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Effect of a Net-covered Windbreak on the Heat Loss from a Heated Greenhouse

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Abstract

Windbreaks constitute a traditional methodology adopted to reduce heat loss from greenhouses. In this study, the influence of a windbreak on the heat loss from a heated greenhouse was investigated. Energy balance and leakage measurements were conducted simultaneously at a plastic-film-covered greenhouse with a forced air heater and a single-layer thermal curtain. A windbreak covered with a plastic net (porosity of 0.60) was built 7.0 m away from the windward side of the greenhouse. The heat transfer coefficients of the greenhouse were derived from the cases where the net was rolled up and deployed on the windbreak. The overall heat transfer coefficient of the entire greenhouse (*U* value) was reduced by the net-covered windbreak. The reduction increased as the windspeed increased: the windbreak reduced the *U* value by 11.9% at a windspeed of 0.5 m s^{-1}, and by 22.4% at a windspeed of 3.0 m s^{-1}. The effect of the windbreak on the *U* value was mainly due to the well-known dependency of leakage on windspeed. The windbreak also influenced the *U* value owing to the reduction of the overall heat transfer coefficient of the greenhouse cover (*K* value) in windy and radiative cooled conditions.

Discipline: Agricultural Engineering
Additional key words: heating, leakage, *U* value, *K* value, energy balance

Introduction

Heating is the largest energy consumption component for horticultural production in greenhouses in the Northeast Asian, Northern and Central European and North American countries (de Villiers et al. 2011, Roy et al. 2008, Torrellas et al. 2012). Reduction of heat loss from greenhouses has been an important task from the viewpoints of secure and environment-friendly greenhouse management for many years. Heat insulation using double cladding, infrared-absorbing polyethylene films and thermal screens has been intensively studied and successfully applied to commercial greenhouses in many regions (Simpkins et al. 1976, Bailey 1981, Zhang et al. 1996, Papadakis et al. 2000, Kawashima 2015, Park et al. 2015).

Windbreaks are also recommended to reduce the energy consumption for heating office buildings and greenhouses because heat loss from such facilities is closely related to windspeed (Whittle & Lawrence 1960, Wang 2006, West Park History Contributors 2009). For buildings, the reduction of heat loss in heating space is achieved through the reduced air leakage first, and thereafter the reduced convection on windows (Wang 2006). For greenhouses, the enhancement of windspeed increases their leakage rate (Fernández & Bailey 1992) and the ratio of the leakage heat loss to the heat input for a low-cost plastic greenhouse (Baille et al. 2006). The leakage rate of a non-heated greenhouse was reduced by a net-covered windbreak by the same degree as the reduction of the windspeed around the greenhouse (Kuroyanagi et al. 2014). In addition, the hot-box measurement resulted in increases in the overall heat transfer coefficient of greenhouse-covering materials by enhancing the windspeed (Geoola et al. 2009). These cited literature publications provide qualitative evidence that windbreaks contribute to the reduction of energy consumption for heating a greenhouse. However, the quantitative evaluation of the effect of windbreaks on the heat loss from a greenhouse is still unclear. The lack of information may cause a quotation of windbreaks as a panacea for the reduction of heat loss from greenhouses,

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and grower's excessive investment in windbreaks.

The objective of this study was to elucidate the influence of a windbreak on the heat loss from a heated greenhouse. Measurements of the leakage rate and the energy balance of the greenhouse were conducted simultaneously. The response of the overall heat transfer coefficient of the entire greenhouse and its components to windspeed is presented to clarify the effect of a windbreak on the heat loss from a greenhouse.

Materials and methods

1. Model description

The nocturnal heat loss from a heated greenhouse results from the overall heat transfer of the covering material, heat storage in the greenhouse system, and air leakage (Albright et al. 1985, Papadakis et al. 2000). The magnitude of heat loss from a greenhouse can be determined by the U value, which represents the overall heat transfer coefficient of the entire greenhouse (Papadakis et al. 2000). The U value includes the overall heat transfer coefficient of the greenhouse cover, which is defined as the K value, and the leakage heat transfer coefficient. The K value includes conductive, convective, and radiative heat exchanges between the inner and outer parts of the greenhouse (Nijskens et al. 1984), and it can be determined using the hot-box method (Geoola et al. 2009, Hayashi et al. 2011). The heat loss owing to air leakage can be determined by the leakage measurements using a tracer gas or energy balance equation (Fernandez & Bailey 1992).

