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Climate change impacts on insect management and conservation in temperate regions: can they be predicted?

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Introduction

Global environmental change is amongst the greatest long-term threats to humans. We need sufficient food, clean air and a comfortable environment in which to live and our current way of life threatens all of these. We have thrived as a result of the major changes that we have imposed on the planet, particularly with respect to clearing space for modern agriculture and the development and use of related technologies. However, we now understand sufficiently the nature of interactions and feedbacks within and between abiotic and biotic components of the environment to realize the potential dangers from perturbation of any of these components.

Insects are the most diverse class of organisms on Earth (May, 1990). As insects have many detrimental and beneficial effects on humans and natural ecosystems, both directly and indirectly, it is not surprising that considerable thought has already been given to the impacts that global environmental change may have on them (e.g. Porter *et al.*, 1991; Cammell & Knight, 1992; chapters in Kareiva *et al.*, 1993; chapters in Harrington & Stork, 1995; Patz & Martens, 1996; Cannon, 1998; Epstein, 2000; Rogers & Randolph, 2000).

The reason for trying to predict the impacts of climate change within the context of agriculture and forestry is to help to determine whether present systems will be sustainable. Relevant questions include: will we be able to manage insects and their habitats in the future the way we do today and, if not, what can we do about it; will we need to consider every insect in every situation independently or is there any hope of generalizing; can we expect to develop adequately predictive process-based models of change, and can statistical analyses of long-term data lead to useful predictions?

This paper is concerned mainly with predicting the effects of climate change on insect pests and beneficial insects of agriculture and forestry in the northern hemisphere's temperate zones, although the general principles may be applied more widely. Whilst mindful of interactions with other factors, we concentrate mainly on temperature because, of the climate variables, it is the one for which there is most confidence in

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predictions of future climate change scenarios (Houghton *et al.*, 2001) and for which we have most evidence from which predictions of impacts might be derived. The potential rate of increase of many insects is strongly dependent on temperature, and their survival is impaired at low and high temperatures. Changes in both mean temperature and the extent and frequency of extremes can hence have major impacts on insect populations. First we outline what one might intuitively expect to happen to insects as a result of a general rise in temperature and then we look at various complicating factors that have the potential to confound these expectations. Next we give examples of changes that are already occurring and are consistent with expectation. Finally we consider some of the possible implications of these changes for insect pest management and insect conservation.

Intuitive expectations

A recent review divided the potential impact of climate change on individual organisms into effects on their physiology, phenology and distribution (Hughes, 2000). We consider these in turn for insects in temperate regions, where low temperatures tend to limit these processes. Where high temperatures are currently limiting, the reverse may be expected. Whether changes at the organism level feed through to effects at the population or community level, and hence have any relevance to ecology, conservation and pest management, will depend on the outcome of the interactions and complications discussed later.

Physiology

In areas where temperatures affecting physiological processes tend to be below species optima for most of the year, increases in temperature may be expected to speed up these processes and lead to more rapid development, more generations in a season, more movement and reduced mortality from abiotic factors. For example, Yamamura & Kiritani (1998) estimated the potential increase in number of generations for a range of insect orders and other invertebrates such as mites and nematodes. With a 2 °C temperature rise there may be between one and five additional generations per year. Champions in this respect are the aphids, which, with their low developmental threshold and short generation time, may be expected to produce four or five extra

generations a year. Aphids may therefore be particularly sensitive indicators of temperature change and are discussed in more detail later. Some insect species are constrained, through responses to other stimuli, to a set number of generations each year, and changes in generation time must be compensated by increases in the duration of a dormancy period.

