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Eguchi, Hiromi
Biotron Institute Kyushu University

Yoshida, Satoshi
Biotron Institute Kyushu University

Toh, Kunji
Biotron Institute Kyushu University

Hamakoga, Michio
Biotron Institute Kyushu University

他

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GROWTH OF CUCUMBER PLANTS (*CUCUMIS SATIVUS* L.) UNDER VARIABLE–VALUE CONTROL OF AIR TEMPERATURE BY USING NATURAL LIGHT INTENSITY AS FEEDBACK SIGNAL

H. EGUCHI, S. YOSHIDA, K. TOH, M. HAMAKOGA and M. KITANO

Biotron Institute, Kyushu University 12, Fukuoka 812–81, Japan

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EGUCHI, H., YOSHIDA, S., TOH, K., HAMAKOGA, M. and KITANO, M. *Growth of cucumber plants* (Cucumis sativus *L.*) *under variable–value control of air temperature by using natural light intensity as feedback signal.* BIOTRONICS **25**, 45–53. 1996. A system for variable–value control of air temperature by using natural light intensity as a feedback signal was newly developed, and growth of cucumber plants (*Cucumis sativus* L.) under the variable–value control was examined. In the variable–value control, the set value of air temperature increased quadratically with natural light intensity in the range of 18℃ to 32℃. Growth of mature leaves and dry matter accumulation were promoted under the variable–value control, but rapid increases in stem length, leaf area per plant and number of leaves were found under the constant–value control (25℃). Thus, cucumber plant growth appeared healthier under the variable–value control of air temperature, while it became somewhat succulent under the constant–value control of air temperature.

Key words: cucumber plant; *Cucumis sativus* L.; growth; air temperature; variable–value control; feedback control; natural light intensity.

INTRODUCTION

Air temperature is one of important environmental factors affecting plant growth, and different manners of air temperature control have been applied to systems for plant environment control (*2, 7*). It is well known that temperature difference between day and night affects plant growth in terms of carbon balance between photosynthesis and respiration in leaves (*6, 8*). Air temperature controlled according to the fluctuating intensity of the natural light is considered to improve plant growth through light– and temperature–dependent processes such as the carbon balance. In the present paper, a system for the variable–value control of air temperature by using natural light intensity as a feedback signal was newly developed, and growth of cucumber plants (*Cucumis sativus* L.) was examined.

MATERIAL AND METHODS

Plant material

Cucumber (*Cucumis sativus* L. cv. Chojitsu–Ochiai) seeds were sown in 14 cm pots with vermiculite on March 2, 1995, and they were germinated at an air temperature of 23℃ and a relative humidity of 70% in an artificial light (a photoperiod of 12 h with a light intensity of 350 μmol m^{-2} s^{-1}). Four cotyledonary plants at 8 days after sowing were transferred into a natural light growth chamber, and the plants were grown for 24 days under variable–value control of air temperature at a constant relative humidity of 70±5%. The root medium was moistened enough with a complete nutrient solution (Mg^{2+}, 1.8 mM; Ca^{2+}, 4.2 mM; K^{+}, 7.6 mM; $H_2PO_4^-$, 1.6 mM; NO_3^-, 16.4 mM with iron–EDTA and micronutrients). Stem length, number of leaves and midrib lengths of the respective leaves were measured in course of time at an interval of 4 days. Leaf area (*LA*; cm^2) of each leaf was evaluated from leaf length (*LL*; cm) by using a $LL-LA$ relationship obtained empirically as $LA=1.265\ LL^2-4.784\ LL+12.79$ (*5*). At 32 days after sowing, the fresh and dry weights were measured in leaves, petioles and stems.

Control system

Figure 1 shows a schematic diagram of the system developed for variable–value control of air temperature, where the set value of air temperature in a natural light growth chamber varied with the light intensity under a constant relative humidity. An intensity (P; μmol m^{-2} s^{-1}) of the natural light incident into the growth chamber was detected by using a PPFD sensor, and the sensor signal was transmitted to a computer. The set value of air temperature (T_{set}; ℃) in the growth chamber was determined in the computer by the following quadratic equation of P;

$$T_{set}=\frac{T_i-T_{min}}{P_i^2-2P_{max}P_i}P^2-2P_{max}\frac{T_i-T_{min}}{P_i^2-2P_{max}P_i}P+T_{min} \quad (1)$$