The heat loss from a heated greenhouse is represented by the U value because the heat loss from a greenhouse occurs not only on the covering material but also through air leakage which reaches up to 20% or more (Takakura & Okada 1972, Baille et al. 2006) for the heating input in windy conditions. In this study, the U value was defined as follows:

$$U = K + k_v \tag{1}$$

where K is the overall heat transfer coefficient of the greenhouse cover (W m^{-2} K^{-1}), k_v is the leakage heat transfer coefficient (W m^{-2} K^{-1}), and U is the overall heat transfer coefficient of the entire greenhouse (W m^{-2} K^{-1}). In this instance, the U value obtained from the hot-box experiment by Geoola et al. (2009) can be regarded as the K value because their box had no air leakage.

The U value is derived from the nocturnal energy balance equation of a heated greenhouse, and is expressed as (Baille et al. 2006):

$$Q_h = A_c (H_c + H_v) + A_f H_f \tag{2}$$

where A_c is the area of the greenhouse cover (m^2), A_f is the area of the greenhouse floor (m^2), Q_h is the sensible heat provided by heating equipment (W), H_f is the heat flux on the greenhouse floor (W m^{-2}), H_c is the overall heat flux through the greenhouse cover (W m^{-2}), and H_v is the heat flux by air leakage (W m^{-2}). H_c, and H_v are expressed as:

$$H_c = K(T_{in} - T_{out}) \tag{3}$$

$$H_v = k_v(T_{in} - T_{out}) \tag{4}$$

where T_{in} and T_{out} are the air temperatures inside and outside the greenhouse (K), respectively. The U value can be obtained from Eqs. 1, 2, 3, and 4 as follows:

$$U = \frac{1}{A_c} \frac{Q_h - A_f H_f}{T_{in} - T_{out}} \tag{5}$$

The K value can be determined using Eqs. 1, 5, and the following equations:

$$Q_h = \eta H q \tag{6}$$

$$k_v = \frac{n}{3600} \frac{V_g}{A_c} \rho_a c_a \tag{7}$$

where c_a is the specific heat of air (J kg^{-1} K^{-1}), H is the heat of combustion of kerosene (J kg^{-1}), n is the leakage rate (h^{-1}), q is the kerosene consumption of the heating equipment (kg s^{-1}), V_g is the greenhouse volume (m^3), ρ_a is the density of air (kg m^{-3}), and η is the combustion efficiency of the heating equipment (-). In this study, latent heat transfer through air leakage is not considered because of the lack of the measurement of water balance of the greenhouse, especially for condensation flow which leaks out from where the films are fixed by spring wire clamps on the frame of the greenhouse.

2. Experimental greenhouse and windbreak

The greenhouse and windbreak used in this study were described by Kuroyanagi et al. (2014). A greenhouse oriented along the east-west-direction with an arc-shaped roof was used (floor area, 6 m × 14 m; eaves height, 2.0 m; ridge height, 3.5 m; greenhouse volume, 254 m^3). The greenhouse and a storage container (2.2 m × 1.5 m × 2.1 m) were located on the eastern edge of the site of a paddy field in Kagawa, Japan (34.214°N, 133.787°E, 59.8 m amsl). The area of the site was 76.8 m × 42.8 m, and it was covered with manicured weeds (Fig. 1).

A net-covered windbreak (3.5 m × 30 m) was built at a distance of 7 m from the west end of the greenhouse. A plastic net with a mesh size of 2 mm and a porosity of

