Possible Impacts of Climate Change on Rice Insect Pests and Management Tactics in Taiwan

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ABSTRACT

Climate change may have an effect on all organisms, including plants, insects and their interactions among weather, plants and herbivores. Moreover, the insect physiology, behavior, development and species distribution may also be affected in a changing climate. On the other hand, the population abundance of an insect species is manipulated by the host plant, natural enemies or extreme weather conditions. The current warming trend may drive the climate pattern of Taiwan from subtropics to tropics in the future, and provide more suitable conditions for propagations of most rice insect pests excluding those of obligatory univoltine. At present, the impacts of climate change on insect pests are not clear and unpredictable. The successive monitoring changes in pests' population in the paddy fields is a priority job for pest control. Once the key insect pests have been identified, the follow-up control measure can be set-up and apply at right place in the right time. Concluding from the experience and research findings in either tropical or temperate region, the integrated pest control system incorporating cultural and biological control is still the best tactics for lower down pest populations under acceptable levels. Pesticides are used only when they are needed.

Key words: Climate change, Rice, Insect pests, Taiwan.

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氣候變遷對臺灣水稻害蟲及其管理方法之可能影響

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摘要

氣候變遷可能影響包含植物、昆蟲等之各種生物，以及氣候因子與植物及其與植食性昆蟲之間的相互作用，全球溫暖化亦將直接影響昆蟲之生理、行為、發育及分布。每一昆蟲族群之豐度，則受到其寄主植物、天敵及極端天氣等因素之直接或間接影響。溫度為環境因子中之重要因素之一，在暖化的氣候變遷趨勢下，臺灣的氣候環境可能由亞熱帶逐漸走向熱帶氣候，如此使得提供一年一世代寡食性昆蟲以外的大部分水稻害蟲更適合發育及繁殖。雖然目前全球氣候變遷對害蟲的影響仍模糊不清，而且無法準確預測，惟持續性監測水稻害蟲發生種類及族群變動依舊是一項優先且重要之工作。當水稻重要害蟲種類確定之後，適當的防治措施即可隨著修正、改進。吾人從水稻害蟲的防治經驗及熱（溫）帶地區的蟲害防治研究，發現以結合耕作及生物防治的綜合防治體系仍為抑制害蟲族群於可接受水準之最佳策略，化學除蟲藥劑僅在需要時適時施用即可。

關鍵詞：氣候變遷、水稻、害蟲、臺灣。

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC 2001) pointed out that most of the global warming observed over the last 50 years was attributable to human activities. During the past 100 years global-average surface temperatures have increased by approximately 0.6℃ (the largest increase of any century during the past 1,000 years) (Houghton *et al*. 2001). Meanwhile, the temperature raised 1.1-1.6℃ in Taiwan (Lee 2008), higher than that of global average. The phenomenon of temperature increase, especially in the seasons of winter and spring, has also been observed in south Asia and world wide. The trend of averaged precipitation was not different within past 40 years, but the dry and wet seasons become more and more distinct (Lee 2008). Analysis of precipitation data over the past 100 years showed that the total precipitation did not change, but the frequency of light rain decreased and while the frequency of heavy rainfall increased (Liu *et al*. 2008). Heavy rain often destroyed life and properties on the ground surface.

The Third version of IPCC report predicted that the global-averaged surface-temperature will increase further by 1.4-5.8℃ by 2100, based on the increase of atmospheric carbon dioxide (CO_2) concentrations. It is expected that CO_2 will increase from 540 to 970 ppm over the same period. The precipitation, ultra-violet B (UVB) penetration and extreme weather events (e.g., flooding, storminess, and drought) are also predicted increasing, but there is less certainty about the magnitude of these changes (IPCC 2001).

Insects are likely to be affected by climate change because they are ectothermic and sensitive to precipitation (Bale *et al*. 2002). These effects can be direct, through the influence of climatic factors on the insects' physiology and behavior (Bale *et al*. 2002, Cannon 1998, Harrington *et al*. 2001, Merrill *et al*. 2008, Parmesan 2007), or indirectly mediated by host plants, competitors or natural enemies (Bale *et al*. 2002, Harrington *et al*. 2001, Kiritani 1999, 2006, Laštůvka 2009, Lincoln *et al*. 1984, Thomson *et al*. 2010).

POSSIBLE IMPACTS ON INSECTS UNDER CLIMATE CHANGE

Climate change may influence the physiology, abundance, phenology and distribution of the insect pests (Bale *et al*. 2002, Dukes *et al*. 2009, Laštůvka 2009), and the major factors include temperature, CO_2 concentration, precipitation, natural enemies and their host plant (Chu and Chao 2000). The possible impacts on insects are illustrated as followings.

