Potential effects of global warming on the occurrence of Japanese pest insects

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(Received 4 July 1997; Accepted 11 August 1997)

Abstract

The potential effects of global warming on the occurrence of four types of Japanese pest insects were studied by developing a computer program. The number of generations of each insect under present thermal condition and after 2°C warming at 960 locations in Japan where temperature data was measured by the AMeDAS system was estimated. Thermal summation and daylength models were used to describe insect development and deleterious effects of low and high temperatures on the insects. In most regions, a non-diapausing insect, *Plutella xylostella* would complete two additional generations compared to the present. In a winter diapausing insect, *Chilo suppressalis*, the northern boundaries of zones of two and three generations would shift northward by about 300 km. A cold weather susceptible insect, *Tribolium confusum*, would expand its distribution area northward, but the northern front of its distribution would not shift markedly, except for in the central mountainous regions of the Main Island. *Ephestia kühniella*, which is susceptible to hot weather, would not be able to occur in the western part of the Main Island and Shikoku and Kyushu Islands due to high temperatures in summer, leading to a large shrinkage in its distribution area in Japan. Our results demonstrated that the effects of global warming on insect occurrence would be significant, but should vary depending on the biological characters of the insects.

Key words: Global warming, insect occurrence, thermal summation models, *Plutella xylostella*, *Chilo suppressalis*, *Tribolium confusum*, *Ephestia kühniella*

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC, 1990) reported that the atmospheric concentrations of greenhouse gases such as CO₂, methane and nitrogenous oxide, which absorb long-wave terrestrial radiation from the warm surface of the Earth and lead to global warming, have been increasing since the 1760's, the beginning of the industrial revolution. The rates of increase in the concentrations of these gases and chlorofluorocarbons (CFCs), which also have a strong greenhouse effect, were noticeably accelerated after 1950. IPCC (1996b) predicted that under their mid-range emission scenario (IS92a), CO₂ concentration, including that from other greenhouse gases converted into a relative radiative effect (the equivalent CO₂ concentration) would double by the year 2100. Under the IS92a scenario which includes the effects of aerosol, it is also

predicted that the CO₂ doubling will result in an increase in global mean temperature of about 2°C above the present value.

The predicted global warming is likely to have an influence on agricultural production in the future (e.g. Uchijima, 1990; Parry and Rosenzweig, 1993; Parry, 1990, 1995; IPCC, 1996a). Although these studies also suggest that global warming may cause increased crop losses by pest insects, detailed studies on the effect of global warming on insect occurrence are necessary to quantitatively predict insect damage to crops.

Because insects are poikilothermic animals, their development, reproduction and behavioral activities are dependent on temperature (Uvarov, 1931). Thus, global warming should have critical effects on insect distribution and abundance. Several papers have mentioned possible effects of global warming on the occurrence of pest insects (Kiritani, 1988, 1991, 1997;

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Collier et al., 1991; Mochida, 1991; Porter, 1995; Porter et al., 1991; Cammell and Knight, 1992; Landsberg and Smith, 1992; Sutherst et al., 1995). (Collier et al. (1991) studied a possible impact of global warming on the occurrence of the cabbage root fly, *Delia radicum*, in the UK using a simulation model which described induction of aestivation and diapause. Using a computer model CLIMEX with a scenario that envisaged a rise of 0.1°C per degree of latitude with an increase of 20% rainfall in summer and a decrease of 10% rainfall in winter, Sutherst et al. (1995) predicted that the effect of global warming would greatly increase the risk from a livestock tick, *Haemaphysalis longicornis*, in Europe. The predictions of some papers are, however, rather qualitative (Kiritani, 1988, 1991, 1997; Cammell and Knight, 1992; Landsberg and Smith, 1992), and some neglected critically important biological traits, such as diapause (Porter et al., 1991; Porter, 1995).

In this paper, we use a computer program which we have designed to predict the potential effects of global warming (elevated temperature) induced by CO₂ doubling on the occurrence of four types of pest insects: non-diapausing, winter diapausing, cold weather susceptible and hot weather susceptible insects.