where P_{max} is the maximum value of P, T_{min} is the value of T_{set} in darkness, and T_{set} is fixed at T_i when P is equal to the intermediate value (P_i). T_{set} increases with P in the case of $T_{min} \neq T_i$, and the increase rate is declined linearly with increase in P. This determination of T_{set} was repeated with an interval of 1 min. The signal of T_{set} in each determination was transmitted to an air temperature controller and held for 1 min. Air temperature in the growth chamber was measured by a thermometer (Pt 100Ω) and transmitted to the controller for the feedback control. The values of P_i, P_{max}, T_i and T_{min} were preset in the computer, and the dependence of T_{set} on P was altered by changing the preset values of P_i, P_{max}, T_i and T_{min}.

This variable–value control was applied to three natural light growth chambers of (a), (b) and (c) with different preset of T_{min} values of 18℃ (a), 20℃ (b) and 25℃ (c), where P_i, P_{max} and T_i were preset at the respective common

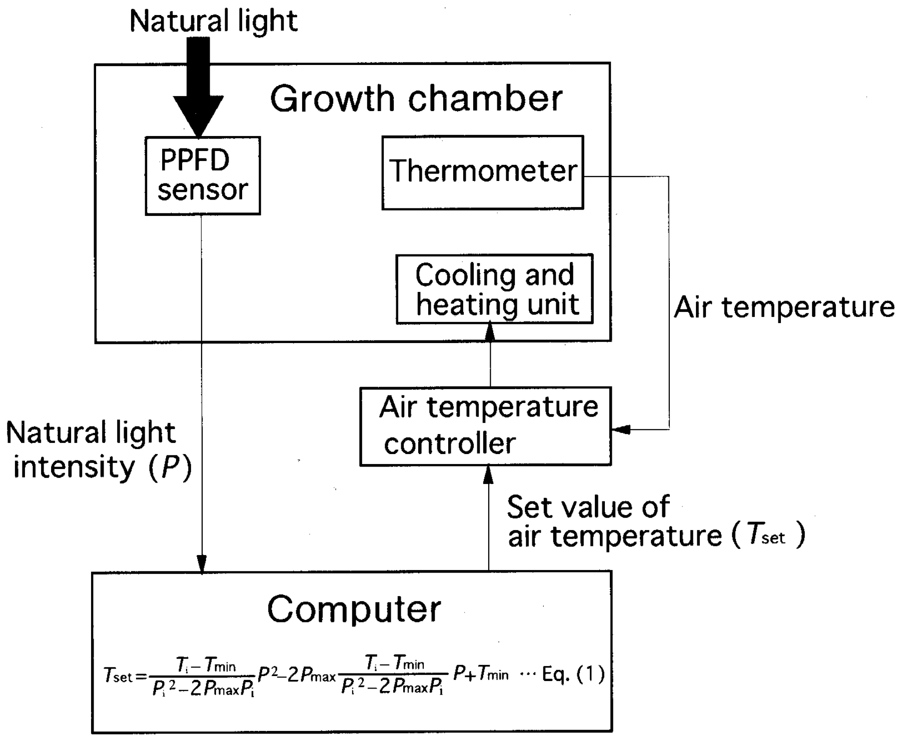

Fig. 1. System diagram of variable–value control of air temperature in a natural light growth chamber by using natural light intensity as a feedback signal: P, natural light intensity (PPFD; μmol m^{-2} s^{-1}); P_i, intermediate value of P; P_{max}, maximum value of P; T_{set}, set value of air temperature (℃) determined by Eq. (1); T_i, fixed value of T_{set} at $P=P_i$; T_{min}, T_{set} in darkness; thick arrow, incidence of the natural light; thin arrows, transmission of signals.

values of 450 μmol m^{-2} s^{-1}, 1500 μmol m^{-2} s^{-1} and 25℃. Figure 2 shows dependence of T_{set} on P in the respective chambers of (a), (b) and (c). T_{set} increased with P in the growth chambers (a) and (b), and higher increase rate was found in the growth chamber (a). On the other hand, T_{set} in the growth chamber (c) was kept constant at T_{min} of 25℃ because of $T_{min}=T_i$ in Eq. (1). That is, air temperature control in the growth chamber (c) resulted in the constant-value control. In all the growth chambers, T_{set} was fixed at T_i of 25℃ when P became equal to P_i (450 μmol m^{-2} s^{-1}).