1. Insect Physiology

(1)Temperature

Insects are ectothermic organisms, the temperature of their body changes approximately with the temperature of their habitats. Therefore, temperature is probably the most important environmental factor influencing their behavior, distribution, development, survival and reproduction (Chu and Chao 2000). Depending on the development "strategy" of an insect species, temperature can exert different effects on it (Bale *et al.* 2002). For the insect pests that produce one generation annually or their development lasts several years, or the number of generations is limited by the photoperiod, most facts remain unchanged by climate change. For those species could breed two or more generations a year, they may gradually adapt to the new climatic conditions by shifting the temperature thresholds, effective temperature totals and critical photoperiod lengths without showing any appreciable changes in their development (Bale *et al*. 2002, Pullin 1986).

The winter mortality is usually a key factor affecting the population dynamics of many temperate insects, especially to those do not enter diapause but continue activity throughout the winter as temperature permits. Higher temperatures in winter or spring are likely to stimulate the reproduction of overwintering adults and leading to faster population growth and an additional generation in some insect pests (Harrington *et al*. 2001, Kiritani 2006).

Although most literature tends to emphasize climate-induced increases in abundance of insect population, it is logical that climate change will also reduce insect abundance in some aspects. For instance, many insects overwinter in forest litter may face higher mortality rates due to the decreased snow depth (Ayres and Lombardero 2000). However, it is possible that warmer habitat is generally better for insects, even in climate that is already warm (Frazier *et al*. 2006).

(2)CO_2

Generally, the impacts of CO_2 on insects are thought to be indirect from changes in their host plant. The majority of plants - particularly those in the C_3 category, which includes most grains (e.g., rice and wheat), legume and root crops - respond to increased CO_2 levels by increasing productivity (a quantitative response) in the form of carbon fixation (Bazzaz 1990, Chu and Chao 2000).

Increased productivity as a result of the direct fertilization effect of CO_2 leads to lower nitrogen concentrations (a qualitative response) as C:N ratios rise, and reduces the nutritive value to herbivores (Nicolas and Sillans 1989). A CO_2-induced reduction in host plant quality resulted in increased larval consumption rates in order to obtain adequate dietary nitrogen in generalist (Coviella and Trumble 1999, Hunter 2001, Lincoln *et al.* 1984). In the majority of cases, increased feeding rates do not compensate fully for the reduced quality of the diet, resulting in poor performance, slowing insect development and increasing length of life stages which place them vulnerable to the attack by parasitoids (Coviella and Trumble 1999, Fajer *et al.* 1989). However, the physiological effects of such CO_2-induced changes in consumption rates vary according to the particular plant-insect interactions (Lindroth *et al.* 1993).

As a result of the C:N ratio change in the plant, phloem sap becomes more concentrated at higher temperatures, and thus acts as a richer source of amino acids for sap feeders. The concentration of a range of secondary plant compounds tends to increase under drought stress, leading to changes in the attraction of plants to insects (Harrington *et al.* 2001). The atmospheric environment in the future is predicted to include correlated increases in CO_2 concentration and temperature. The result of such interactions of CO_2 and temperature, for the diversity and abundance of insect pests, is difficult to predict (Cannon 1998).

2. Abundance

(1)Natural enemy

Natural enemy and host insect populations may respond differently to the global warming. There will also be instances where warmer conditions will increase the effectiveness of many natural enemy species (Cammell and Knight 1992, Kiritani 1999, 2006) and/or increase the vulnerability of their prey (Awmack *et al.* 1997, Thomson *et al.* 2010). In extreme conditions, higher abundance of insect pests may partly be due to lower activity of parasitoids (Hance *et al.* 2007) or to disturbed parasitoid-pest relationship and decreased controlling ability. Other studies suggested that higher temperatures will favor parasitoids rather than their hosts (Davis *et al.* 1998, Kiritani 2006). For those insects and their parasitoids with lower developmental threshold (T_0), it seems that they could match very well and the relationship might not be affected dramatically under global warming (Chu and Chao 2000). However, the effect of higher temperature on the overall abundance of herbivorous insects remains unknown in the absence of equivalent data on the responses of their natural enemies (Davis *et al.* 1998, Thomson *et al.* 2010).

(2)Precipitation

Many pest species favor the warm and humid environment. Both direct and indirect effects of moisture stress on crops make them more vulnerable to be damaged by pests, especially in the early stages of plant growth. There are fewer scientific studies on the effect of precipitation on insects. Some insects are sensitive to precipitation and are killed or removed from crops by heavy rains. A decrease in winter rainfall could result in reduced aphid developmental rates (Pons *et al.* 1993), because drought-stressed tillering cereals reduce the reproductive capacity of overwintering aphids (Pons and Tatchell 1995).

3. Phenology

Parallel evolution gradually resulted in a close relationship between insect pest and its host plant, accompanied by the development of various adaptations of both. This relationship may be disturbed or changed by climate factors. It may result in the phenological asynchrony between insect and plant (van Asch and Visser 2007).