MATERIALS AND METHODS

Insects studied. We studied four major types of Japanese insects: non-diapausing (ND), winter-diapausing (WD), cold weather susceptible (CS) and hot weather susceptible (HS) insects. The diamondback moth, *Plutella xylostella* (L.) (ND), the rice stem borer, *Chilo suppressalis* (Walker) (WD), the confused flour beetle, *Tribolium confusum* Jacquelin DuVal (CS), and the Mediterranean flour moth, *Ephestia kühniella* Zeller (HS), for which the necessary biological data were previously available, were selected as representatives of each respective type.

Effective accumulative temperature (EAT). The basic model to describe temperature-dependent development of insects was based on the thermal summation law (Bodenheimer, 1926). Assuming that the relationship between developmental rate and temperature was nonlinear (Uvarov, 1931), a combination of two

linear equations (triangular model) or the fourth-degree polynomial equation (curvilinear model), was fitted to express the relationship, by giving t_0 (minimum temperature or threshold temperature), t_1 (optimal temperature), t_2 (maximum temperature) and K (thermal constant or effective accumulative temperature for completion of the development, the reciprocal of which represents the slope of line t_0-t_1) (Fig. 1). Because the preoviposition periods of these insects were short, we did not include the thermal requirement for this period in K s. Using the sine wave method (Pruss, 1983), where a sine curve was fitted to the daily minimum and maximum temperatures, the daily effective temperature (DET) was calculated by integrating areas under the fitted sine curve above t_0 . In this integrating process, the temperature was adjusted in proportion to the above mentioned temperature-development rate relationships (Fig. 1). The accumulative temperature effective for the insect development (EAT in degree-days) was calculated by summing up the DETs over a year (January 1–December 31). Thus, the EAT used was based on the thermal unit that was actually effective for the development of the insect.

The accumulative low temperature (ALT) below a critical low temperature (t_c) and the accumulative high temperature (AHT) above a critical high temperature (t_h) were also calculated to assess the deleterious effects of cold weather or hot weather on the occurrence of CS or HS insects. ALT had a negative value. We assumed that when temperature was lower than t_c or higher than t_h , the insects received deleterious effects, and where $|ALT|$ exceeded a critical value $|K_c|$, or AHT exceeded a critical value K_h , the insect was unable to occur.

Daylength. Seasonal changes in the daylength were used to describe the development of diapausing insects. The local daylength (possible duration of sunshine plus duration of twilight (dawn and dusk)) was calculated using the following equation (Kishida, 1986);

$$J = 12 \pm |t|/15 - (135 - e)/15 - z,$$

where J was the time of solar altitude at the place, t was the hour angle, e was longitude and z was the equation of time. t was calculated as;

$$t = \cos^{-1}((\sin h - \sin \delta \times \sin \phi) / \cos \delta \times \cos \phi),$$

where h was the solar altitude, δ was the north

latitude and ϕ was declination.

Computer program. We developed a computer program to estimate insect occurrence in Japan, incorporating the above-mentioned temperature and daylength models. Hourly temperature data averaged over 10 years from 1986 to 1995 measured at the meteorological observation (AMeDAS, Automated Meteorological Data Acquisition System) stations was used for the calculation of local EAT, ALT and AHT. The program estimated the number of generations of the insects at the locations of 960 AMeDAS stations from the following relationships: local EAT vs. K of the insects; local daylength vs. critical day length (CDL) for entering diapause of the WD insect; and local ALT or AHT vs. K_c or K_h of the CS or HS insects. In the last generation, when the thermal unit of 80% of K was satisfied, the program judged that the generation was completed at the location.

The program had the following options; 1) The period of calculation of EAT could be set by giving initial and terminal dates, for which a particular year, or five or ten year averages of AMeDAS data could be selected. 2) Developmental rate-temperature relationship could be selected as a triangular or curvilinear equation (Fig. 1). 3) Any temperature in $^{\circ}\text{C}$ could be added to or subtracted from the AMeDAS data. 4) A constant K or a latitudinal cline of K could be selected as a linear equation by giving the slope and intercept. 5) Three kinds of twilight, Civil twilight (solar altitude (SA) is -6°), twilight of

sunrise-sunset (SA: $-7^{\circ}21'40''$) or nautical twilight (SA: -12°) could be selected for calculation of local daylength depending on the photo-sensitivity of the insect. 6) Non-diapause or diapause type insects could be selected, and when the latter was selected, a constant CDL or a latitudinal cline of CDL for entering diapause could be selected as a linear equation by giving slope and intercept. 7) The developmental stage sensitive for entering diapause could be selected by assigning a portion in the life cycle. 8) The map of insect occurrence calculated could be displayed on the screen for the whole country or for six regions (Hokkaido Island, Tohoku district, Kanto-Chubu districts, Kinki-Chugoku districts-Shikoku Island, Kyushu Island, and Nansei Islands) separately (see Fig. 2; the Nansei Islands were omitted). 9) The photo-thermo graph at any location of the AMeDAS stations could be displayed on the screen by selecting the location, which enabled us to visualize the seasonal occurrence of each generation of the insect and the seasonal change in daylength on the degree-day abscissa.