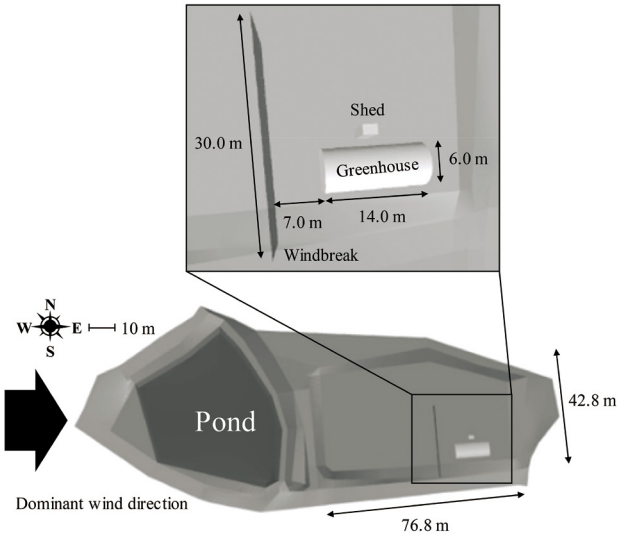

Fig. 1. Top view schematic of the experimental field

0.604 (130, Daio Chemicals, Ltd., Tokyo, Japan) was supported by the frame consisting of steel pipes with diameters of 48.6 mm. The net could be rolled up on the top of the frame. The windbreak reduced the windspeed on the west face of the greenhouse to 70.9% compared with that without the net of the windbreak when western wind blew (Kuroyanagi et al. 2014).

The greenhouse was covered with polyolefin films with a far-infrared absorbent coat (Hanayaka Kyojin, Sekisui Film Co., Ltd., Osaka, Japan; thickness 0.15 mm). The roll-up side vents were on the north and south faces, and sliding doors were installed on the east and west faces. The areas of each side vent and door were 12.1 m × 0.6 m and 1.9 m × 2.0 m, respectively. They were closed during heating hours in the experiment. In the greenhouse, polyolefin films (Vegetaron Super, Sekisui Film Co., Ltd., Osaka, Japan; thickness 0.075 mm) were fixed at the west and east faces, and the films on the north, top, and south faces were rolled up manually during the daytime. A forced-air heater with a heating capacity of 14 kW (KA-125E, Nepon Inc., Tokyo, Japan) was used for heating. Warm air was provided from the two outlets on the upper part of the heater. The heater was operated when the air temperature in the greenhouse fell below 12°C. The floor soil was covered with a black plastic sheet. Indeterminate tomato cultivar (Reiyo, Sakata seed corporation, Kanagawa, Japan) was grown in rockwool culture. The seedlings were transplanted on October 2, 2014. Harvesting was conducted from January 16, 2015 onwards. The leaf area index, which was measured through destructive measurements, was 1.3 on December 24, 2014.

3. Measurement and data analysis

The leakage rate of the greenhouse was measured through the concentration decay method using sulphur hexafluoride (SF_6) as a tracer gas. The SF_6 tracer gas was supplied every 3 h from 1800 to 0600, and distributed to the greenhouse using a horizontal circulator (740HD, Vornado Air LLC, Kansas, USA). Each supply lasted for 3 min at a rate of 1.75 L min^{-1}. The greenhouse air was sampled every 1.5 min at three specific points located 1.7 m above the floor using a multipoint sampler (INNOVA 1309, LumaSense Technologies Inc., CA, USA). The sampled air was transported sequentially from the respective measuring points through 4-mm-diameter polytetrafluoroethylene tubes to a photoacoustic gas monitor (INNOVA 1412-1, LumaSense Technologies Inc., CA, USA) with a built-in air pump. The SF_6 concentration at the centre was used for calculating the leakage rate when the coefficient of variance of the SF_6 concentrations at the three measurement points was within 10%, in accordance with the Society of Heating, Air-conditioning and Sanitary Engineers of Japan (SHASE) standard (SHASE, 2003).

For the energy balance measurement of the greenhouse, the air temperature and relative humidity inside and outside the greenhouse were measured using platinum resistor-type temperature sensors and capacitance humidity sensors (2119A, Eto Denki. Co. Ltd., Tokyo, Japan; accuracy ± 0.3 K, ± 3% RH) in aspirated radiation shelters. The heat flux on the floor was measured at the center of the greenhouse using a heat flux sensor (MF-180M, EKO Instruments Co. Ltd., Tokyo, Japan; reproducibility ± 2%). The kerosene consumption of the heater was measured using a flow meter (OF05ZAT, Aichi Tokei Denki Co., Ltd., Aichi, Japan; accuracy ± 2%). The combustion efficiency of the heater was assumed to be 0.85 according to the performance test conducted by the manufacturer.