The timing of life history stages (phenology) of many insect species has already been demonstrably advanced by warming temperatures (Harrington *et al*. 2001, Logan *et al*. 2003), and there are growing examples of insect distributions extending northward (Parmesan 2006). In general, assuming a constant temperature rise over the year, species with low T_0 and small K (thermal constant) are predicted to have an increasing number of annual generations and an earlier appearance of overwintering individuals (Kiritani 2006, 2007, Yamaguchi *et al*. 2001, Yamamura and Kiritani 1998).

However, phenological synchrony between host plant and insect could become uncoupled during climate warming if the two processes are temperature-driven in different ways. For instance, the winter moth (*Operophtera brumata* (Linnaeus)), where synchrony between the date of budburst and the larval emergence greatly affects larval survival, could be disadvantaged by global warming (Dewar and Watt 1992), especially for the univoltine and host specific insect species (Chu and Chao 2000). The increases in the frequency of extreme events could also disrupt both natural and implemented biocontrol processes, by disrupting the synchrony between the growth, development and reproduction of biological control agents and their hosts (Patterson 1993).

Tight phenological synchrony is often required for certain herbivore species to perform well on a host plant. However, for some species, e.g., *O. brumata* (Linnaeus) on oak (Buse and Good 1996) and Sitka spruce (Watt and McFarlane 1991), tight phenological synchrony does not appear to be essential. Thus, in these cases, the impact of climate change remains unclear. Watt *et al*. (1990) also pointed out that gradual warming as a result of climate change would not affect the degree of phenological coincidence between insect pests and their host plants, because selection pressures would be sufficiently intense to bring the insect populations and their hosts back into synchrony.

4. Distribution

One of the major effects of the global climate changes will be an acceleration of species range shifts. Many insect species have geographic ranges that are not directly limited by vegetation, but restricted by temperature. There is abundant evidence that climate change can influence the distribution of phytophagous insects and particularly Lepidoptera (Batalden *et al*. 2007, Cannon 1998, Kiritani 2006, Laštůvka 2009, Parmesan *et al*. 1999). Warmer conditions may be expected to promote the poleward extension of the range of those species, which are currently limited by low temperature.

Kiritani (1988) suggested that tropical and subtropical species may be able to advance poleward continuously for as long as their cold hardiness allows, because they usually lack diapause in their life cycles. On the other hand, temperate species, which pass the winter in a definite diapause stage, will not advance poleward until the temperature rises sufficiently to complete another generation and expanding their distribution stepwise. Some insects would be capable to track such changes but their host plants may not (Chu and Chao 2000). Hence, the spread of some insect species may be limited by the distribution of host plants.

For the migrant species, which are expected to respond more rapidly to climate change than plants, will also be able to increase the opportunities for survival (Cannon 1998). Climate warming would advance the time of year, and increase the possibility of early immigration (Laštůvka 2009, Woiwod 1997, Zhou *et al*. 1995).

Relatively, insect-borne diseases may become an important problem under global warming (Kiritani 1991, 1999, 2006). For example, one virus strain is particularly common in maize and is transmitted efficiently by the corn leaf aphid *Rhopalosiphum maidis* (Fitch). Maize is a minor crop in the UK, but with climate warming, may become more viable and hence more widespread (Parry 1989). Meanwhile, the corn leaf aphid is also rare in most parts of the UK in most years, but any expansion of maize growing will encourage spread of the aphid. Therefore, warmer conditions, through their effect on interactions between host plants, aphids and viruses, may render the maize strain of barley yellow dwarf virus (BYDV) important in wheat and barley for the first time in the UK (Lucio-Zavaleta *et al*. 2001).

Predicting how climate change will affect regional nuisance species, including the direct effects of climate change, phenotypic and genotypic flexibility of herbivores and parasitoids and interactions between species, is a complex task for a variety of reasons (Araujo and Luoto 2007, Bradshaw and Holzapfel 2006, Parmesan 2006). That is why long-term forecasts of the responses of particular insect pests to climate change are rather uncertain (Bale *et al*. 2002, Cannon 1998, Dukes *et al*. 2009, Thomson *et al*. 2010).

POSSIBLE IMPACTS OF CLIMATE CHANGE ON RICE INSECT PESTS IN TAIWAN

Taiwan is located in the subtropical nearby the tropical region. In Chia-nan area of central Taiwan, the average temperature during rice transplanting period of the first cropping season (from January to February) is about 14-18℃ (lowest average temperature is 12-14℃), and for the second cropping season is about 26-28℃ (highest averaged temperature is around 32℃) from July to August (Cheng 1998).

