B-12.3 Experimental Studies on the Effects of Global Warming on Plants

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Abstract The effects of "global warming" (carbon dioxide (CO_2) concentration, air temperature and/or relative humidity) on the transpiration and growth of crops (C_3 and C_4 plants) were investigated using the environment-controlled growth cabinets. The growths of dry weight and leaf area were accelerated by an increase in CO_2 concentration but were reduced by an increase in air temperature or a decrease in air humidity. These environmental factors modified the several growth parameters and the transpiration rates. The water use efficiency was increased by an increase in CO_2 concentration but decreased by an increase in air temperature or a decrease in air humidity. The relative humidity and CO_2 concentration or air temperature functioned independently in many cases, while the interaction between these factors was significant in some cases. The effects of high temperature (36.5-39.5C) on the fertility of rice plants were also studied. Then, the impacts of "global warming" on rice yield in Japan simulated under 2 x CO_2 (640ppm) climate scenarios were predicted.

Key Words Carbon dioxide, Global warming, Growth, Humidity, Temperature

1. Introduction

After the Industrial Revolution, human activities developed more rapidly and powerfully than previous times, which have caused not only regional pollution problems but also global environment changes. As plants can not move away, they should be easily affected by rapid changes of environments. Therefore, predictive studies on the effects of "global warming" on plants have been conducted.24) An increase in the concentration of carbon dioxides (CO_2) as one of global warming gases in itself is well known to affect the growth of plants, while it is predicted that the elevated CO_2 should change some environmental factors such as an increase in air temperature, a change of precipitation, an acceleration of drought in some regional area and an increase in the concentration of tropospheric ozone22) and so on. Therefore, in order to predict the effects of global warming on plants, it should be needed to accumulate the basic experimental data on effects of environmental factors singly or in combination on plants.

It is well known that the different plant species responses in different manner to each environmental factors and the mechanisms of those responses have been studied well.2, 12, 14) Recently, many scientists have been studying on the effects of environmental factors on the growth of plants with a point of global environment changes,7, 16, 17, 21, 23) and they know the necessity of the studies on the effects of combined environmental factors.1, 3, 8, 25)

2. Research Objective

In the present study, we analyzed the effects of CO_2 concentration, air temperature and relative humidity (RH) singly or in combination on the growth and the transpiration of several crops to clarify the species sensitivity and the existence of the interaction of these environmental factors. Furthermore, we studied the sensitivity to high temperature on the fertility of 2 different cultivars of rice, and predicted the impacts of "global warming" on rice yield in Japan simulated under 2 x CO_2 (640ppm) climate scenarios.

3. Research Method

3.1 Experiments on plant growth to CO_2, temperature and/or humidity

3.1.1 Plant materials

Seeds of crops; eggplant, pimiento, tomato, soybean, pe-tsai, radish, corn and sorghum were sown on the horticultural soil (Kureha Engeibaido) in the naturally lighted environment-controlled glasshouse (25C, 70%RH). After germination, each seedling was transplanted to a plastic pot containing artificial gravel (Hydro-ball, Holland), which was set in the plastic container filled with 0.1 % Hyponex solution aerated plus Hoagland's No. 2 micro nutrients and 142μM Fe(III)EDTA. When the first foliage leaf has just expanded, plants were put into 4 artificially lighted environment-controlled growth cabinets (KG-50HLA-D, Koito) equipped in the phytotron of the National Institute for Environmental Studies (NIES). The similar culture system mentioned above was set in each cabinet for using the following experiments.

3.1.2 Experimental conditions.

In each cabinet, light source consisted of 14 fluorescence lamps (Twin1FPR96EX-N/A, Panasonic) with 4 incandescent lamps (100W, Hitachi). The light intensity measured using a quantum sensor with handy-meter (LI-189, LI-COR) was adjusted by moving with a jack to about $500 \pm 50 \mu E \cdot m^{-2} \cdot sec^{-1}$ at plant height. The light/dark cycle was adjusted as 14hrs/10hrs with timers. The temperature and the RH of air monitored with a psychrometric sensor (E-765, Yokogawa) were regulated with a controlling system using a PID controller (DCP216, Yamatake). Fresh air passed through activated charcoal and catalyst-bearing (containing MnOx and CuO) filters to remove ambient air pollutants was mixed with CO_2 gas induced from a liquid CO_2 cylinder and injected through a thermal mass-flow controller into the air stream. The concentration of CO_2 monitored with an infra-red gas analyzer (ZRH1DZY1-0AZYY, Fuji Electric) was regulated with an automatic mass-flow controlling system.

Experiment 1: Effects of CO_2 concentration and/or relative humidity.

Plant materials were eggplant, pimiento, tomato, pe-tsai, radish and corn. Temperature was regulated at 25C in all 4 cabinets. In each cabinet, plants were treated with one of four conditions: 500ppm CO_2 or 1000ppm CO_2 with 37%RH or 79%RH, during 5, 7 or 10 days.

