Chapter 17

Pests Under Global Change – Meeting Your Future Landlords?

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17.1 Introduction

The term global change embraces a range of natural and anthropogenic environmental changes that are occurring around the world (Vitousek 1994), including changes in atmospheric composition, climate, land use and land cover, and the prevalence of non-indigenous species. This synthesis describes contemporary approaches to the assessment of the vulnerability of ecosystems and human societies to plant pests (arthropods, plant pathogens and weeds that are injurious to plants) in relation to global change. Animal and human health have been covered elsewhere in recent reviews (Sutherst 2001, 2004). While the detailed impacts of global change on the status of pests will only be known as events unfold, it is already clear that some pests will be able to invade new areas and become increasingly problematic for the maintenance of biodiversity, the functioning of ecosystems and the profitability of crop production. Some pests which are already present but only occur in small areas, or at low densities may be able to exploit the changing conditions by spreading more widely and reaching damaging population densities. Our objective is to discuss these potential changes in pest status and to present a framework for effective adaptation.

17.2 Methods

17.2.1 IPCC Processes

In addition to assessing the direct impacts of global change on agriculture and natural ecosystems, the global scientific community faces the task of understanding indirect impacts caused by pests of animals and plants. The numerous interacting species, the myriad of stakeholder interests, and great variation in the quality of available data make this a daunting prospect requiring generic approaches with a hierarchy of analytical tools (Sutherst et al. 1996). In order to develop a holistic approach we need to integrate the methodologies developed by the different research and policy communities into a comprehensive risk analysis framework. Pest risk analysis procedures developed by the International Plant Protection Convention (IPPC) (FAO 2004) provide an accepted standard for analysing the risks posed by pests to areas where they are not currently present or, if present, not widely distributed and under official control. At present, although assessments may focus primarily on impacts under current conditions, the risk analysis framework does allow the effects of global change to be taken into account (Baker et al. 2000; Sutherst 2000). In addition, although designed for invasive non-indigenous species, the procedures can also be used to analyze future threats posed by indigenous species.

The concept of vulnerability is used by the scientific and policy communities investigating the likely threats from climate change (Houghton et al. 1996; IPCC 2001a). *Vulnerability* is a measure of the potential *impacts* of a given change, taking into account the *adaptive capacity* available to respond to that change. The term avoids the consideration of risks in the absence of a natural or societal response, which can give an incomplete picture. *Impacts* are a combination of a change in *exposure* of ecosystems to pests and the *sensitivity* of the system to that change. *Adaptive capacity* depends on the adaptation technologies, cultural tools, and the infrastructure and resources available to implement appropriate management responses:

$$\text{Vulnerability} = \text{Impacts} \times (1 - \text{Adaptive capacity})$$

where

$$\text{Impacts} = \text{Exposure} \times \text{Sensitivity}$$

and

$$\text{Adaptive capacity} = (\text{Adaptation products and practices}) \times \text{Resources}$$

The general issues of adaptive capacity relative to climate change have been reviewed by Smith et al. (2003), who delve into both theoretical considerations and practical examples.

17.2.1.1 *Exposure*

A shift in the geographical distribution of a pest exposes new ecosystems to that pest for the first time. Climate change may enable such shifts to take place as pests track suitable climates. Immigration to new environments may occur through anthropogenic or natural pathways. Anthropogenic pest entry to new areas is already a major cause of invasion, and the numbers of species carried by traded commodities and with passengers are unlikely to be influenced directly by global change. However, entry by natural means may increase with global change if, for example, migrant species extend their range and move closer to threatened areas. While natural spread is generally undertaken by the pests themselves, movement of hosts or vectors with their associated pests may also be responsible for pest entry.

Following entry, a number of abiotic and biotic factors coupled with the intrinsic attributes of a species, e.g., its reproductive rate and adaptability, determine the success of establishment in the new area (Baker et al. 2003; FAO 2004). Climate is usually the first feature of the habitat considered in a risk assessment for pragmatic reasons, but other variables such as the spatial distribution of host plants also need to be considered. The extent to which exposure is affected by climate change will depend on the position of the particular habitat relative to the species' climatic envelope (Sutherst 2001). Populations closer to the edges of a species' range are likely to respond more quickly to climate change than populations near the center where conditions are closer to the optimum. Natural enemies of the pests may be left behind so the pest can proliferate unchecked (the enemy release hypothesis; Colautti et al. 2004), although predators and parasites may adapt to the invading species over time. Genetic observations can also contribute to understanding patterns of invasions by pests in new environments, as shown by studies of population structure of a non-pest fruit fly, *Drosophila subobscura*, in the Americas (Balanya et al. 1994; Noor et al. 2000).

Predictions of current and future distribution based on climate have been enhanced by the availability of monthly local and global gridded climatologies, e.g., the 1961–1990 global climatology interpolated to a 10' latitude/longitude grid (New et al. 2002). Where climate change scenarios are available at the same resolution as the baseline climatologies, predictions of changes in potential distribution under climate change can be made (Baker et al. 1998; Baker et al. 2003; Kriticos et al. 2003a).