The major rice insect pests in Taiwan include the native species, immigrant species and invasive species. The yellow stem borer (*Scripophaga incertulas* Walker), striped rice borer [*Chilo suppressalis* (Walker)], pink borer [*Sesamia inferens* (Walker)], smaller brown planthopper [*Laodelphax striatella* (Fallen)], green rice leafhopper [*Nephotettix cincticeps* (Uhler)], rice hispa [*Dicladispa armigera* (Olivier)] and rice leaf beetle [*Oulema oryzae* (Kuwayama)] are the native species. The immigrant species, such as brown planthopper (*Nilaparvata lugens* Stål), whitebacked planthopper (*Sogatella furcifera* Horváth) and rice leaffolder [*Cnaphalocrocis medinalis* (Guenée)], can overwinter with a low population in Taiwan, but the population abundance mainly depend on the number of immigrants. The invasive species, such as rice water weevil (*Lissorhoptrus oryzophilus* Kuschel), invade into Taiwan mostly through international trade. Among them, rice leaf beetle and rice water weevil are the obligatory univoltine species and will diapause on adverse environmental conditions in Taiwan (Cheng 2002, Cheng and Huang 2009).

Due to the global warming, winter temperature will become more suitable for pest overwintering if the host plants are available, and the brown planthopper, whitebacked planthopper and rice leaffolder and so on, may not only decrease the mortality in winter generation but also accelerate the rate of development and thus increase the opportunity to build up and damage on crop in the following generations (Kiritani 1999, 2007). The high temperature is usually not favorable to the development of some insects in summer, while other insects are able to adapt or decrease the injury by physiological or habitat accommodation (Hoffman and Blows 1993).

Many researchers have proved that insect is varied in its genetic variability and some may tolerate to high temperature (Huey *et al*. 1991, Quintana and Prevosti 1990). For example, brown planthopper in different areas show different abilities in heat tolerance; the LT_{50} of the first and third instar nymphs from Khon Kaen, Thailand is 57.2 and 144.6 hours, respectively, but it is only 23.4 and 22.8 hours, respectively, for the IRRI's strain in the Philippines (Heong and Domingo 1992). Similar results were observed in a mirid bug (*Cyrtorhinus lividipennis* Reuter), a predator of brown planthopper. The heat tolerance of mirid in Thailand is about 30 times higher than that of the Philippine's strain (Heong and Domingo 1992, Peters 1991). These results showed that insects may adapt in high temperature environment by selection and evolution.

For some insect pests, such as smaller brown planthopper, rice leaf beetle, rice water weevil, Taiwan is considered their south most distribution area. Higher temperature in summer may cause them disappear or become the minor insect pests. Contrarily, for those insect pests that Taiwan is considered as their north most distribution limit, such as green rice leafhopper [*Nephotettix virescens* (Distant)], temperature increase may help the insect to become more abundant (Cheng 1998).

It is well known that taxonomically related species usually have the same range of values in T_0 (lower developmental threshold temperature) and K (thermal constant). Mean values of T_0 and K for either E/A (egg to adult) or E/OP (egg to the start of oviposition) represented by taxonomic or functional groups are calculated, and the potential increase in number of generations of each group is also estimated when global warming of 2℃ has taken place. Obligatory univoltine species, e.g., *Ou. oryzae* (Kuwayama) and *Diplonychus major* Esaki, were assumed to remain univoltine (Kiritani 1997, 1999, 2006). All the current rice pests except planthoppers are expected to increase at least one more generation. However, parasitoids [such as *Anagrus incarnatus* Haliday and *Apanteles chilonis* (Munakata)] and predators (such as *C. lividipennis* Reuter), other than spiders (such as *Pardosa astrigera* (L. Koch) and *Tetragnatha vermiformis* Emerton), would breed two to three more generations a year. These facts imply that the extent of biological control of rice pests by natural enemies will increase in intensity under the global warming (Kiritani 1999).

The insect pests of obligatory univoltine species with high K value for E/A (egg to adult emergence), such as *Ou. oryzae* (Kuwayama) and *L. oryzophilus* Kuschel, are assumed not to change much.

Theoretically, rice insect pests may increase more generations and their ability to cause damage due to global warming, but in fact, this is not true. The insect damage on susceptible rice variety without chemical application in Japan, Philippines and Indonesia resulted in a yield loss of 50.4, 42-54 and 48.3-58%, respectively (Mochida *et al*. 1983). In Taiwan, the yield loss caused by insect pests in the first and second rice crops was about 15% (878.2 kg ha^{-1}) and 30% (1427.8 kg ha^{-1}) respectively. Similar yield loss of 20-25%, about 1,000 kg ha^{-1} was reported in Philippines (Pathak and Dkaliwal 1986). These results reveal that the yield loss caused by insect pests does not differ distinctly among the temperate, subtropical and tropical regions, though temperature, rice variety, major insect species and cultural practices are different to a certain extent. However, when we make a thorough analysis, the cultural practices and rice variety are also the important factors affecting yield loss in addition to temperature. In agriculture developing region, more fertilizers and insecticide are usually used for a high yield, which often result in the resurgence or replacement of insect pests to cause a more severe damage than that of agriculture developed region (Garcia and Lwin 1997, Heinrichs 1994, Schiller *et al*. 1997, Sogawa *et al*. 2003).