Experiment 2: Effects of temperature and/or relative humidity.

Plant materials were eggplant, pimiento, soybean, pe-tsai, radish, corn and sorghum. CO_2 concentration was regulated at 500ppm in all 4 cabinets. In each cabinet, plants were treated with one of four conditions: 28C or 31C with 37%RH or 79%RH, during 7 days.

3.1.3 Measurement of transpiration rate and leaf conductance

The transpiration rate of plants in each cabinet was calculated from a decrease of weight of culture solution with plants as compared with a decrease of that without plants, which was measured with a balance (KA15, Mettler) and was logged in a personal computer (PC9801Vm, NEC). The measurement was performed during the treatment.

In the temperature x humidity experiments, the leaf and air temperatures, transpiration rate and leaf resistance were measured just before the harvest, using a steady state porometer (LI-1600, LI-COR).[5] Leaves that expanded fully and were exposed to light sufficiently were selected to measure these values in each species during 9:00 to 15:00 in light period. The leaf conductance of each plant was calculated as the reciprocal value of leaf resistance.

3.1.4 Harvest and growth analysis

In each experiment, 10 plants were harvested just before the treatment as an initial value, and 10 plants in each treatment were also harvested 5, 7 or 10 days thereafter. The leaf area of whole plant was measured by an automatic planimeter (AAM-7, Hayashi Denko). Then, plants were divided into leaf laminae, stem and root, which were dried at 80-90 C for 2-3 days and weighed. Leaf buds and folding leaves were included in stem part. Leaf petioles of pe-tsai and radish were included in leaf part, while those of other species were included in stem one.

In order to ascertain the effects on basic processes of plant growth, growth analysis was performed using following formulae for obtaining relative growth rate (RGR), net assimilation rate (NAR), leaf area ratio (LAR), specific leaf area (SLA) and leaf weight ratio (LWR).[18]

$$\begin{aligned}
\mathrm{RGR} &= 1/\mathrm{W}\cdot d\mathrm{W}/dt &&= (\ln \mathrm{W}_2 - \ln \mathrm{W}_1)\,/\,(t_2 - t_1)\\
\mathrm{NAR} &= 1/\mathit{F}\cdot d\mathrm{W}/dt &&= [(\mathrm{W}_2 - \mathrm{W}_1)(\ln \mathit{F}_2 - \ln \mathit{F}_1)]\,/\,[(t_2 - t_1)(\mathit{F}_2 - \mathit{F}_1)]\\
\mathrm{LAR} &= \mathit{F}/\mathrm{W} &&= [(\mathit{F}_2 - \mathit{F}_1)(\ln \mathrm{W}_2 - \ln \mathrm{W}_1)]\,/\,[(\ln \mathit{F}_2 - \ln \mathit{F}_1)(\mathrm{W}_2 - \mathrm{W}_1)]\\
\mathrm{LWR} &= \mathrm{F}/\mathrm{W} &&= [(\mathrm{F}_2 - \mathrm{F}_1)(\ln \mathrm{W}_2 - \ln \mathrm{W}_1)]\,/\,[(\ln \mathrm{F}_2 - \ln \mathrm{F}_1)(\mathrm{W}_2 - \mathrm{W}_1)]\\
\mathrm{SLA} &= \mathit{F}/\mathrm{F} &&= [(\mathit{F}_2 - \mathit{F}_1)(\ln \mathrm{F}_2 - \ln \mathrm{F}_1)]\,/\,[(\ln \mathit{F}_2 - \ln \mathit{F}_1)(\mathrm{F}_2 - \mathrm{F}_1)],
\end{aligned}$$

where Wi, Fi and *Fi* are the dry weight of whole plant, dry weight of leaves and leaf area at time ti (t_1: initial, t_2: final), respectively.

3.2 Experiments on fertility of rice to high temperature and simulation of rice yield in Japan.

3.2.1 Plant materials and growth conditions.

Rice cultivars: Koshihikari and Akihikari were grown using rice-field soil filled with water in pots (1/5000 *a*). In each pot, 0.2g N, 0.5g P and 0.5g K were included as basal fertilizers, and 0.4g N was given as additional one. Plants grown to the reproductive stage were put into a naturally lighted environment-controlled glasshouse (26C, 70%RH), then a high temperature (36.5C, 38.0C or 39.5C) was treated during 6 hrs (10:00-16:00) in a day, for 8 days.

3.2.2 Measurement of fertility and pollen development.

The fertility of rice spikelets flowered on 1- to 3-day of the high temperature treatment started was measured. On a stigma of spikelets flowered on 1- or 3-day, the total number and the germination percentage of shed pollen grain were measured to compare the fertility.