Winter mortality as a result of low temperature is a key factor in the dynamics of many temperate insects, especially those that do not enter diapause but continue activity throughout the winter as temperature permits. Warmer winters, or a reduction in the frequency of extremely cold periods, may thus improve the prospects for survival of such species. However, insects display a range of strategies in relation to the threat from low temperature (Bale, 1993) and these will, in part, determine the impact of warmer conditions. Survival of insects that can tolerate freezing may not be improved as much by warmer winters as survival of those that cannot and, within the latter group, physiological and behavioural attributes will be influential in determining the impact of change. Species that are quiescent in winter may even be disadvantaged by periods of unusual warmth, because activity increases, possibly in the absence of food, and depletes vital energy reserves required for survival until adequate food supplies are available.

Phenology

Where life-cycle events are controlled by temperature, they may be expected to occur earlier, and higher temperatures are likely to facilitate extended periods of activity at both ends of the season, subject to constraints that other factors such as day length and drought might impose. For example, insects often enter diapause in response to photoperiodic cues. Unless the duration of food availability is also extended, insects will be unable to benefit from the increased potential given by changes in temperature alone. There is some evidence that adults of insects that normally have a single generation and fly late in the season, such as the winter moth *Operophtera brumata*, might emerge even later under climate warming (Buse & Good, 1996). This may help to maintain the advantage of avoiding natural enemies such as bats, which flying in cold conditions achieves, and may also help to maintain synchronization of egg hatch and bud burst in spring.

Distribution

Warmer conditions may be expected to promote the poleward extension of the range of species currently limited by low temperature, or the altitude at which they can survive. A 2 °C rise in temperature, which is expected in northern temperate latitudes over the next century, is equivalent to a shift of current conditions of 600 km latitude or 330 m in elevation (Parry, 1989). This is equivalent to approximately 6 km per year latitude or 3.3 m per year elevation. Most insects would be capable of tracking such changes but some host plants may not (Lawton, 1995). Hence, the spread of some insect species may be limited by the spread of host plants. In the case of crops, if growing conditions become suitable they can, of course, be moved by humans. International trade and tourism also offer the opportunity for species to spread. Insects may come into contact with

new potential hosts, and these hosts may already be under some stress, for example as a result of drought, and hence less able to defend themselves. This increases the likelihood of host switching. Under conditions of drought stress, ozone or pollution episodes, for example, there is a tendency for increased susceptibility of plants to insects and the diseases they transmit (e.g. Mattson & Haack, 1987; Bell *et al.*, 1993; Fleming, 1996). If any host plants are not under stress then any impact will be determined by the balance of advantages and disadvantages conferred on the insect. For example, phloem sap becomes more concentrated at higher temperatures, and thus acts as a richer source of amino acids for sap feeders, but 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. The physical nature of the host plant may also change. Leaves may become thicker or waxier, or may change colour, which could make them less palatable or attractive to insects.

It is not necessarily the case that, if a species that is a pest in one area arrives in a new location, it will be a problem there as well. The reverse is also true. As numerous examples of exotic biological invasions attest (Mattson & Haack, 1987), a species that is not a pest in one location may become one if it establishes, for example, in an area relatively free of natural enemies or where hosts have not evolved adequate defensive mechanisms.

Complicating factors

We now consider some of the complications that may prevent these suggestions from feeding through predictably to population- and community-level effects. In particular we consider some aspects of the interactions between variables, the potential for dissociation in time and space between currently interacting species, and factors affecting the ability of species to adapt physiologically to changed conditions.

Changes in multiple variables

Temperature does not act in isolation to influence pest status and it is important to consider interactions with other variables. Rainfall, for example, is also critical to survival. Some insects are unable to tolerate extremes of drought, whereas others are disadvantaged by extremes of wetness. Increased concentrations of carbon dioxide increase carbon : nitrogen ratios of plants. This leads to the need for insects to eat more in order to obtain adequate dietary nitrogen. This may be compensated by increases in plant biomass or levels of carbon-based defences (see reviews by Bezemer & Jones, 1998; Cannon, 1998). For insects, the net result may be slower larval development and increased mortality (Coviella & Trumble, 1999). Economic and other considerations may lead to changes in land use, agronomic practice or human population distribution. Increasing transportation leads to increased risk of invasion by exotics. Such considerations may dominate or override any effect of climate on insects.