The reference windspeed and its direction were measured at a height of 3.5 m, 10.5 m apart from the windbreak on the windward side, using a three-dimensional (3D) ultrasonic anemometer (81000, R. M. Young Company, Michigan, USA). The windspeed in 3D coordinates was sampled every second and averaged over 60 s. The net radiation (0.3 to 30 μm) was measured using a net pyradiometer (MF-11, EKO Instruments Co. Ltd., Tokyo, Japan). The precipitation was measured using a tipping bucket rain gauge (TKF-1, Takeda Meteorological Instrument Co. Ltd., Tokyo, Japan). The pyradiometer and rain gauge were placed at a weather observation field approximately 300 m apart from the greenhouse.

The leakage and energy balance measurements were conducted from December 5 to 22, 2014. During the

measurements, the net of the windbreak was rolled up from December 5 to 15, and the net was thereafter deployed from December 15 to 22. All the variables were recorded every minute on data loggers (CR1000, Campbell Scientific Inc., Utah, USA; Cadac 21, Eto Denki Co. Ltd., Tokyo, Japan). The data were averaged for each hour of the measurement, and used to calculate the U value, leakage rate, and K value on an hourly basis.

For the analysis of data, the data satisfying the following criteria were adopted: i) when the wind blew predominantly from the west-southwest to west-northwest directions, ii) when the outside air temperature was 5°C or less (Appendix). The data during and after precipitation of 0.5 mm and more were excluded. The heating hours were defined as the period from 1800 to 0600.

Results and discussion

1. Weather conditions

Figure 2 shows the hourly averaged windspeed and air temperature outside the greenhouse through the measurement of leakage and energy balance of the greenhouse. The mean windspeed and air temperature during the heating hours were 1.51 m s^{-1} and 3.8°C, respectively. The west and west-southwest wind was the prevailing wind in the experimental site during the heating hours throughout the measurements (Fig. 3).

The available data for analysis were limited by the wind direction and outside air temperature. The number of leakage and energy balance observations when the windbreak was rolled up and deployed were 55 and 41, respectively.

2. *U* value and leakage heat transfer coefficient

Figure 4 shows that the U value correlated significantly with the reference windspeed for both conditions at which the windbreak was either rolled up or otherwise ($r = 0.64$, $P<0.001$ when the net was rolled up; $r = 0.58$, $P<0.001$ when the net was deployed). The simple regression equations for the conditions when the net was rolled up and deployed are:

$$U=0.187v+1.531 \quad (8)$$

$$U=0.077v+1.392 \quad (9)$$

where v is the reference windspeed (m s^{-1}).

The positive correlation between the U value and the windspeed in Figure 4 is consistent with the results from the greenhouse compartments covered with various covering materials (Zhang et al. 1996). In this measurement, the slope of the simple regression equation for the rolled-up condition [Eq. (8)] was much higher than for the deployed condition [Eq. (9)] whereas the difference of the intercepts between both conditions was 9.9%. The difference of the U values between the rolled-up and deployed conditions increased as the windspeed increased. For example, the net on the windbreak reduced