3.3.3 Simulation model of rice yield using general circulation models (GCM).

The simulation model for rice-weather relationship (SIMRIW) to simulate rice growth and yield in relation to CO_2 concentration, temperature and solar radiation conditions was applied to estimate the rice yield of whole Japan area.[6] We used the doubled CO_2 (2 x CO_2: 640ppm) climate scenarios predicted by GFDL, GISS and UKMO general circulation models (GCMs) for dynamics of earth's atmosphere. We estimated the regional rice yields using 2 different cultivars; high temperature-sensitive genotype: Akihikari and high temperature-tolerant genotype: Koshihikari, which were observed by our experiments mentioned above.

4. Results and Discussion

4.1 Effects of CO_2 concentration and/or relative humidity on plant growth.

The initial and the final dry weights of 6 plant species; Eggplant, pimiento, tomato, pe-tsai, radish and corn, were shown in Fig. 1. The growths of all plant species were accelerated by 1000ppm CO_2 treatment as compared with 500ppm CO_2, while those were reduced by 37%RH treatment as compared with 79%RH, though the extents were varied with species. The acceleration of dry weight caused by an increase in CO_2 concentration was remarkable in all C_3 plants, while the effect was slightly in a C_4 plant; corn. The reduction of plant growth caused by a decrease in RH was rather obvious in eggplant and tomato than other species. The growth of leaf area of eggplant, tomato or pe-tsai was also accelerated by an increase in CO_2 concentration, while no growth acceleration was observed in corn. On the other hand, the reduction of leaf area growth caused by a decrease in RH was obvious in all plant species.