Temporal dissociations

Changes in climate may affect interactions between species within or between trophic levels by disrupting temporal

synchrony. For example, many insects are dependent on synchrony between time of bud burst (or flowering) and the emergence of feeding stages. Surprisingly, there is little evidence of feeding stages being cued directly by bud burst. Instead, similar external cues often affect both bud burst and the appearance of feeding stages. However, the requirements are often complex combinations of day length and specific combinations of periods and extents of chilling and warming. Requirements are rarely identical for the plant and insect, and have developed over evolutionary time. It is quite conceivable that, under the current rapid changes in climate being experienced, synchrony between trophic levels could become decoupled as a result of subtle differences in the impacts of changes on the timing of cues determining the phenology of constituent species (Harrington *et al.*, 1999). For example, changes in synchrony may occur between winter moth *O. brumata* larval emergence date and bud burst of its host plant, sitka spruce *Picea sitchensis* (Dewar & Watt, 1992). With a temperature increase of 2 °C bud burst date is not expected to change dramatically, but larval emergence date is likely to advance dramatically, potentially leading to larval emergence dangerously (for the moth) ahead of bud burst. Pest problems may then be reduced. The decoupling of one synchronous trophic interaction may also lead to the development of others. This can occur when a participant of the original interaction is later brought into synchrony with different members of adjacent levels of the local trophic web. Such switches in synchrony allow pre-adapted exploiters immediate access to new hosts, although it may take time for the member of the higher trophic level to evolve the ability (if it has the capacity for such evolution).

Spatial dissociations

It seems highly improbable that all members of a community will respond in the same way to climate change, and this is likely to lead to rearrangements of current communities. Davis *et al.* (1998) showed that if *Drosophila melanogaster* is left on its own in linked incubators at different temperatures, it does best at 25 °C but still does well at 10 °C. Let it compete with two other *Drosophila* species, and it does even better at 25 °C, but is eliminated at 10 °C. When parasitoids are added to the system the situation gets more complicated. Indeed, *D. melanogaster* reappears at 10 °C, probably because the parasitoids are preferentially eliminating some of its competitors. This is a very simple and artificial system, but it demonstrates the principle that current communities will not necessarily remain intact under climate change. This corroborates earlier mathematical models predicting that climate change could destabilize ecosystems and change their structure (e.g. Antonovsky *et al.*, 1990).

Plant viruses add another layer of complexity to the potential impact of climate change on problems caused by insects. The extent of the complication can be understood by considering the example of barley yellow dwarf virus (BYDV) in the UK. The virus is important world-wide and has a range of grass and cereal hosts and a range of strains that are transmitted with different efficiencies by different vector aphid species. One 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). 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. The aphid has no cold-hardy egg stage and an increased frequency of warm winters will further aid its survival. At higher temperatures, other aphids become capable of transmitting the maize strain of BYDV to cereals such as wheat and barley (Rochow & Eastop, 1966; Lucio-Zavaleta *et al.*, 2001). Therefore, warmer conditions, through their effect on interactions between host plants, aphids and viruses, may render the maize strain of BYDV important in wheat and barley for the first time in the UK.

Changes in relative abundance without loss of synchrony

Differential effects of increasing temperatures on crop pests and their natural enemies may lead to changes in pest potential at higher temperatures without affecting temporal or spatial synchrony. For example, below 11 °C, reproductive rate of the pea aphid *Acyrtosiphon pisum* exceeds the rate at which the coccinellid *Coccinella septempunctata* can consume it, but above 11 °C, the tables are turned (Dunn, 1952). By contrast, natural enemies of spruce budworm *Choristoneura fumiferana* tend to be less effective at higher temperatures (Fleming, 1996).

