat island mitigation effect of rooftop greening was evaluated. The results showed that, under the calculation conditions of this research, the maximum temperature reduction in the case of large-scale adoption of rooftop greening was about 0.13°C. The relationship between this temperature reduction effect and evapotranspiration was also clarified.

(2) The CO_2 reduction effect of rooftop greening was evaluated. In particular, this evaluation was carried out by taking into account both the CO_2 reductions that resulted from the decreases in surface temperatures and cooling energy and the CO_2 emissions associated with watering. The data showed that the former was clearly greater in terms of direct effects. Thus, a CO_2 reduction effect can be achieved in buildings where rooftop greening is adopted.

(3) In addition to the standard conditions assumed in the above research, calculations were also conducted for variations in the roof insulation performance and evaporation efficiency of the rooftop greening area. The findings showed that the effectiveness of rooftop greening at mitigating heat island effects and reducing CO_2 emissions strongly depends on building structure and insulation performance.

One future research direction should be to incorporate a detailed water balance model that takes into account precipitation and the water retention effectiveness of the soil layer. In many previous simulation models of urban thermal environments, surface wetness has been parameterized as a constant value and simulations have been carried out by assuming that evaporation continues indefinitely in accordance with weather conditions. However, in a relatively closed environment such as a building rooftop, the amount of evapotranspiration strongly depends on water supplied through watering and precipitation. Therefore, more accurate results could be obtained by conducting a more detailed evaluation that takes into account the water balance of rooftop greening areas by incorporating precipitation and water retention effectiveness into the thermal environment simulation model.

Acknowledgment

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