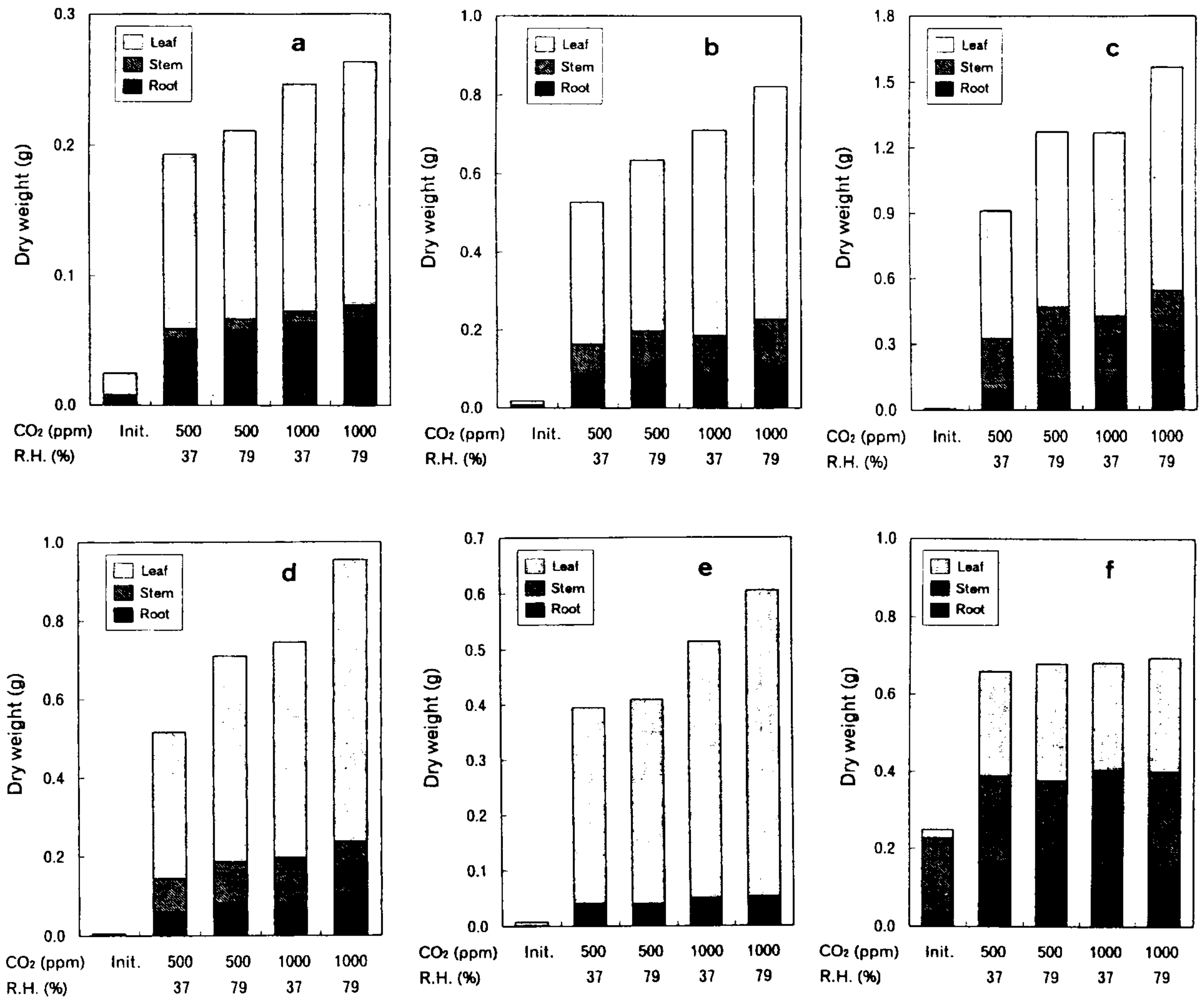


Fig. 1. Effects of CO_2 concentration and/or relative humidity on the dry weight growth of several plant species. a: radish (treated for 5 days), b: pimiento (10 days), c: tomato (10 days), d: eggplant (10 days), e: pe-tsai (7 days), f: corn (5 days).

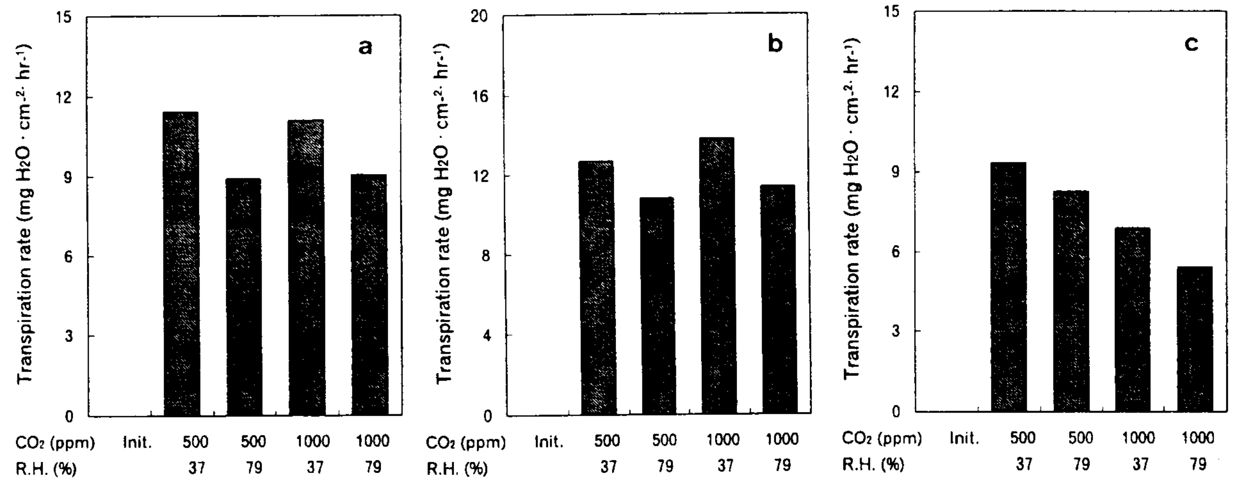


Fig. 2. Effects of CO_2 concentration and/or relative humidity on the transpiration rates of several plant species. a: eggplant (10 days), b: pe-tsai (7 days) and corn (5 days).

From the growth analysis, RGRs were increased by an increase in CO_2 concentration in all plant species. Furthermore, the elevated CO_2 increased NAR much more than RGR, while decreased LAR clearly due to a decrease in SLA but not that in LWR. Similar results of a decrease in SLA caused by a long-term CO_2 enrichment were reported in other plant species.4) Though 37%RH treatment decreased RGRs of all plant species, a decrease in NAR was observed in only eggplant and tomato and decreases in LAR and SLA were observed in pe-tsai and radish. RH affected hardly on LWR.

The acceleration on plant growth by an increase in CO_2 concentration and the reduction on that by a decrease in RH were remarkably in C_3 plants but hardly in corn; a C_4 plant. It is needed to accumulate the data of other C_4 plants affected by CO_2 and/or RH.7) In the present study, CO_2 and RH functioned independently (additive) in many cases on plant growth. However, the growth reduction of pe-tsai by 37%RH with 1000ppm CO_2 was more obvious than that with 500ppm CO_2, which suggested the interaction between these environmental factors. The interaction between these factors was observed in some other cases.

The effects of CO_2 and/or RH on transpiration were shown in Fig 2. CO_2 affected transpiration rates differently with different plant species. An increase in CO_2 concentration increased transpiration rates slightly of pe-tsai and radish although it decreased obviously those of pimiento and corn. However, low RH treatment accelerated the transpiration of all plant species. CO_2 and RH should function independently on transpiration rates.

From the results of growth and transpiration, the elevated CO_2 concentration maintained the water use efficiency of many plant species at high level, especially a C_4 plant; corn.9) On the other hand, a decrease in RH lowered the water use efficiency of all plant species, and C_3 plants were more affected than a C_4 plant.