Based on these studies, it is clear that the occurrence and damage of the rice insect pests can be affected by human's operations as well as climatic factors. As long as the cultural practices do not modify drastically, the occurrence and damage of the rice insect pests in Taiwan will not change greatly in the near future under global warming trend (Cheng 1998).

Results from a long-term monitoring of the rice insect pests in Taiwan suggest that population of many insect pests, including the native and immigrated species, increase greatly during the past 10 years (Huang *et al*. 2009a). Although many factors may play a role in the population increase, global warming is definitely an important factor. For estimating a possible change of rice insect pests in the coming years, long-term monitoring the population dynamics of these insect pests is very important for a sound pest management (Cheng 1998, Huang *et al*. 2009b).

Global warming could also induce some important tropical insect pests invading Taiwan. For instance, the Asian rice gall midge (*Orseolia oryzae* (Wood-Mason)) distributed in South and Southeast Asia (included southern China) may invade and settle down in Taiwan. Besides, surveillance on other important insect pests of rice in tropical area, such as white rice borer [*Scirpophaga innotata* (Walker)], dark-headed striped stem borer [*Chilo polychrysus* (Meyrick)], rice leafhoppers [*N. virescens* (Distant), *N. malayanus* Ishiha & Kawase] and Malayan rice black bug [*Scotinophara coarctata* (Fabricius)], are also needed when temperature is getting higher (Dale 1994).

The migratory rice insect pests occur mainly in East Asia. It is believed that the occurrence of emigration of migrants in the source area will become earlier and abundant due to global warming. Attention should also be paid to the changes of the immigrant properties, including pest species, chemical resistance and biotype, and associated diseases they transmitted. Any change in the properties may result a serious problem of pest management in immigrated area, including Taiwan (Cheng 2009, Huang *et al*. 2009b).

IMPLICATIONS ON RICE INSECT PEST MANAGEMENT UNDER CLIMATE CHANGE IN TAIWAN

Accompanied with the faster development of rice insect pests, it is conjectured that rice insect pests may have higher population densities and overlapping generation in paddy fields. We believe that successive monitoring of the species and population changes in paddy fields is the priority need to be done than others. If the insects are key pests, then their population fluctuation, potential ability of damage and their relative biological and ecological characters have to be studied carefully, and then a control plan can be drew up, modified and set up finally.

There are many measures can be used for curbing rice insect at present. The biological and physical controls are the well-known measures to most rice farmers, so as cultural practices and chemical spraying. However, each control method has its own virtues and defects, it is impossible to suppress the pests to an acceptable level by applying any control method alone. Therefore, a combination of more than one method to curb the population of insect pests below an economic threshold level has been suggested, the so-called "integrated control" or "integrated pest management". The concept of integrated pest management is also adoptable in the case of climate change (Cheng 1998).

At present, the impacts of climate change on population dynamics and distribution of rice insect pests remain unpredictable. It is not easy to propose an appropriate tactic for controlling the insect pests in the future. However, based on experience and strategy of insect pest control used in tropical area, the integrated pest management approach seems feasible and applicable.

CONCLUSIONS

Climate change is getting more attention by most people recently. However, little is known about the actual impact on insect biological and ecological aspects. It is well known that weather, particular the temperature, is the most important factor to limit the distribution, rate of development, number of generation and population abundance of an insect species in a region. The interaction among the environmental factors (biological and physical), host plants and insects are very complicated. In addition, most of insect pests can adapt to a wide range of environment through selection and evolution. Therefore, it is improper to conjecture the possible impact of unpredictable climate change on the insects just basing on the results getting from factor-limited studies. On the other hand, higher temperature would affect the change of agroecosystem in a region, and the cultural system and insect would also be changed following the global warming. As a result, keep watching and monitoring closely on the species and population changes of insect pests is the first priority than the others. Beside the native, immigratory insect pests, the invasion of insect pests of rice from the tropical region should be watched carefully. Only when the situation of insect pests in environment of global warming is really understood, then an appropriate control tactic can be set up accordingly.

REFERENCES

Araujo MB, M Luoto (2007) The importance of biotic interactions for modeling species distributions under climate change. **Global Ecol. Biogeogr.** 16:743-753.

Awmack CS, CM Woodcock, R Harrington (1997) Climate change may increase vulnerability of aphids to natural enemies. **Ecol. Entomol.** 22: 366-368.

Ayres M.P, MJ Lombardero (2000) Assessing the consequences of global change for forest disturbance from herbivores and pathogens. **Sci. Total Environ.** 262: 263-286.