The program was written in N88BASIC by T. K. and run on a personal computer PC-9801RA (NEC Inc.) with a MS-DOS system.

Prediction procedures. First we estimated the present occurrence of the insects by the program using current temperature data, and examined the results with literature and personal observations and communications to verify the validity of the models and parameters used. Then, when the results were confirmed to be an accurate representation of the current occurrence of the insect, 2°C , which was the predicted warming due to CO_2 doubling around 2100 (IS92a scenario, IPCC, 1996b), was added to AMeDAS hourly data using the above-mentioned option 3) and the potential effect of global warming on the insect occurrence was assessed by comparing the current and future occurrence. The results in the Nansei Islands were omitted from this paper.

RESULTS

Non-diapausing insect

P. xylostella is a non-diapausing insect which is a serious pest of cruciferous crops and is cosmopolitan in its distribution. In Japan a possible overwintering area is limited to the areas

Fig. 1. Two models, triangular model (broken line) and curvilinear model (solid line) used to describe developmental rate-temperature relationship.

Fig. 2. Islands and districts in the Main Island of Japan. Nansei Islands are omitted.

south of the southern part of the Tohoku district where the period of continuous snow cover on the ground in winter is less than 60 days (Honda and Miyahara, 1987). The adult moths emerging in spring make a northward migration, and in the warm seasons they occur in the northern part of Japan where they cannot overwinter (Honda and Miyahara, 1987). In Ohono-machi, Hokkaido Island (see Fig. 2), adult moths which migrated were caught by pheromone traps in early April when the mean temperature was 4°C (Hokkaido Plant Protection Office, 1995); the temperature was much lower than the threshold temperature t_0 (8.5°C) for the development of *P. xylostella* (Yamada and Kawasaki, 1983). Thus, for the estimation of the occurrence of *P. xylostella*, we assumed that the insect overwintered at all locations.

The parameters, t_0 , t_1 , t_2 and K were 8.5°C, 30°C, 37°C and 274 degree-days, respectively (Yamada and Kawasaki, 1983), and the triangular model was chosen. The estimated occurrence of *P. xylostella* at present is shown in Fig. 3. The results indicate that 1–3 generations of the moth occurs on most parts of Hokkaido Island and the northern part of the Tohoku district, 4–6 generations in most parts of the Tohoku district and the northern parts of the Hokuriku and Kanto districts, and 7–9 generations in the western part of the Main Island (Honshu), Shikoku Island and Kyushu Island. In Sapporo, Hokkaido Island (see Fig. 2), the number of generations estimated was three,

which conformed to the observed voltinism (Hokkaido Plant Protection Office, 1995). Concluding that the results for the present occurrence were satisfactory, we predicted the occurrence of *P. xylostella* under the condition of 2°C warming (Fig. 4). The insect would complete two more generations in most regions.

Winter-diapausing insect

Global warming will affect the voltinism of diapausing insects by increasing local EAT and shifting the appearance of the sensitive stage for entering diapause. The rice stem borer, *C. suppressalis*, a well known rice pest, is widely distributed in South-East Asia. *C. suppressalis* enters diapause with a cue of short-day length in the fall (Kishino, 1974). We assumed that the insect had latitudinal clines in K and CDL (Kishino, 1974): K (degree-days) = $-27 \times \text{latitude} + 1,880$ and $\text{CDL (h)} = 0.185 \times \text{latitude} + 8$. For the CDL, twilight of sunrise-sunset was selected (Kishino, 1974). Parameters, t_0 , t_1 and t_2 were 10°C, 36.7°C and 40°C, respectively (Kishino, 1974). The curvilinear model was used for EAT. Figure 5 shows the estimated present occurrence of *C. suppressalis*. The results indicate that the moth is unable to occur in the easternmost part of Hokkaido Island due to thermal deficiency and occurs once a year in the rest of Hokkaido Island and the northern part of the Tohoku district on the Main Island. Although it occurs twice a year in the rest areas of the Main Island, Shikoku and Kyushu Islands, it can occur three times in the southernmost parts of Shikoku and Kyushu Islands. The results conformed well to the actual observed occurrence of the insect (Ishikura, 1955; Itoga et al., 1960; Kishino, 1974). Under 2°C warming, *C. suppressalis* would occur throughout Hokkaido Island, the western part of which the moth would complete two generations (Fig. 6). The northern boundaries of the zones of two and three generations would shift northward by about 300 km.