4.2 Effects of temperature and/or relative humidity on plant growth.

The initial and the final dry weights of eggplant, pimiento, soybean, pe-tsai, radish, corn and sorghum were shown in Fig. 3. The growths of many plant species except soybean and corn were reduced by 31C treatment as compared with 28C. In the present range of temperature, however, those of radish, eggplant and corn were reduced by 37%RH treatment as compared with 79%RH, though others were hardly affected by RH. The growth of leaf area was reduced by an increase in temperature in many plant species such as radish, pe-tsai, pimiento, eggplant and sorghum, while that was affected hardly in corn and rather accelerated in soybean. A decrease in RH also reduced the leaf area growth of eggplant, pimiento and sorghum, but hardly affected those of others. Therefore, the effects of lowered RH were obscure with 28C and 31C treatments as compared with 25C mentioned above.

From the growth analysis, RGRs were decreased by an increase in air temperature in many plant species. However, effects of temperature on NAR were varied with species. High temperature decreased the NAR of sorghum but increased that of eggplant, pe-tsai and radish. In many plant species, high temperature decreased LAR due to a decrease in SLA but not that in LWR. There was no clear tendency on the effects of RH on growth parameters in this experimental temperature range. The effects were varied with species.

Temperature and RH functioned independently (additive) on dry weight growth and leaf area growth in many plant species, while the interaction between these environmental factors was observed apparently in sorghum. The interaction was also observed on NAR and LAR in eggplant and sorghum. Furthermore, the effects of lowered RH were obscure under 28-31C as compared with 25C. The more experiments should be needed on the effects of the interaction between temperature and RH.

The effects of temperature and/or RH on transpiration were shown in Fig 4. Temperature affected transpiration rates differently with different plant species. An increase in temperature increased transpiration rates of pe-tsai, radish and corn, while it affected hardly those of other plant species. However, low RH treatment accelerated the transpiration of all plant species. CO_2 and RH seemed to function independently on transpiration rates.

From the results of growth and transpiration, an increase in temperature had little effects on the water use efficiency of many plant species, while a decrease in RH lowered the water