RESULTS AND DISCUSSION

Control performance

Figure 3 shows time course patterns of natural light intensity and controlled variables of air temperatures (T_a, T_b and T_c) in the respective growth chambers of (a), (b) and (c) on a fair day (March 20, 1995). In darkness, T_a, T_b and T_c were kept constant at the respective T_{min}s of 18℃ (a), 20℃ (b) and 25℃ (c). T_a increased more rapidly as compared with T_b after sunrise and reached about 32℃

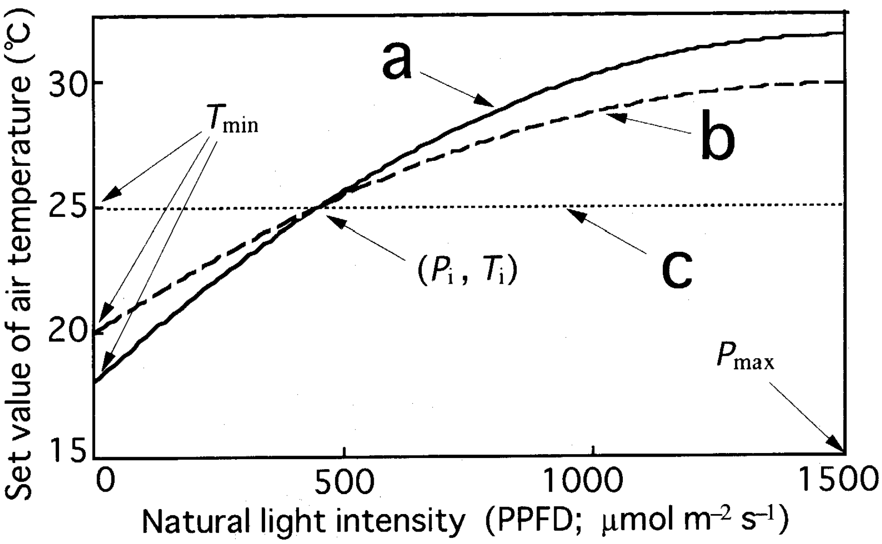

Fig. 2. Set values of air temperature (T_{set}) determined by Eq. (1) under the variablevalue controls in the respective growth chambers of (a), (b) and (c), where values of T_{set} in darkness (T_{min}) were preset at 18℃ (a), 20℃ (b) and 25℃ (c) with P_{max} of 1500 μmol m^{-2} s^{-1}, P_i of 450 μmol m^{-2} s^{-1} and T_i of 25℃: The symbols are explained in Fig. 1.