Insect susceptible to cold weather

The confused flour beetle, *T. confusum*, a serious cosmopolitan stored-product pest, is cold susceptible. The occurrence of the beetle in Japan is determined by two factors: available local EAT and low temperature in winter. The

Fig. 3. Current occurrence of *P. xylostella* in Japan. G. represents generations.

Fig. 5. Current occurrence of *C. suppressalis* in Japan. G. represents generation(s).

Fig. 4. Predicted occurrence of *P. xylostella* under 2°C warming in Japan. G. represents generations.

Fig. 6. Predicted occurrence of *C. suppressalis* under 2°C warming in Japan. G. represents generation(s).

present occurrence of the beetle was first calculated with the triangular model (t_0 : 16.7°C, t_1 : 32.5°C, t_2 : 37.5°C and K : 391 degree-days, (Howe, 1960)). Then the locations where the beetle cannot overwinter were estimated by summing up the negative temperature ALT below t_c (7.5°C) at each location and comparing local ALT with K_c (-273 degree-days); t_c and K_c were calculated from Takashima et al. (1969). Finally, the present occurrence was estimated by superimposing the places where the insect is unable to overwinter on the results calculated based on EAT (Fig. 7). The beetle is unable to occur in the northernmost part of the Main Island

and throughout Hokkaido Island excluding the western part due to thermal deficiency. However, the superimposed results indicate that winter coldness rather than thermal deficiency makes the beetle unable to occur in most parts of the Tohoku and Hokuriku districts. Thus, the winter coldness determines the northern front of the distribution of *T. confusum* in Japan (Fig. 7). Confirming that the results were satisfactory (Shinha and Utida, 1967; Takashima et al., 1969; Ito et al., 1976; Imura, 1980, personal observation; Yamashita et al., 1990), the occurrence of *T. confusum* under the condition of 2°C warming was predicted

Fig. 7. Current occurrence of *T. confusum* in Japan. G. represents generation(s).

Fig. 9. Current occurrence of *E. kuhniella* in Japan. G. represents generation(s).

Fig. 8. Predicted occurrence of *T. confusum* under 2°C warming in Japan. G. represents generation(s).

Fig. 10. Predicted occurrence of *E. kuhniella* under 2°C warming in Japan. G. represents generation(s).

(Fig. 8). Under this condition, the beetle could go through one more generation in a year in each region, but the northern front of the possible distribution area would not shift very far northward, except for in the central mountainous area of the Main Island, because winter coldness could still constitute a critical factor in limiting the northern front of the distribution.

Insect susceptible to hot weather

The Mediterranean flour moth, *E. kuhniella* Zeller, is a temperate pest insect of stored-products. The moth is known to enter diapause, but the tendency is not strong (Cox et al., 1984),

and adults emerge all year round (Imura, 1980). The southern front of the distribution in Japan is restricted by high temperature in summer. As in the case of *T. confusum*, the present distribution was estimated by superimposing the area where the moth was unable to occur due to high temperature in summer (the critical high temperature, t_h was 28°C and the estimated accumulative deleterious temperature, K_h was 20 degree-days, Raichoudhury, 1936; Imura, 1986) on the results calculated by local EAT (t_0 : 8.2°C, t_1 : 28°C, t_2 : 29°C and K : 760 degree-days, Imura, 1986) using the triangular model (Fig. 9). *E. kuhniella* is unable to occur in some coastal

regions in the southwestern part of the Main Island, Shikoku Island and Kyushu Island due to the deleterious effect of high temperatures in summer. Confirming that the estimated present occurrence of the moth was satisfactory (Ito et al., 1976; Imura, 1980, personal observation; Hirao, 1996), we predicted the occurrence of *E. kühniella* under the condition of 2°C warming (Fig. 10). The global warming would have a significant effect on the distribution of the moth by largely shifting the southern front of the distribution area northward, thereby restricting occurrence of the moth to limited northern areas of Japan.