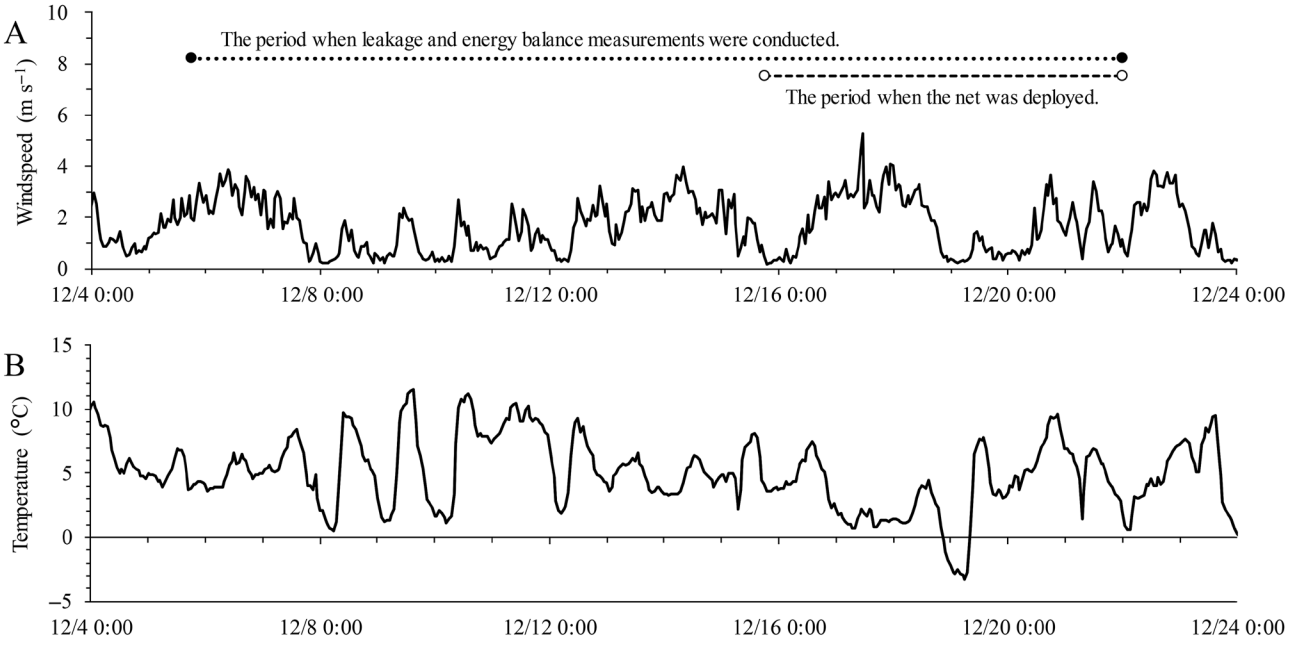

Fig. 2. Windspeed (A) and air temperature (B) outside the greenhouse
The dotted line represents the period when leakage and energy balance measurement was conducted; the dashed line represents the period when the net of the windbreak was deployed.

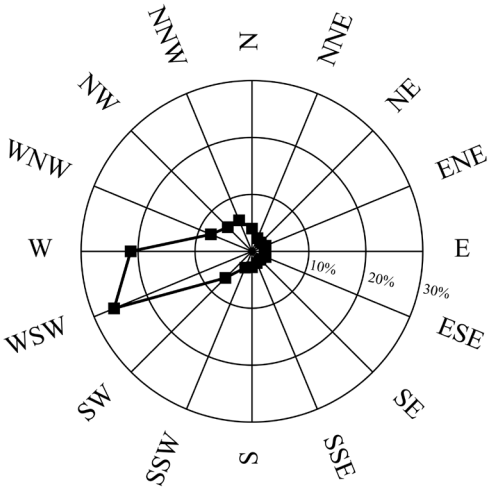

Fig. 3. Relative frequency of wind direction outside the greenhouse during the heating hours

the U value by 11.9% at a windspeed of 0.5 m s^{-1} and by 22.4% at a windspeed of 3 m s^{-1}.

As shown in Figure 5, the leakage heat transfer coefficient, k_v, correlated significantly with the reference windspeed for both conditions at which the net was either rolled up or otherwise (r = 0.82, $P<0.001$ when the net was rolled up; r = 0.92 $P<0.001$ when the net was deployed). The ratio of the leakage heat transfer coefficient to the U value varied with the reference windspeed (Fig. 6). The ratio of the leakage was below 10% regardless of the presence of the net of the windbreak for windless situations. The ratio increased with an increase in windspeed, and the difference of the ratio between the presence and absence of the net on the windbreak also increased. When the reference windspeed was 3 m s^{-1}, the leakage heat transfer coefficient reached 19% of the U value without the net of the windbreak, whereas its value was 15% when the net was deployed.

For home heating, leakage represents one-third of the heat loss from a home in winter, and windbreaks conserve energy used for home heating by reducing the leakage rate in homes (DeWalle & Heisler 1988, Wang 2006). DeWalle & Heisler (1988) also indicated that the effect of windbreaks on energy savings for home heating varies from 26% to a null depending on the types and location, and the benefits of windbreaks for home heating are likely to be higher at "leaky" homes in a windy climate.

For greenhouse heating, the ratio of the leakage to the total heat loss ranged from 20% to 35% for the parral-type greenhouse (Baille et al. 2006), and it was approximately 20% for the small experimental glasshouse (Takakura & Okada 1972). Although the leakage rate in

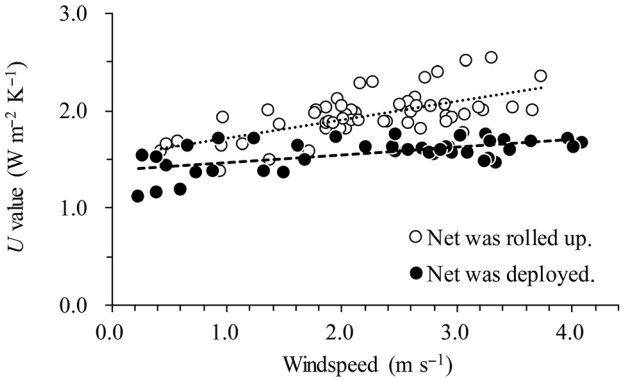

Fig. 4. Dependency of the overall heat transfer coefficient of the entire greenhouse (U value) on windspeed outside the greenhouse
The dotted line represents data collected when the net on the windbreak was rolled up; the dashed line represents data collected when the net was deployed.