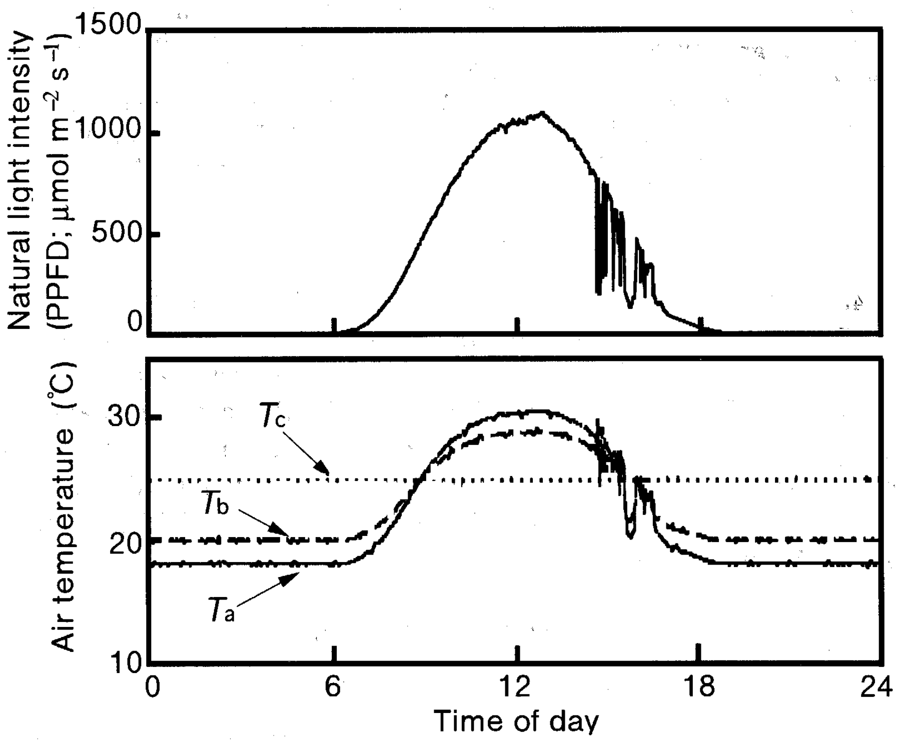

Fig. 3. Time course patterns of natural light intensity (PPFD) and controlled variables of air temperature (T_a, T_b and T_c) on a fair day in the respective growth chambers of (a), (b) and (c), where set values of air temperature (T_{set}) varied with natural light intensity at respective T_{min}s of 18℃ (a), 20℃ (b) and 25℃ (c) in Eq. (1): The symbols are explained in Fig. 1.

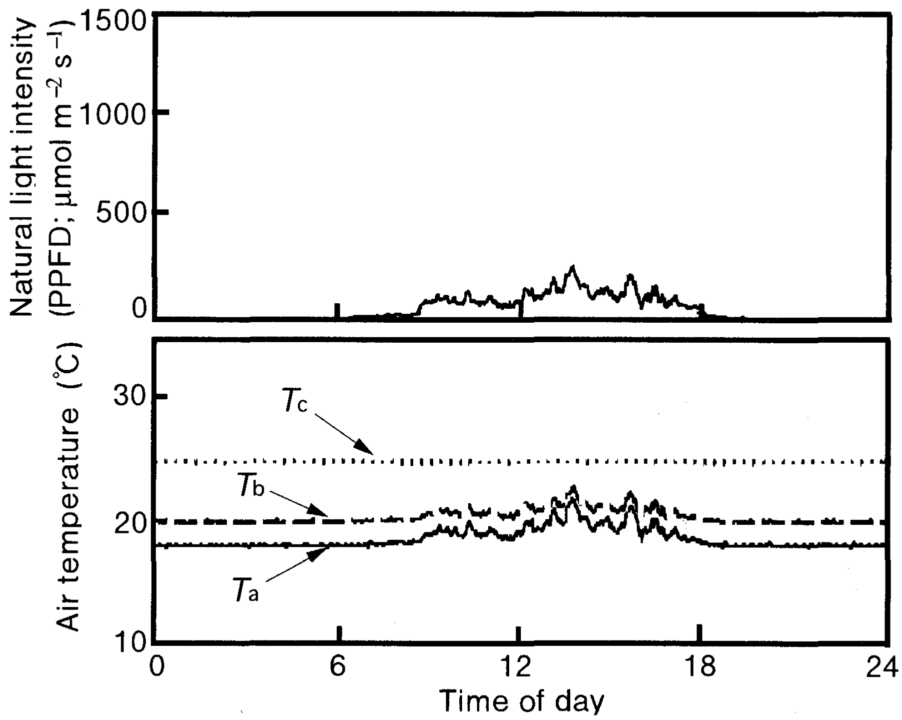

Fig. 4. Time course patterns of natural light intensity (PPFD) and controlled variables of air temperature (T_a, T_b and T_c) on a cloudy day in the respective growth chambers of (a), (b) and (c), where set values of air temperature (T_{set}) varied with natural light intensity at respective T_{min}s of 18℃ (a), 20℃ (b) and 25℃ (c) in Eq. (1) : The symbols are explained in Fig. 1.

at midday. In the afternoon, the variable-value controls of T_a and T_b reliably responded to rapid fluctuation of light intensity. On the other hand, T_c was kept constant at 25℃ for the whole day. Figure 4 shows the time course patterns on a cloudy day (March 30, 1995). P in the daytime did not exceed P_i (450 μmol m^{-2} s^{-1}), and the respective rises in T_a and T_b were lower than 3℃ and 2℃. Therefore, T_a and T_b were kept lower than T_c even in the daytime. Thus, in any sky conditions, the variable-value control of air temperature by feedback of natural light intensity was performed within the temperature region of 18℃ to 32℃, which was estimated to be around the optimum temperature for growth of cucumber plants.