Bale JS, GJ Masters, ID Hodkinson, C Awmack, TM Bezemer, VK Brown, J Butterfield, A Buse, JC Coulson, J Farrar, JEG Good, R Harrington, S Hartley, TH Jones. RL Lindroth, MC Press, I Symrnioudis, AD Watt, JB Whittaker (2002) Herbivory in global climate change research: direct effects of rising temperatures on insect herbivores. **Global Change Biol.** 8:1-16.

Batalden RV, K Oberhauser, AA Peterson (2007) Ecological niches in sequential generations of eastern North American monarch butterflies (Lepidoptera: Danaidae): the ecology of migration and likely climate change implications. **Environ. Entomol.** 36:1365-1373.

Bazzaz FA (1990) The response of natural ecosystems to the rising global CO_2 levels. **Annu. Rev. Ecol. Evol. Syst.** 21:167-196.

Bradshaw W, C Holzapfel (2006) Climate change - evolutionary response to rapid climate change. **Science** 312:1477-1478.

Buse A, JEG Good (1996) Synchronization of larval emergence in winter moth (*Operophtera brumata* L.) and budburst in pedunculate oak (*Quercus robur* L.) under simulated climate change. **Ecol. Entomol.** 21:335-343.

Cammell ME, JD Knight (1992) Effects of climatic change on the population dynamics of crop pests. **Adv. Ecol. Res.** 22:117-162.

Cannon RJC (1998) The implications of predicted climate change for insect pests in the UK, with emphasis on non-indigenous species. **Global Change Biol.** 4:785-796

Cheng CH (1998) Impact of global climate change on crop insect pests in relation to pest control strategies in Taiwan (in Chinese with English summary). p.74-85. *In*: Proceedings of Symposium of Crop Production in Response to Global Climate Change. CY Lin, CM Yang (eds.) Taiwan Agricultural Research Institute Press. Taichung Hsien, Taiwan.

Cheng CH (2002) Rice insect pests (in Chinese). p.31-172. *In*: A Series Illustrated Handbook of Plant Protection No. 8. Rice Protection. CH Cheng (ed.) BAPHIQ. Taipei, Taiwan.

Cheng CH, SH Huang (2009) Reconsideration of the rice insect pests control in Taiwan (in Chinese with English summary). p.65-82. *In*: Proceeding of Symposium on Achievement and Perspectives of Rice Protection in Taiwan. Chiayi, Taiwan.

Cheng JA (2009) Rice planthoppers and relevant problems in China. p.215-234. *In*: Proc. APEC-RDA Workshop on the Epidemics of Migratory Insect Pests and Associated Virus Diseases in Rice and Their Impact on Food Security in APEC Member Economies. Education and Culture Center, Seoul. 7-10 Oct. 2009. Rural Development Administration, Korea.

Chu YI, JT Chao (2000) The impact of global change on insects (in Chinese). p.341-366. *In*: Applied Entomology. TC Wang, WJ Wu (eds.) National Taiwan University. Taipei, Taiwan ROC.

Coviella C, J Trumble (1999) Effects of elevated atmospheric carbon dioxide on insect plant interactions. **Conserv. Biol.** 13:700-712.

Dale D (1994) Insect pests of the rice plant - their biology and ecology. p.363-485. *In*: Biology and Management of Rice Insects. EA Heinrichs (ed.) Wiley Eastern, New Delhi, India.

Davis AJ, LS Jenkinson, JH Lawton, B Shorrocks, S Wood (1998) Making mistakes when predicting shifts in species range in response to global warming. **Nature** 391:783-786.

Dewar RC, AD Watt (1992) Predicted changes in the synchrony of larval emergence and budburst under climatic warming. **Oecologia** 89:557-559.

Dukes JS, J Pontius, D Orwig, JR Garnas, VL Rodgers, N Brazee, B Cooke, KA Theoharides, EE Stange, R Harrington, J Ehrenfeld, J Gurevitch, M Lerdau, K Stinson, R Wick, M Ayres (2009) Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? **Can. J. For. Res.** 39:231-248.

Fajer ED, MD Bowers, FA Bazzaz (1989) The effects of enriched carbon dioxide atmospheres on plant-insect herbivore interactions. **Science** 243:1198-1200.

Frazier M, R Huey, D Berrigan (2006) Thermodynamics constrains the evolution of insect population growth rates: ''warmer is better''. **Amer. Nat.** 168:512-520.

Garcia AG., PP Lwin (1997) Rice agriculture and general situation of rice insect pests in Myanmar. p.184-205. *In*: Proc. Migration and Management of Insect Pests of Rice in Monsoon Asia. China Natl. Rice Res. Inst., Hangzhou. PRC.

Hance T, van Baaren J, P Vernon, G Boivin (2007) Impact of extreme temperatures on parasitoids in a climate change perspective. **Annu. Rev. Entomol.** 52:107-126.