Adaptation

The extent to which species genetically adapt to change will be dependent on the strength of the selective forces for change acting on the species and the genetic capacity of the species to respond. This capacity can be expected to increase with the species' genetic variability, geographical range, reproductive rate, migratory ability and competition with other biotic components of the changing environment. The more adaptable species are likely to be the more mobile species (because pre-adapted phenotypes are more likely to be able to move in from elsewhere) and the faster reproducing species (which are likely to give rise to appropriate genotypes more frequently). Unfortunately, pests tend to show these characteristics.

Disturbances and feedbacks

In contrast to most agriculture, where soil, water and pest management are intensive, many forests (particularly the vast boreal forests of North America and Russia) are left to grow with relatively little management intervention until harvest. Under these circumstances, natural disturbances such as forest fires and outbreaks of the more damaging insects (e.g. mountain pine beetle *Dendroctonus ponderosae* (Hopk.), spruce budworm *C. fumiferana*) can affect carbon cycles. In boreal forest stands, trees tend to be even-aged, having originated together after the last disturbance at the site. Young stands typically contain relatively little biomass and small, fast growing trees. Very mature stands are usually growing very slowly, if at all, but have accumulated large amounts of carbon in their tissues and soil, and are often more prone to fire or insect attack. Such disturbance can spread quickly over large areas, opening the canopy and causing tree mortality or reduced growth. Opening the canopy

leads to increased ground temperatures and, consequently, increased rates of decomposition and carbon release from the soil, where most of a stand's carbon is stored. Tree mortality can produce sudden carbon releases, whereas reduced growth slows the rate of carbon accumulation.

When disturbances occur frequently, trees have shorter lifespans, and hence fewer years of growth to accumulate carbon before it is released back to the atmosphere or transferred to dead organic matter (Cooper, 1983). In general, the more often disturbances occur, the less carbon the forest contains in its living biomass and dead organic matter, and the more carbon is released to the atmosphere. Consequently, a major concern is that if climate warming leads to more frequent disturbances, then through this process it may accelerate the accumulation of greenhouse gases in the atmosphere and thus bring on more climate warming. Ayres & Lombardero (2000), Fleming (2000) and Volney & Fleming (2000) suggest that such a possibility could develop with certain forest insect disturbance regimes.

Most forest disturbances do not occur at large enough scales to affect atmospheric carbon in any substantial way. Fire is an exception (Stocks, 1987; Woodwell *et al.*, 1995). Despite large-scale harvesting and modern fire control efforts, wildfire is still considered to be the disturbance that drives succession in most of North America's boreal landscapes (Hall, 1995; Weber & Flannigan, 1997). This is particularly true in the drier western regions. In the wetter eastern parts, insects play a larger role. Fire and major insect-caused disturbances both affect extensive forest areas, tend to occur in cycles and play a role in forest succession (Bergeron & Dubuc, 1989). However, unlike wildfire, insects are host specific and their outbreaks typically result in continuous damage over a period of years rather than in the days to weeks characteristic of fire. Insect outbreaks are also often much more extensive than wildfires (Fleming *et al.*, 2000) and in approximate synchrony over large areas (Hardy *et al.*, 1986; Candau *et al.*, 1998; Williams & Liebhold, 2000). Moreover, even during mild insect outbreaks, the damage to trees reduces their growth and consequently their sequestration of carbon, in contrast to the effects of wildfire, which are probably offset by photosynthetic uptake elsewhere (McNaughton *et al.*, 1997). Certain insects, particularly the spruce budworm, are capable of imposing the oscillatory signature of their outbreak cycles on net carbon fluxes even at continental scales. In fact, the spruce budworm alone is estimated to cause annual losses of $35.1 \times 10^6 \text{ m}^3$ from Canada's productive wood volume. This amounts to over 60% of all losses to insects and is virtually equivalent to the $36.0 \times 10^6 \text{ m}^3$ in total estimated losses to fire (Fleming, 2000).