Growth analysis

Figure 5 shows time course patterns of stem lengths. Slower increase in stem length was found in T_a and T_b than in T_c. Final stem lengths in T_a, T_b and T_c were 34 cm, 62 cm and 83 cm, respectively, and the differences were significant at 1% level. Figure 6 shows leaf area per plant in T_a, T_b and T_c. Lower increase rates were found in T_a and T_b. Final leaf areas per plant in T_a, T_b and T_c were 826 cm^2, 1329 cm^2 and 1739 cm^2, respectively, and the defferences were significant at 1% level. Thus, the increases in stem length and leaf area per plant were slower under the variable-value controls of T_a and T_b than under

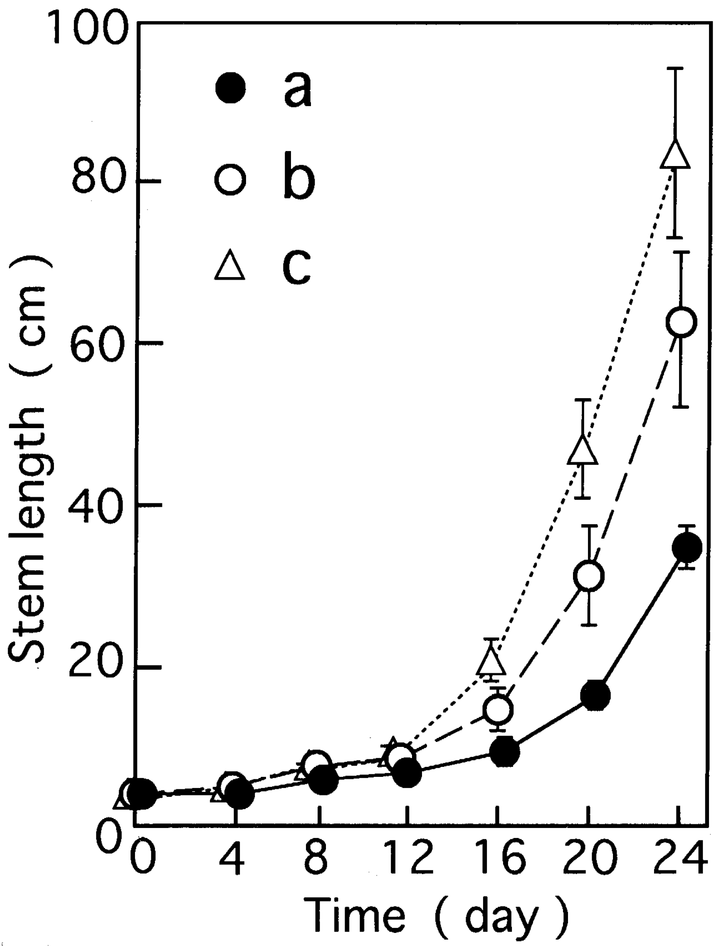

Fig. 5. Time course patterns of stem length in the respective growth chambers of (a), (b) and (c), where set values of air temperature (T_{set}) varied with natural light intensity at respective T_{min}s of 18℃ (a), 20℃ (b) and 25℃ (c) in Eq. (1): The means of measured values in 4 plants were shown with 95% confidence limits.

the constant-value control of T_c.

Figure 7 shows the photograph of the 32-day-old plants grown for 24 days in T_a, T_b and T_c. As described above, the rapid growth was clearly found in T_c. However, chlorosis of leaves was slightly found in T_c, and the plant growth appeared healthier in T_a and T_b. For further analysis of growth characteristics, distribution of leaf areas along the stem was shown in Fig. 8: Leaf area of each leaf was plotted on the position of the node. Stem length and number of leaves in T_c were apparently larger than those in T_a and T_b. The rapid nodal development found in T_c resulted in the longest stem length (Fig. 5) and the largest leaf area per plant (Fig. 6). However, in lower nodes where the leaves were matured, internode lengths and leaf areas in T_a and T_b were slightly larger than those in T_c.