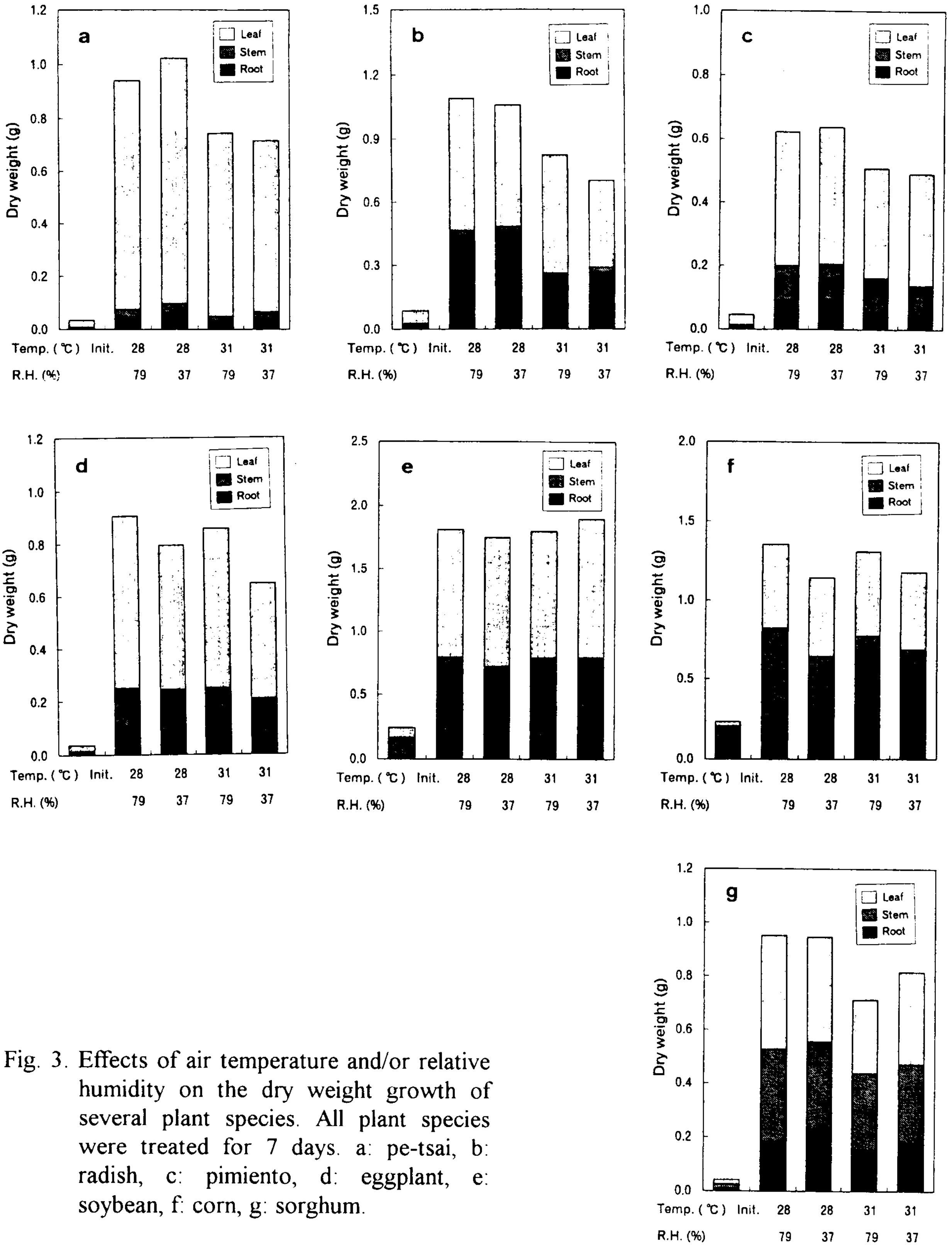


Fig. 3. Effects of air temperature and/or relative humidity on the dry weight growth of several plant species. All plant species were treated for 7 days. a: pe-tsai, b: radish, c: pimiento, d: eggplant, e: soybean, f: corn, g: sorghum.

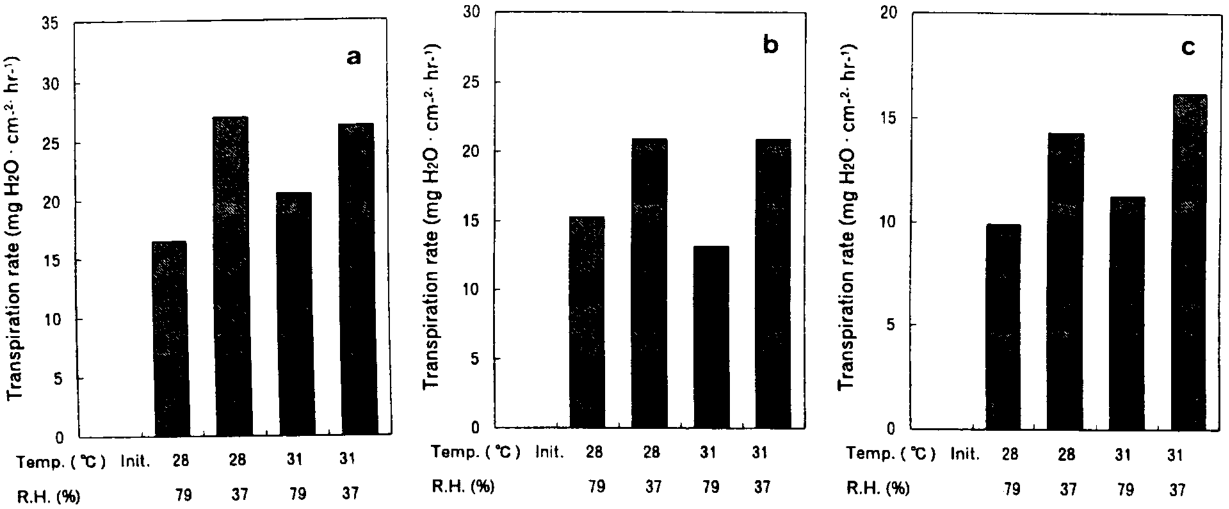
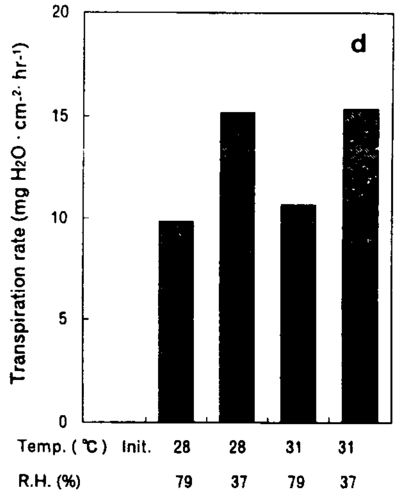


Fig. 4. Effects of air temperature and/or relative humidity on the transpiration rates of several plant species. All plant species were treated for 7 days. a: eggplant, b: soybean, f: corn, g: sorghum.



use efficiency. The tendency of the transpiration rate measured by porometer was almost similarly as that measured by balance. The transpiration rates of many plants were increased slightly by high temperature, and those were increased remarkably by lowered RH. The interaction between temperature and RH was observed in pe-tsai and sorghum. High temperature affected the diffusive conductance differently with different species, while lowered RH decreased it in many species. The value of leaf temperature minus air temperature became slightly lowered by an increase in air temperature and remarkably lowered by a decrease in RH in many C_3 plants, while it became remarkably lowered by temperature rather than by RH in C_4 plants; corn and sorghum. Further, leaf temperature was shown cooler than air temperature in C_3 plants, although the reverse occurred in C_4 plants. In the case of sorghum under the treatment of 31C air temperature, the leaf temperature of the plants treated with 79%RH showed higher than that with 37%RH. The remarkable growth reduction observed in sorghum treated with 31C and 79%RH might be caused by the higher leaf temperature, i.e., heat stress.2)