As large-scale disturbance agents, forest insects have two other potential roles to play in accelerating climate change. First, the downed and dead debris in insect-attacked stands often constitutes excellent fuel for fires (Stocks, 1987), and fires are generally much more thorough in releasing a stand's carbon than insect infestations. Second, insect outbreaks could act as disturbance agents, which change successional pathways irreversibly. This has been suggested by theoretical mathematical models (e.g. Antonovsky *et al.*, 1990) and later supported by an applied modelling study by Hogg (2001) indicating that under a warmer and drier future climate, defoliation by forest tent caterpillar *Malacosoma disstria*, in combination with

drought, could lead to conversion of aspen stands to grassland in the Canadian prairies. In this latter situation, the site loses its capacity to sequester the same amount of carbon because grasses generally have less storage capacity than trees.

Effects already observable

Because of the complex interactions that must be considered when assessing the potential impacts of environmental change, combined with interspecific, intraspecific and even intraclonal variability in responses, attempts at generalization are likely to be largely unproductive. Process-based modelling can help to demonstrate the combined effects of some of these interactions, but it is unrealistic to expect to be able to parameterize all the relevant interactions in any system. Long-term datasets can be useful in demonstrating impacts of environmental change, and in validating predictions. They inherently take into account all of these interactions, but do not explain them individually. Problems may arise because combinations of variables expected as a mean at a given future date may be outside the range of experience from which relationships were derived, even if means expected for individual variables at the future date are within the range of current experience. However, some such models have proved robust and reliable to date. Nonetheless, all such 'effects already observable' are essentially correlative (i.e. correlations of observable patterns with model or theoretical expectations); it is an enormous logistical challenge to conduct the manipulative experiments necessary to establish causation rigorously. We know of no such experiments to date.

Phenology

Evidence of phenological change has now been shown from all the long-running insect datasets in the UK: for butterflies by Sparks & Yates (1997); for moths by Woiwod (1997) and for aphids by Fleming & Tatchell (1995) and Zhou *et al.* (1996). The Rothamsted Insect Survey has been operating a network of suction traps in the UK since 1964 in order to monitor flying aphids and study their dynamics (Woiwod & Harrington, 1994). The traps are emptied daily and all aphids identified. Similar traps are operated throughout much of Europe, providing what is probably the most extensive, standardized dataset for any terrestrial invertebrate group (Harrington *et al.*, 2002). For many species at many sites, there is a remarkably strong relationship between the timing of the start of the spring migration and winter temperature (Harrington *et al.*, 1990, 1995). The milder the winter, the earlier the migration. This is probably due to a combination of more rapid development and reproduction, and reduced mortality due to low temperatures. This conclusion is backed up by the fact that aphids that pass the winter as an egg tend to show very much weaker relationships between migration time and winter temperature than those that pass the winter in the active stages (Harrington *et al.*, 1990). Eggs are very much more cold-hardy than the active stages and are hence less affected by low temperature. However, they are in diapause and, unlike the active stages, cannot take advantage of warm periods with a burst of development and reproduction. Thus, biological expectation shows through in these purely statistical relationships. The clear implication is that, even after taking account of the complica-

tions explained above, milder winters will result in earlier aphid migrations and hence in earlier threat to crops. The extent of change in economic damage will depend partly on the extent of change in the planting and emergence times of crops. As an approximation, the aphid species that have been examined show an advance in the timing of the spring migration of about 14 days for every °C rise in temperature.

The long-term nature of the aphid dataset makes it possible to look for trends with time that may be attributable to climate change, as well as trends with meteorological variables themselves. Fleming & Tatchell (1995) and Zhou *et al.* (1996) used the data to look at a range of species and found that over a 21-year period, the average advance in phenology at any given latitude was 10 days, which is the equivalent to going south about 2.5° in the UK. In other words, in 1990, aphids were flying in northern England at about the same time as they were in the midlands in 1969.