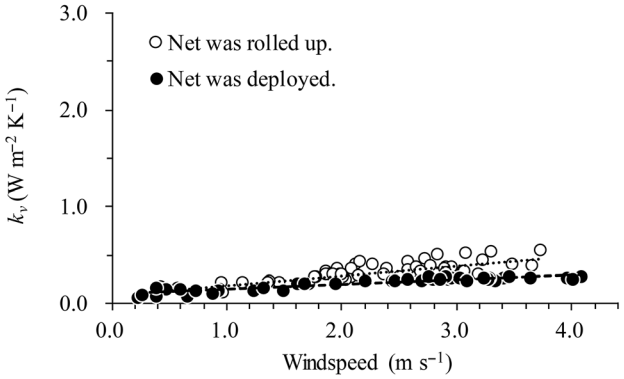

Fig. 5. Dependency of the leakage heat transfer coefficient on windspeed outside the greenhouse
The dotted line represents data collected when the net on the windbreak was rolled up; the dashed line represents data collected when the net was deployed.

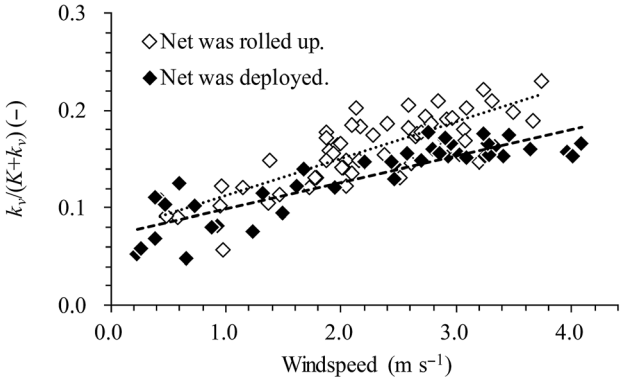

Fig. 6. Ratio of leakage heat transfer coefficient to the overall heat transfer coefficient (U value)
The dotted line represents data collected when the net on the windbreak was rolled up; the dashed line represents data collected when the net was deployed.

the aforementioned studies resulted from the absence of a thermal curtain, the air tightness of greenhouses is limited by the cheap structure and construction of doors, vents, and cladding materials. Therefore, the effect of the windbreak on the reduction of the *U* value could be explained by the suppression of the leakage.

3. *K* value

The *K* value is dominantly governed by the combination of convective and radiative heat transfer coefficients, i.e., the *K* value depends, in principle, on windspeed and net radiation. However, the results of multiple regression analysis showed that, regardless of the presence of the windbreak, net radiation significantly affected the *K* value but windspeed did not (Table 1). As shown in Figure 7, the *K* value correlated significantly with net radiation for the condition at which the net was either rolled up or otherwise ($r = 0.48$, $P<0.001$ when the net was rolled up; $r = 0.67$, $P<0.001$ when the net was deployed). Figure 8 shows that the *K* value correlated with the reference windspeed when the net was rolled up ($r = 0.41$, $P<0.01$ when the net was rolled up; $r = 0.24$, N.S. when the net was deployed). Table 1 and Figures 7 and 8 also show that the *K* value was reduced by the windbreak in windy and radiative cooled conditions.

In contrast to the general relationship between the *K* value and net radiation in Figure 7, the weak dependency of the *K* value on windspeed shown in Figure 8 was in conflict with the dependency of the convective heat transfer on windspeed (e.g., Nijskens et al. 1984). However, the results shown in Figure 8 are partly consistent with the findings from a hot-box experiment (Geoola et al. 2009) in which the cladding material had condensation, and in the presence of the thermal curtain. This conflict would be explained by assuming a tradeoff between convective and radiative heat exchanges: the convective heat transfer reduces the difference of temperature between air and the covering material, whereas the radiative heat transfer increases it inversely. In other words, windy conditions draw heat from the covering material in weak radiative conditions, but help the greenhouse cover obtain heat from ambient air in strong radiative cooling conditions. This assumption was supported by the experimental result in which the convective heat flux outside the greenhouse cover varied between positive and negative values for a heated plastic greenhouse (Baille et al. 2006).