Figure 9 shows shoot fresh weight per plant, leaf fresh weight per leaf area and leaf dry weight per leaf area. Shoot fresh weights in T_a and T_b were 22.8

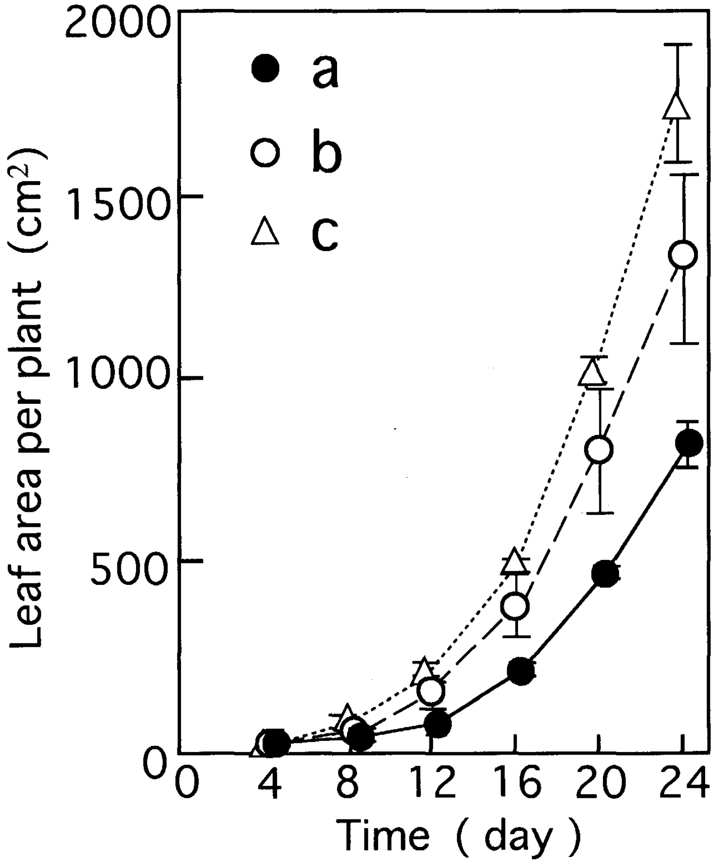

Fig. 6. Time course patterns of leaf area per plant in the respective growth chambers of (a), (b) and (c), where set values of air temperature (T_{set}) varied with natural light intensity at respective T_{min}s of 18℃ (a), 20℃ (b) and 25℃ (c) in Eq. (1): The means of measured values in 4 plants were shown with 95% confidence limits.

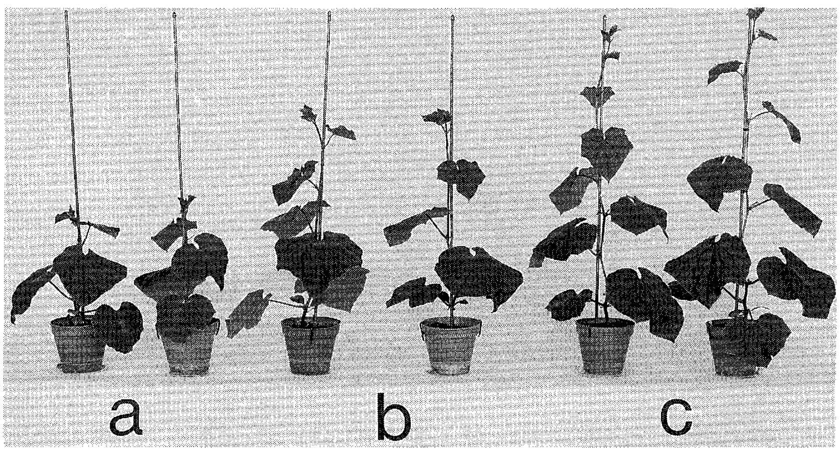

Fig. 7. Photograph of 32-day-old plants grown for 24 days in the respective growth chambers of (a), (b) and (c), where set values of air temperature (T_{set}) varied with natural light intensity at respective T_{min}s of 18℃ (a), 20℃ (b) and 25℃ (c) in Eq. (1).