Abundance

Insects are usually subject to large between-generation and between-year fluctuations in abundance. These fluctuations may be caused by a wide range of interactions between biotic and abiotic factors so it is not surprising that it has been very difficult to assign trends in the abundance of any particular species directly to climate change.

Amongst the most thoroughly studied groups in this respect are British butterflies, for which there are some of the best long-term datasets. An analysis of the population trends between 1974 and 1992 from the national Butterfly Monitoring Scheme (BMS), co-ordinated by the Centre for Ecology and Hydrology, found that the common and widespread species had generally increased in abundance during that period, with particularly strong increases in the east of England. However, a number of possible explanations were given for the observed trends, climate only being one of them (Pollard *et al.*, 1995). In a more recent analysis of the BMS data, strong associations were found between weather and population fluctuations and trends in 28 out of the 31 species studied (Roy *et al.*, 2001). Simple statistical models incorporating temperature and rainfall were then constructed on subsets of the data, which were tested on later subsets. Species that had models with high predictive ability were used to simulate population change under a medium-high UKCIP98 climate change scenario up to 2080. Eight species were included and, of these, five predicted increasing abundance trends, one a decline and two predicted no long-term trend (Roy *et al.*, 2001). The interesting feature here is the suggestion that even in a group of species whose populations might be expected to be very sensitive to climate, not all species are predicted to react in the same way.

Larger numbers of aphids are trapped during the critical spring and early summer period following milder winters (Harrington *et al.*, 1990). At this time, some crops tend to be particularly sensitive to damage caused by aphids through removal of plant sap and through transmission of plant viruses. However, this again is true only for aphids passing the winter in the active stages. Furthermore, peak numbers of aphids later in the season are often lower after milder winters. This is because natural enemies emerging from winter diapause tend to do well as a

result of the large numbers of aphids present, and produce a large number of offspring that help to reduce aphid numbers later (Entwistle & Dixon, 1989).

Distribution

Some of the most convincing data on changing insect distributions and climate come again from work on butterflies. In a study of Edith's checkerspot butterfly *Euphydryas editha* in North America, Parmesan (1996) showed that there had been a long-term change in distribution, with populations surviving better at the northern edge of the species range in Canada, but with a marked decline in colony numbers at the southern edge in Mexico. Interestingly, within the main range, the butterfly was also doing better at higher altitudes in later years. Parmesan *et al.* (1999) went on to look at the distribution data for 35 non-migratory European butterflies over 100 years and found 63% to have northern boundaries that extended northwards, 34% to have been stable and only 3% to have retracted southwards. As southern boundaries have remained largely unchanged, this constitutes an extension of range for the 63% expanding northwards.

Historical and current butterfly distribution data are available at very high resolution for the UK (Asher *et al.*, 2001). This has enabled empirical models of species' range to be developed, which have been used successfully to explain historical patterns (Hill *et al.*, 1999) and are also being used to predict future distributions under climate change scenarios. For the three species so far analysed there is expected to be a northward range expansion under climate change, only modified where habitat fragmentation prevents colonization (Hill *et al.*, 2001).

Potential implications of climate change for pest control

Not only may our pest problems change in response to climate change, but the effectiveness of control strategies may also change.

Considering chemical control, the number of days that are suitable for spraying is likely to increase where it is drier and decrease where it is wetter. The toxicity of active ingredients may change through, for example, changes in conditions affecting the chemicals' stability or volatility or through changes in the behaviour or susceptibility of the pest.

The success of entomopathogenic fungi generally depends on a reasonably high relative humidity and, under drier conditions, they may be less effective. Radiation levels are also important as, under high levels of solar radiation, their effectiveness can be rapidly reduced. Thus, the mortality of *Plutella xylostella* caused by *Zoopthora radicans* is reduced with increased exposure to simulated levels of tropical radiation (Furlong & Pell, 1997), and high temperature tends to decrease the effectiveness of the fungus *Beauveria bassiana* in controlling wax moth *Galleria* species in soil treated with certain pesticides (Mietkiewski *et al.*, 1997).