There remains uncertainty in the reduction of the *K* value owing to the windbreak in Figure 7. It is well-known, however, that the microclimate behind a windbreak (McNaughton 1988) can be modified by creating sheltered zones with the increase in the temperature of air (Campi et al. 2009), water, and leaf surface (Maki 1980). McNaughton (1988) suggested that less turbulent transport behind a windbreak promotes

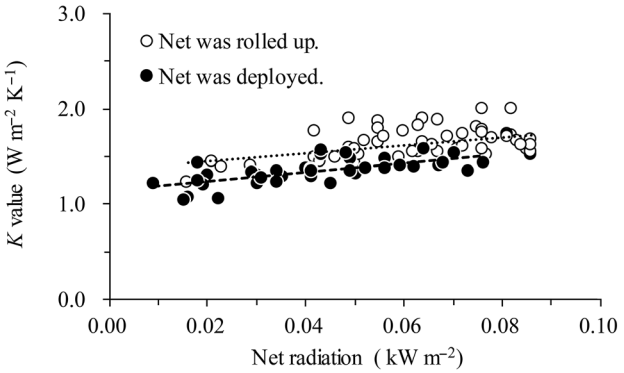

Fig. 7. Dependency of the overall heat transfer coefficient of the greenhouse cover (*K* value) on net radiation outside the greenhouse
The dotted line represents data collected when the net on the windbreak was rolled up; the dashed line represents data collected when the net was deployed.

Table 1. Statistical result of multiple regression analysis as the objective variable was the *K* value

The net status	Rolled up	Deployed
Coefficient of independent variables		0.01
Windspeed	0.04 n.s.	0.02 n.s.
Net Radiation	3.11 *	4.61 ***
Intercept	1.34 ***	1.13 ***
R	0.51	0.69
N	55	41

n.s., *, and *** indicate not significant or significant differences of $P<0.1$ and 0.001, respectively.

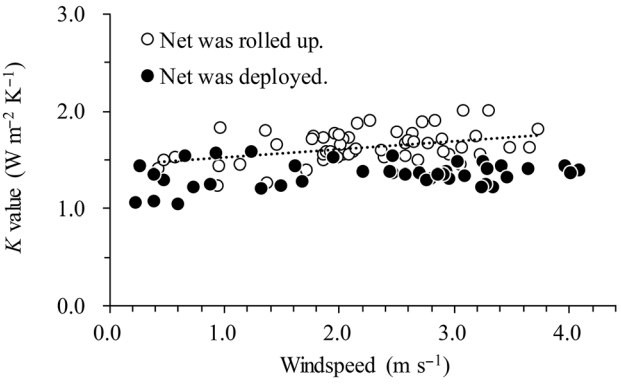

Fig. 8. Dependency of the overall heat transfer coefficient of the greenhouse cover (*K* value) on windspeed outside the greenhouse
The dotted line represents data collected when the net on the windbreak was rolled up.

vertical transport of scalars such as heat from the ground, and creates a warmer zone within the distance of several-time height of the windbreak. Accordingly, the reduction of the K value might be provided by warming ground temperature, resulting in a decrease in radiative heat transfer from the greenhouse cover to the ground. According to another literature, a windbreak induces the opposite phenomenon which is colder ground temperature causing frost formation because of the prevention of mixing of cold air near the ground with warm air above the inversion layer (Mihara et al. 1977). In this study, measurement of the sensible and latent flux or net radiation on the ground behind the windbreak was not conducted. Therefore, it was not possible to verify the effects of the windbreak on the K value because of the lack of measurements.