Harrington R, R Fleming, I Woiwod (2001)

Climate change impacts on insect management and conservation in temperate regions: can they be predicted? **Agric. For. Entomol.** 3: 233-240.

Heinrichs EA (1994) Impact of insecticides on the resistance and resurgence of rice planthoppers. p.571-598. *In*: Planthoppers: Their Ecology and Management. RF Denno, TJ Perfect (eds.) Chapman and Hall, New York, USA.

Heong KI, I Domingo (1992) Shifts in predator-prey ranges in response to global warming. **Intl. Rice Res. Inst. Newsl.** 17:29-30.

Hoffman AA, MW Blows (1993) Evolutionary genetics and climate change: Will animals adapt to global warming? p.165-178. *In*: Biotic Interactions and Global Change. PM Kareiva, JG Kingsolver, RB Huey (eds.) Sinauer, Sunderland, MA, USA.

Houghton JT, Y Ding, DJ Griggs, M Noguer, PJ van der Linden, D Xiaosu, K Maskell, CA Johnson (2001) Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge. 881pp.

Huang SH, CH Cheng, CN Chen, WJ Wu. (2009a) The trend of occurrence and prospective control measures of rice insect pests in Taiwan. (in Chinese with English summary). p.131-147. *In*: Proceedings of Symposium on Achievement and Perspectives of Rice Protection in Taiwan. Chiayi Agricultural Experiment Station, Taiwan Agricultural Research Institute. Chiayi, Taiwan.

Huang SH, CH Cheng, CN Chen, WJ Wu. (2009b) The migratory rice insect pests and management in Taiwan. p.276-294. *In*: Proceedings of APEC-RDA Workshop on the Epidemics of Migratory Insect Pests and Associated Virus Diseases in Rice and Their Impact on Food Security in APEC Member Economies. Education and Culture Center, Seoul, 7-10 Oct. 2009. Rural Development Administration, Korea.

Huey RB, L Partidge, K Fowler (1991) Thermal sensitivity of *Dorsophila melanogaster* responses rapidly to laboratory natural selection. **Evolution** 45:751-756.

Hunter MD (2001) Effects of elevated atmospheric carbon dioxide on insect-plant interactions. **Agric. For. Entomol.** 3:153-159.

IPCC Intergovernmental Panel on Climate Change (2001) Summary for policymakers. Visit on 07/20/2010. http://www.ipcc.ch/

Kiritani K (1988) Effects of climate change on the insect fauna. (in Japanese) **Meteorol. Res. Rept.** 162:137-141.

Kiritani K (1991) Potential impacts of global warming on insects. (in Japanese) **Insectarium** 28:212-225.

Kiritani K (1997) The low development threshold temperature and the thermal constant in insects, mites and nematodes in Japan. **Misc. Publ. Natl. Inst. Agro-Environ. Sci.** 21:1-72.

Kiritani K (1999) Shift of IPM strategy for rice under global warming in temperate areas. p.235-244. *In*: Integrated Pest Management in Rice-Based Ecosystem. R Zhang, D Gu, W Zhang, C Zhou, Y Pang (eds.) Zhongshan University Press, Guangzhou, PRC.

Kiritani K (2006) Predicting impacts of global warming on population dynamics and distribution of arthropods in Japan. **Popul. Ecol.** 48:5-12.

Kiritani K (2007) The impact of global warming and land-use change on the pest status of rice and fruit bugs (Heteroptera) in Japan. **Global Change Biol.** 13:1586-1595.

Laštůvka Z (2009) Climate change and its possible influence on the occurrence and importance of insect pests. **Plant Protect. Sci.** 45:S53-S62.

Lee CS (2008) The characteristics and tendencies of the climate in the past hundred years in Taiwan. (in Chinese) **Commu. Global Climate Change** 59:23-26.

Lincoln DE, N Sionit, BR Strain (1984) Growth and feeding response of *Psudoplusia includens* (Lepidoptera: Noctuidae) to host plants grown in controlled carbon dioxide atmosphere. **Environ. Entomol.** 13:1527-1530.

Lindroth RL, KK Kinney, CL Platz (1993) Responses of deciduous trees to elevated atmospheric CO_2: productivity, phyto-chemistry, and insect performance. **Ecology** 74:763-777.

Liu CM, MC Wu, SH Li, YC Chen, YT Yang, WS Lin, YH Tzeng, CD Chen (2008) The estimation of future climate change in Taiwan. (in Chinese with English abstract) Global Change Center, National Taiwan University. Taipei, Taiwan.

Logan JA, J Regniere, JA Powell (2003) Assessing the impacts of global warming on forest pest dynamics. **Front. Ecol. Environ.** 1:130-137.

Lucio-Zavaleta E, DM Smith, SM Gray (2001) Variation in transmission efficiency among barley yellow dwarf virus - RMV isolates and clones of the normally inefficient aphid vector, *Rhopalosiphum padi*. **Phytopathology** 91:792-796.