DISCUSSION

Mochida (1991) reported a possible effect of global warming on the distribution of 12 pest insects in Japan, but his predictions were simply based on empirically known isothermal lines of annual or monthly mean temperatures. We predicted the potential effects of global warming on the occurrence of pest insects by developing a computer program incorporating several models to describe insect development, diapause and susceptibilities to adverse temperature conditions. Aside from insect development, we used thermal summation models to describe deleterious effects of low and high temperatures, assuming that the effects were accumulative. The distribution and the number of generations in each region estimated by the model accurately represented the current actual occurrence of those different types of insects in Japan.

Although *C. suppressalis* is known to occur three times a year on Kyushu Island (Itoga et al., 1960), there is currently no widely recorded trivoltine life cycle there (Fukamachi, personal communication). The late transplanting of paddy seedlings in this region may be responsible for the reduced voltinism (Ishikura, 1955). Kishino (1974) stated that a population in Kagoshima, Kyushu Island (see Fig. 2) had a longer post diapause developmental period, leading to delayed adult emergence of the overwintering generation. The trivoltine population in the southernmost part of Shikoku Island and the bivoltine population in Kyushu Island are recognized as different ecotypes, the Shonai-type and the Saigoku-type, respectively (Kiritani

and Iwao, 1967). Because adult emergence of *C. suppressalis* tends to shift in response to delayed or early season cultivation of paddy fields within several years (Ishikura, 1955; Miyashita, personal publication), the moth would readily adapt to conditions under global warming.

The distribution of *T. confusum* was predicted to be restricted by cold winter and that of *E. kühniella* by hot summer under global warming. Winter temperature is predicted to increase more and summer temperature less than the average temperature rise (IPCC, 1990). If so, then there is a possibility that global warming would shift the distribution front of *T. confusum* further northward and shift the southern front of the distribution of *E. kühniella* less than in our predictions. Further, these stored-product insects are living in artificial environments such as warehouses or mills, the temperatures of which often deviate from that measured at the weather observation stations at the same location (Imura, 1980). For example, *T. confusum* is usually found in mills and feed factories where the temperatures are generally higher than the outdoors (Kiritani et al., 1963). Thus, our present predictions on these insects must be viewed with some caution.

As discussed in *C. suppressalis*, local voltinism of an insect is also influenced by host plant availability. Global warming will extend the growing area of many crops as well as lengthen their growing season (Iwakiri, 1988; Porter, 1995). For more realistic predictions, we may incorporate the effect of seasonal and regional availability of the host plants under global warming in our models. It is unlikely that global warming would affect food availability in the stored-product insects such as *T. confusum* and *E. kühniella*.

Global warming will proceed along with elevated CO₂ concentrations in the air, changes in precipitation, soil moisture and fertility, etc. Those changes should also affect insect development. For example, insect development tended to be delayed and relative growth rate tended to decrease on plants grown under elevated CO₂, however the insect performance varied depending on the combinations of insect herbivore-host plant species (Lincoln et al., 1984; Fajer et al., 1989; Lindroth et al., 1993). The combined

effects of global warming and these associated factors have not yet been carefully examined.

Our study demonstrated that the predicted global warming would have significant effects on the occurrence of pest insects. However, the effects would vary depending on the types of insects. Global warming could operate in favor of some insects and deleteriously in other insects regarding their occurrence. Thus the effects of global warming on pest insects should be evaluated by careful examination of insect biology. Although the present predictions were made with restrictions, the results suggest the potential risks of these pest insects to the crops under global warming.

ACKNOWLEDGEMENTS

We thank Dr. K. Kritani for critical reading of the manuscript. We are indebted to Drs. M. Hirao, K. Kishino and S. Fukamachi for their invaluable information on the insect occurrence. This study was supported by a fund, Managing the Agro-, Forestry, and Marine-Ecosystems to Control Global Change, from the Ministry of Agriculture, Forestry and Fisheries, Japan.

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