Conclusions

The influence of a windbreak on the heat loss from a heated greenhouse was investigated using energy balance and leakage measurements. The overall heat transfer coefficient of the entire greenhouse (U value) and its components, the overall heat transfer coefficient of the greenhouse cover (K value), and the leakage heat transfer coefficient, were reduced by a net-covered windbreak. The magnitude of the reduction of the overall heat loss was affected by windspeed: the windbreak reduced the U value by 11.9% at a windspeed of 0.5 m s^{-1} and by 22.4% at a windspeed of 3.0 m s^{-1}. The effect of the windbreak on the U value was mainly due to the well-known dependency of leakage on windspeed. The contribution of the windbreak to the reduction of the U value was also influenced by changes in the K value induced from a complementary relationship between convective and radiative heat transfer in windy and radiative cooled conditions. The results of this study would be useful for estimating the effect of a windbreak on the heating cost of a greenhouse using an energy simulation model.

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Appendix

Small air-temperature difference between inside and outside the greenhouse causes significant error in the U value calculated using Eq. (5). To ensure the accuracy in the calculation of the U value, sensitivity of systematic error of air-temperature measurement to the U value was examined using the measurement results of the U value and the following equations:

$$U' = \frac{1}{A_C} \frac{Q_h - A_f H_f}{(T_{in} + \varepsilon_{in}) - (T_{out} + \varepsilon_{out})} \quad \text{(A.1)}$$

$$E = \left| 1 - \frac{U'}{U} \right| \times 100 \quad \text{(A.2)}$$

where E is the relative error of the U value (%), and ε_{in} and ε_{out} are the accuracy of the inside and outside air-temperature sensors (K). In this study, the same type of the air-temperature sensors were used. Thus, the U' values were calculated by substituting 0.3 or −0.3 for the value of ε_{in} and ε_{out} in Eq. (A.1), and thereafter, the relative error of the U value was calculated using Eq. (A.2).

As shown in Figure A.1, the relative errors decreased asymptotically as the air-temperature difference increased, and they were approximated well using power functions. When the air-temperature difference between inside and outside the greenhouse was 7 K, the relative errors of the U value for ε_{in} or ε_{out} = −0.3 and 0.3 were 9.5% and 7.9%, respectively.

The relative error of 10% was regarded as a reasonable compromise for the analysis of data in this study. Therefore, the air-temperature difference of 7 K and more, which was equivalent to the outside air temperature of 5°C or less because the setting point of the heating equipment was 12°C, was adopted as the criterion of data selection.

Nomenclature

A_c area of the greenhouse cover, m^2
A_f area of the greenhouse floor, m^2

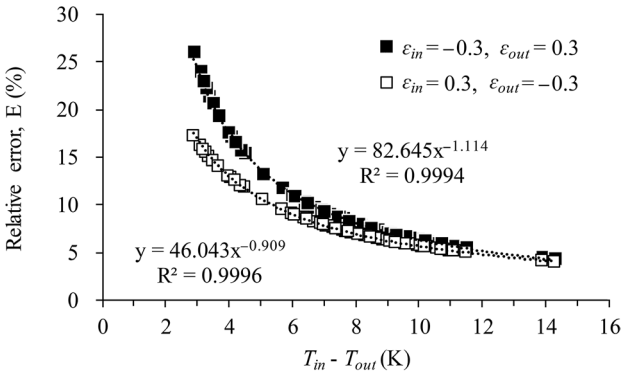

Fig. A. 1. Influence of the air temperature difference between inside and outside the greenhouse on the relative error of the *U* value

c_a specific heat of air, J kg^{-1} K^{-1}
E relative error, %
H heat of combustion of kerosene, J kg^{-1}
H_c overall heat flux through the greenhouse cover, W m^{-2}
H_f heat flux on the greenhouse floor, W m^{-2}
H_v heat flux by air leakage, W m^{-2}
K overall heat transfer coefficient of the greenhouse cover, W m^{-2} K^{-1}
k_v leakage heat transfer coefficient, W m^{-2} K^{-1}
n leakage rate, h^{-1}
Q_h sensible heat provided by the heating equipment, W
q kerosene consumption of the heating equipment (kg s^{-1})
T_{in} air temperature inside the greenhouse, K
T_{out} air temperature outside the greenhouse, K
U overall heat transfer coefficient of the entire greenhouse, W m^{-2} K^{-1}
V_g greenhouse volume, m^3
v reference windspeed, m s^{-1}
ε_{in} accuracy of inside air-temperature sensor, K
ε_{out} accuracy of outside air-temperature sensor, K
ρ_a density of air, kg m^{-3}
η combustion efficiency of heating equipment, -

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