4.3 Effects of high temperature on fertility of rice and simulation of rice yield in Japan.

The treatment of high temperature (36.5C, 38.0C or 39.5C) reduced the grain yield through the reduction of spikelet fertility in 2 rice cultivars: Koshihikari and Akihikari, shown in Fig. 5. High temperature affected to damage rice spikelets at the moment of their flowering, and made them sterile. Though the fertility of both cultivars decreased with increasing

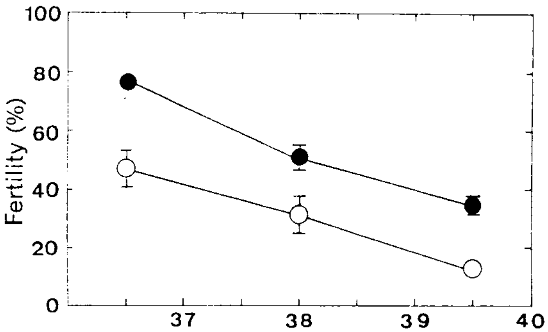


Fig. 5. Effects of high temperature on the fertility of spikelets.
○: Akihikari, ●: Koshihikari.

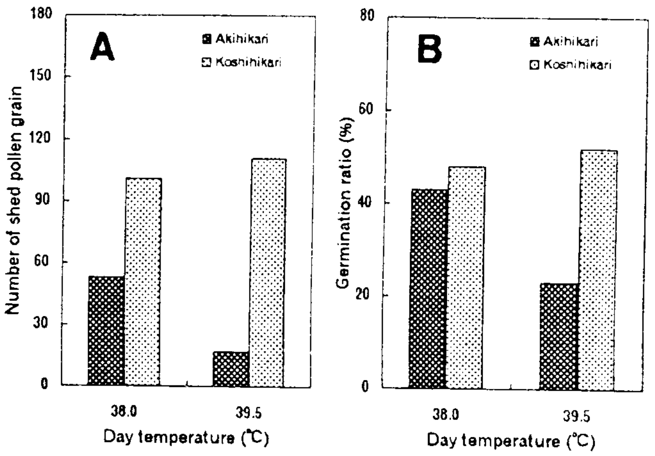


Fig. 6. Effects of high temperature on the total number and germination ratio of pollen grain on a stigma of spikelets. A:Total number, B:Germination ratio.

temperature treated, the sensitivity to high temperature differed with cultivars. The treatment of 39.5C reduced the fertility lower than 20% in Akihikari, but about 40% in Koshihikari. The temperature at which 50% spikelets are sterile was 38.2C for Koshihikari; a high temperature-tolerant genotype and was 36.6C for Akihikari; a high temperature-sensitive genotype.

On a stigma of spikelets flowered on 1- or 3-day, the total number of shed pollen grain and the germination percentage of them were measured as shown in Fig. 6. As compared with Koshihikari, Akihikari was affected remarkably in the number of shed pollen grain on a stigma and slightly in the germination percentage by the high temperature (38.0C or 39.5C). There was a closed correlation between the spikelet fertility and the number of germinated shed pollen grain on a stigma of spikelet. Therefore, the sterility might be caused by a decrease in the number of germinated pollen on a stigma treated with high temperature, and the difference of the cultivar sensitivity to high temperature should relate to this mechanism.

As the reduction of fertility caused by high temperature might affect the grain yield, global warming might cause severe damages on rice yield of some sensitive cultivars. With applying the results mentioned above, therefore, the rice yield of sensitive or tolerant cultivar in Japan area was predicted using the simulation model for rice-weather relationship (SIMRIW).6) The predicted relative changes of rice yield under the doubled CO_2 (2 x CO_2: 640ppm) climate scenarios by GFDL, GISS and UKMO general circulation models (GCMs) were shown in Fig. 7. For a high temperature-sensitive genotype, severe yield reductions in the southern Japan by ca. 10%, 20% and 40% from the present were predicted under 2 x CO_2 climates from GFDL, GISS and UKMO GCMs, respectively, while for a high temperature-tolerant genotype, those by less than 10% were predicted under 2 x CO_2 climates from 3 GCMs. In the northern Japan, however, positive effects of 2 x CO_2 climates, ranging from ca. 10% (GFDL) to ca. 25% (GISS and UKMO), on an increase in yield were predicted, irrespective of cultivar sensitivity to high temperature damage.