Merrill R, D Gutieŕrez, O Lewis, J Gutieŕrez, S Diez, R Wilson (2008) Combined effects of climate and biotic interactions on the elevational range of a phytophagous insect. **J. Anim. Ecol.** 77:145-155.

Mochida O, EA Heinrichs, GB Aquino (1983) Pest management systems on rice in the Pacific basin. Dunedin, New Zealand. 11pp.

Nicolas G, D Sillans (1989) Immediate and latent effects of carbon dioxide on insects. **Annu. Rev. Entomol.** 34:97-116.

Parmesan C (2006) Ecological and evolutionary responses to recent climatic change. **Annu. Rev. Ecol. Syst.** 37:637-669.

Parmesan C (2007) Influences of species, latitudes and methodologies on estimates of phenological response to global warming. **Global Change Biol.** 13:1860-1872.

Parmesan C, N Ryrholm, C Stefanescu, JK Hill, CD Thomas, H Descimon, B Huntley, L Kaila, J Kullberg, T Tammaru, WJ Tennent, JA Thomas, M Warren (1999) Poleward shifts in geographical ranges of butterfly species associated with regional warming. **Nature** 399: 579-583.

Parry ML (1989) The potential impact on agriculture of the greenhouse effect. p.27-46. *In*: The Greenhouse Effect and UK Agriculture. RM Bennett (ed.) Centre for Agricultural Strategy, Reading, UK.

Pathak MD, GS Dhaliwal (1986) Insect control. p.357-386. *In*: Global Aspects of Food Production. MS Swaminathan, SK Sinha (eds.) IRRI, Philippines.

Patterson DT (1993) Implications of global climate change for impact of weeds, insects, and plant diseases. p.273-280. *In*: International Crop Sciences. I. DR Buxton *et al*. (eds.) Crop Science Society of America, Madison, WI, USA.

Peters RL (1991) Consequences of global warming for biological diversity. p.99-118. *In*: Global Climate Change and Life on Earth. RL Wyman (eds.) Chapman and Hall, London, UK.

Pons X, J Comas, R Albajes (1993) Overwintering of cereal aphids (Homoptera: Aphididae) on durum wheat in a Mediterranean climate. **Environ. Entomol.** 22:381-387.

Pons X, GM Tatchell (1995) Drought stress and cereal aphid performance. **Ann. Appl. Biol.** 126: 19-31.

Pullin AS (1986) Effects of photoperiod and temperature on the life-cycle of different populations of the peacock butterfly *Inachis io*. **Entomol. Exp. Appl.** 41:237-242.

Quintana A, A Prevosti (1990) Genetics and environmental factors in resistance of *Drosophila subobscura* adults to high temperature shock. **Theor. Appl. Genet.** 80: 847-851.

Schiller JM, V Sengsoulivong, V. Manivong (1997) Rice and IPM research in the Lao PDR. p.167-183. *In*: Proc. Migration and Management of Insect Pests of Rice in Monsoon Asia. China Natl. Rice Res. Inst., Hangzhou, PRC.

Sogawa K, GJ Lin, JH Shen (2003) A review on hyper-susceptibility of Chinese hybrid rice to insect pests. **Chinese J. Rice Sci.** 17 (Supplement):23-30.

Thomson LJ, S Macfadyen, AA Hoffmann (2010) Predicting the effects of climate change on natural enemies of agricultural pests. **Biol. Control** 52:296-306.

Van Asch M, ME Visser (2007) Phenology of forest caterpillars and their host trees: the importance of synchrony. **Annu. Rev. Entomol.** 52:37-55.

Watt AD, AM McFarlane (1991) Winter moth on Sitka spruce: synchrony of egg hatch and budburst and its effect on larval survival. **Ecol. Entomol.** 16:387-390.

Watt AD, LK Ward, BC Eversham (1990) Invertebrates. p.32-37. In: The Greenhouse Effect and Terrestrial Ecosystems of the UK. MGR Cannell, MD Hopper (eds.) Institute of Terrestrial Ecology, Research Publication 4. HMSO, London, UK.

Woiwod IP (1997) Detecting the effects of climate change on Lepidoptera. **J. Insect Conser.** 1: 149-158.

Yamaguchi T, K Kiritani, K Matsuhira, K Fukuda (2001) The influence of unusual hot weather on the occurrence of several arthropod crop pests. (in Japanese with English summary) **Jpn. J. Appl. Entomol. Zool.** 45:1-7.

Yamamura K, K Kiritani (1998) A simple method to estimate the potential increase in the number of generations under global warming in temperate zones. **Appl. Entomol. Zool.** 33:289-298.

Zhou X, R Harrington, IP Woiwod, JN Perry, JS Bale, SJ Clark (1995) Effects of temperature on aphid phenology. **Global Change Biol.** 1:303-313.

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