GM technology is not immune from climate change considerations. For example, in Australia, the effectiveness of Ingard cotton, which has been genetically modified to produce a Bt toxin precursor, appears to be greater at a given node when

that node is produced at a higher temperature (J. Daly, pers. comm.). This work was done under laboratory conditions, but there is evidence that Bt plants grown in tropical locations perform better than those in cooler conditions (J. Daly, pers. comm.). No doubt examples could be found where the reverse is true, and it cannot be assumed that any given control method will be equally effective under the environmental conditions of the future.

Potential implications of climate change for insect conservation

Any uncontrolled and rapid environmental change is likely to be of concern to those involved in the long-term preservation of insect biodiversity. As outlined in some of the examples already given, climate-related effects may be species specific and idiosyncratic. Mobile species might be expected to track the environment as it changes. Of more concern are those species with specialized habitat requirements or those adapted to high altitudes or latitudes. As these environments fragment and even disappear under climate change, these species may become extinct. Again, butterflies are instructive in this respect. Many of the widespread mobile species in Europe are becoming more abundant and expanding their range northwards, whilst at the same time there are a considerable number of species, often with restricted habitat requirements, that are declining alarmingly despite any recent climate amelioration (e.g. Asher *et al.*, 2001).

Conclusions

So where does all this leave us? Climate change studies are full of caveats and there is some inevitability in this, bearing in mind the diverse and complex systems of interest. However, there is already evidence that changes in pest ecology that are consistent with predictions of climate change impacts are occurring. Whilst there is good reason to expect some pest problems to increase, it tends to be difficult to publish negative results, and consequently there is a danger of giving the impression that all pests and diseases will increase in importance. Control programmes that include monitoring and forecasting and take account of ecological and economic factors in determining the need for using chemicals are crucial to preventing the overuse of pesticides and the development of insect resistance to them. Pest management decisions also need to be integrated into the broader context of total resource management. For instance, pesticides may reduce food sources for birds and other animals of conservation interest. The 'Global Change and Terrestrial Ecosystems' (GCTE) project of the International Geosphere and Biosphere Programme (Schermer *et al.*, 2000) is an example of an initiative aimed at bringing interested parties together to facilitate such a systems approach.

Changes in phenology, distribution and abundance consistent with climate change are also starting to be observed in insect species of no direct economic importance in agriculture and forestry. However, all species are part of the natural biodiversity and may be important in ecosystem function, for example as food items for birds and mammals. They may also be of conservation concern in their own right. For some species, climate change may be of benefit, for others it might be the last straw on top of

declines due to other forms of human-induced environmental change. Careful long-term monitoring of as wide a range of species as possible is probably the first step in any strategy to understand and deal with changes as they occur. However, for long-term amelioration of the most deleterious effects, a whole suite of strategies may be needed, such as habitat restoration and creation, provision of corridors between habitat fragments and, in some cases, the translocation of species between isolated habitat patches.

It is clear from the examples and counter-examples given above, that there has been very little success in generalizing predictions of global change impacts on insects. However, those working with pest insects generally claim that problems will become worse in the face of global change (i.e. pest insects will become more abundant), whereas those concerned with conservation generally suggest that insects will fare worse. If both are right, and if this is related to the earlier premise that mobility and reproductive potential tend to predispose insects to be pests, then perhaps there is some hope that a classification system can be developed that predicts how different insects are likely to respond to climate change. Cold hardiness strategy (Bale, 1993), life-cycle type (Harrington *et al.*, 1990), feeding guild or a combination of these and other attributes may prove useful in developing such a strategy. There may be parallels in the insect world with the triangular 'stress tolerators, ruderals and competitors' classification for vascular plants developed by Grime (1974). Hodgson (1993) had some success when looking at attributes of butterflies associated with commonness and rarity. It has to be worth a try – otherwise the results from studies of global change impacts will remain parochial.

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