It should be needed to study the effects on reproduction, adaptation, competition, etc., to predict the impacts of global environment changes on natural ecosystems including plants.15) Recently, studies on ecosystems using the large environment-controlled glasshouses11,13) or the field system10) for controlling CO_2 concentration have been conducted. Nowadays, other changes related to global warming, such as an increase in O_3 concentration that was known to cause a reduction on plant growth,20) are predicted. Further, it has been apprehended that other global environment changes; increases in acid deposition and in UV-B radiation also affect plants and ecosystems. Therefore, we should intend to study the effects of the combined environmental factors on plants and ecosystems.19)

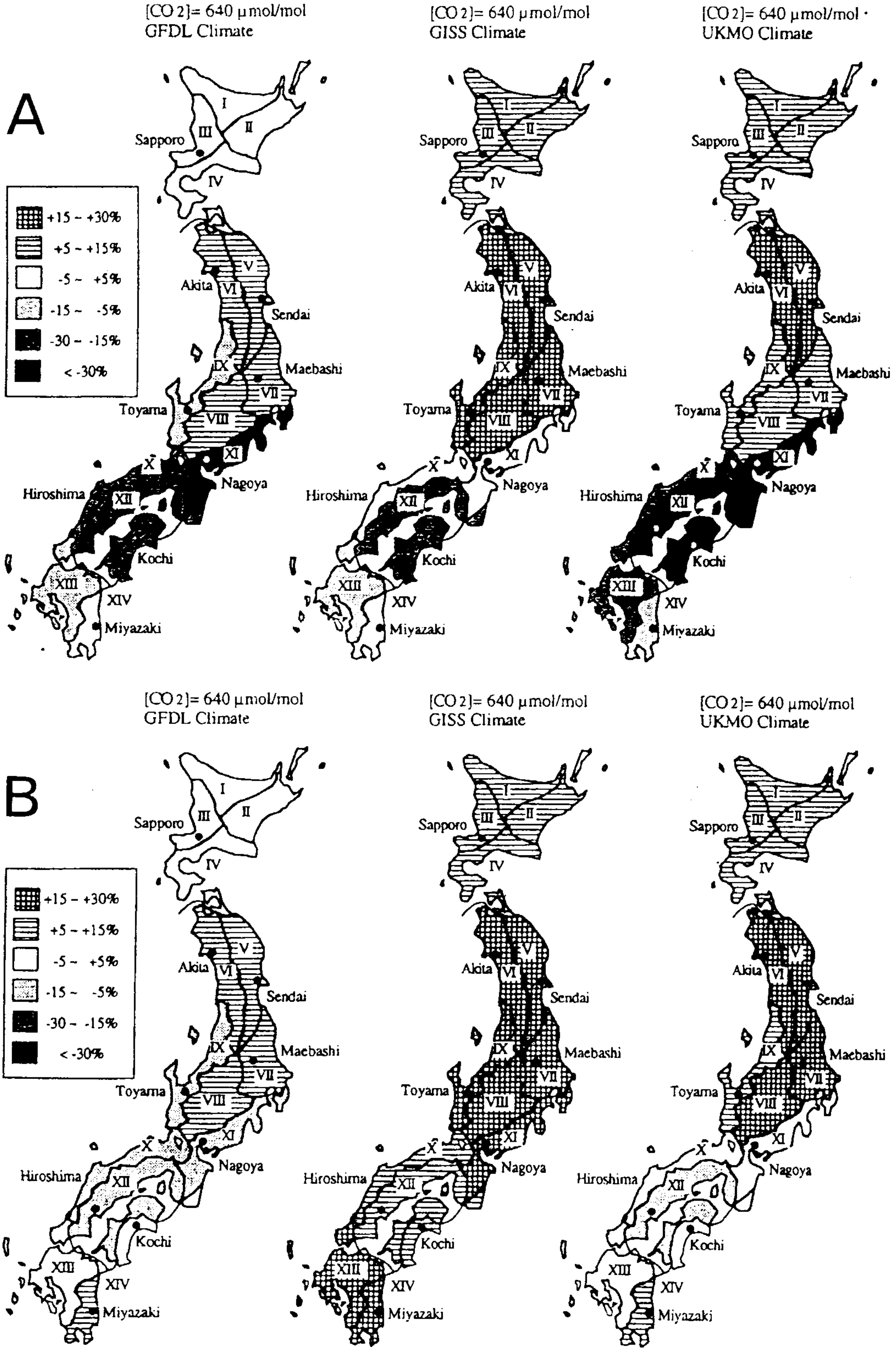


Fig. 7. The prediction of relative changes of rice yield in Japan using the SIMRIW,6) under the 2 x CO_2 (640ppm) climate scenarios by GFDL, GISS and UKMO GCMs. A: High temperature-sensitive genotype, B: High temperature-tolerant genotype.

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