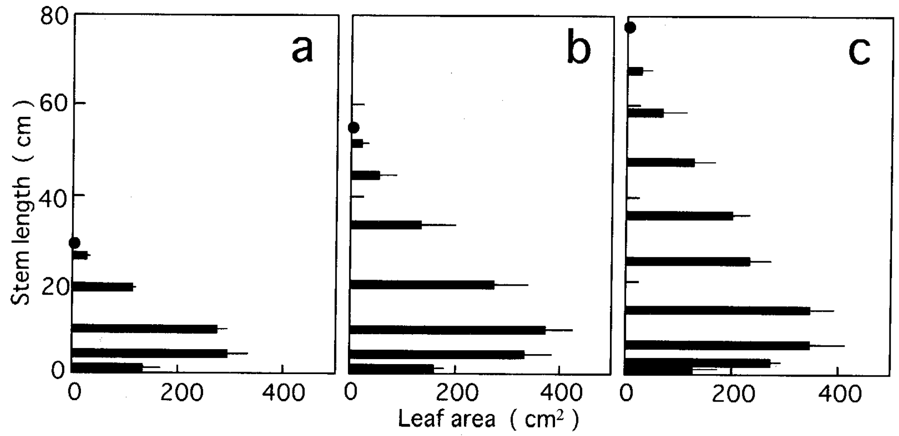

Fig. 8. Distribution of leaf area of each leaf along the stem in plants grown for 24 days in the respective growth chambers of (a), (b) and (c), where set values of air temperature (T_{set}) varied with natural light intensity at respective T_{min}s of 18℃ (a), 20℃ (b) and 25℃ (c) in Eq. (1): The means of measured values in 4 plants were shown with 95% confidence limits.

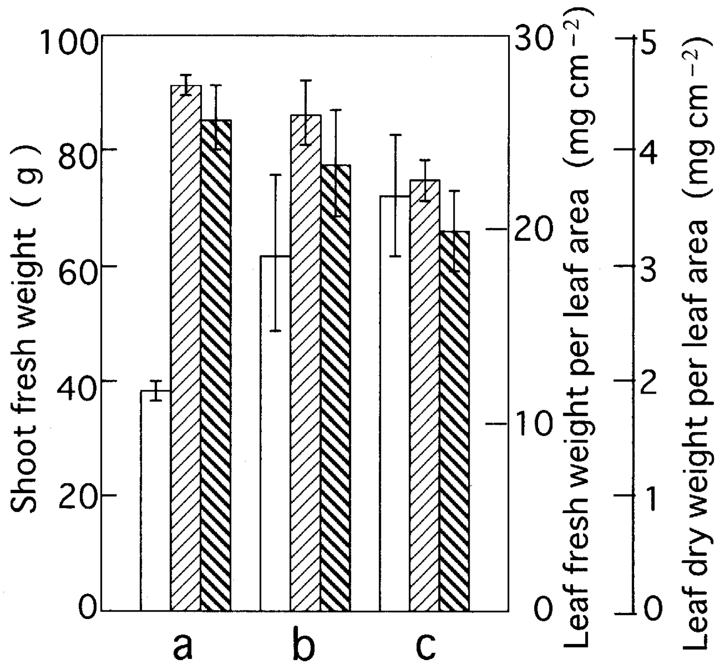

Fig. 9. Shoot fresh weight per plant (□), leaf fresh weight per leaf area (▨) and leaf dry weight per leaf area (▧) in plants grown for 24 days in the respective growth chambers of (a), (b) and (c), where set values of air temperature (T_{set}) varied with natural light intensity at respective T_{min}s of 18℃ (a), 20℃ (b) and 25℃ (c) in Eq. (1): The means of measured values in 4 plants were shown with 95% confidence limits.

g and 34.4 g, respectively, and the highest shoot fresh weight of 39.1 g was found in T_c. The fresh and dry weights per leaf area became higher in T_a and T_b than in T_c, and the differences between T_b and T_c and between T_a and T_c were significant. Thus, the rapid shoot growth appeared, and it was estimated to be succulent under the constant-value control of T_c. On the other hand, the promoted growth and higher accumulation of dry matter in each leaf were found under the variable-value control of T_a and T_b.

Iwakiri and Inayama (*4*) have reported that the photosynthetic rate at light saturation increased at higher leaf temperatures. Ehleringer and Pearcy (*3*) have found that quantum yield for CO_2 uptake was depressed with increase in photorespiration at higher leaf temperatures. From those facts, photosynthesis at higher P could be promoted by higher T_{set}, and photosynthesis at lower P could be kept higher to some extent by lower T_{set} with the depressed photorespiration. The promoted photosynthesis can be considered to bring higher accumulation of non-structural carbohydrates and larger dry weights per leaf area (*1, 4, 9*). Thus, it is possible that the variable-value control of air temperature might affect the plant growth through light- and temperature-dependent carbon balance between photosynthesis and respiration. From these results, it could be considered that the variable-value control of air temperature by using natural light intensity as a feedback signal can be applicable to optimalization of environment for plant growth.

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