17.2.1.2 *Sensitivity*

Sensitivity is the degree to which a system responds to a perturbation such as climate change (IPCC 2001a). Responses are often complex and non-linear due to a number of features of biological systems (Sutherst 1998) including thresholds (Scherm and van Bruggen 1994; Scherm 2004), discontinuities at the edges of species' ranges including hybrid zones (Barton and Hewitt 1989), multiplicative effects of population growth in multivoltine species (Sutherst 1983), the Allee effect (Stephens et al. 1999; Garrett and Bowden 2002; Taylor and Hastings 2005) and competition or predation (Silvertown 2004). A consequence of these effects is the need to augment empirical and descriptive approaches, such as statistical models, with dynamic and mechanistic simulation models (Sutherst 2001).

Once the sensitivity of the target system or species has been defined, a measure of the likely impact on the population can be derived, in the absence of any intervention. This provides a baseline measure of risk against which to estimate the benefits of alternative adaptation options.

17.2.1.3 *Impacts*

Both 'top-down' and 'bottom-up' approaches have been recommended for analyses of impacts of climate change (Parry and Carter 1998). The former is based on scenarios from global climate models (GCMs) while the latter uses sensitivity analyses (Sutherst 1998; Sutherst 2001). The two approaches have been combined into a risk management approach (Jones 2000). Integrated assessment frameworks are under development to bring some of these elements together, e.g., in a framework for analysing impacts on parasites (Sutherst 2001). The science needed to assess impacts of global change on pests is the same as for other species. However, the emphasis is different in that pests usually reproduce, disperse and colonize new habitats faster than many species of conservation value.

17.2.2 Monitoring, Benchmarks and Indicators for Measuring Impacts

We need *monitoring* data for pest-related *indicators*, covering long time-series in order to detect changes in ecology and impacts associated with global change. Such indicators need to relate to environmental, economic and social systems. We also need *benchmarks* to provide reality-checks for attribution of changes in status of populations.

The 1961–1990 climatology has become a standard from which to gauge climate change impacts, although, as climate change accelerates, its use as a baseline reflecting current climatic conditions is becoming less justifiable. Records of species presence need to include collection dates so that potential range expansion can be detected reliably. Records of absence are also useful. The difficulty of accurately determining the distribution of even well-known pest species (Yonow et al. 2004) suggests that more emphasis is needed on incorporating high-quality pest data into databases of species distributions.

A benchmark for the effects of temperature change *per se* is provided by the relationships with altitude and latitude (Linacre 1992). Each 1 °C increase in global temperature corresponds to a potential increase of ~170 m in a species' altitudinal range. As warming over the past century has been about 0.6 °C (IPCC 2001a), altitudinal range changes caused by global warming are unlikely to exceed 100 m. Similarly, in the absence of other factors, latitudinal shifts of about 1.7° (~200 km) can be expected for each 1 °C increase in temperature, corresponding to a shift of ~118 km with the observed temperature increase of 0.6 °C.

Whether changes of this order are achieved by a pest, i.e., whether the species is able to track temperature change, will depend on its rate of dispersal through fragmented habitats. In this context, it is worth drawing attention to the 'conservation-regulation' paradox. Those working on pests, i.e., species that require regulation, generally claim that, under global change, their species will become more abundant and widespread. By contrast, those working on species that require conservation generally state that their species will become less abundant and less widespread (Thomas et al. 2004). There are many exceptions on both sides, and some of the conclusions may be artefacts of the assessment tools employed (Thuiller 2003). Nonetheless, the paradox can be explained in part by the fact that the characteristics which tend to make an organism a pest, i.e., high reproductive and dispersal potentials, are the same ones that allow it to adapt to environmental change. For example, if the ability to migrate in fragmented habitats is impaired in plant species of conservation concern compared with weeds, climate change is likely to favor the weeds (Collingham et al. 2000).

Yamamura and Kiritani (1998) developed an indicator for tracking change in seasonal population dynamics of invertebrates. They devised a formula for the expected increase in the number of generations (voltinism) per year with a given temperature increase, based on values of the lower developmental threshold (T_0) and generation time (K). Using this index, those species with the largest increase in voltinism will be those with the lowest T_0 and the shortest K. Of 12 invertebrate orders examined, aphids are expected to show the greatest increase in voltinism with an extra two to three generations per 1 °C warming. Naturally, an increase in voltinism will not necessarily translate into larger population densities if, for example, required moisture conditions are not satisfied or if there is strong density-dependent parasitism, predation or lack of food.

The establishment of a global network of long-term monitoring sites will facilitate the development and implementation of indicators to monitor effects of global change. Examples of such measurements include the number of non-indigenous species in each country, the number of species extinctions, losses of agricultural production, and incidence of disease in humans (Pimentel et al. 2000b). In the context of biodiversity, suitable indicators include measures of physiological processes such as photosynthesis, metabolism and development rates, geographical distributions, phenology, and microevolutionary adaptation (Hughes 2000).

Perhaps most intuitive for policy makers is the expression of impacts in monetary terms. For agricultural crops, Oerke and Dehne (2004) gave potential yield losses for a range of commodities and regions. According to their synthesis, weeds currently cause losses of 32% with animal pests and pathogens causing 18 and 15%, respectively. Costs of pests in six countries (United States, UK, Australia, South Africa, India and Brazil) were estimated at US$336 billion, with about 9% of those representing costs of control. Extrapolated to the world the estimate was US$1.4 trillion. These figures would be multiplied several times if losses of biodiversity and ecosystem services in natural systems were included. How these costs will be impacted by global change is difficult to project, but Pimentel et al. (2000a) provide an example of how this can be estimated. Their estimate for a single global change driver (non-indigenous species) for a single country (the United States) suggests annual environmental and economic costs of nearly US$137 billion, of which almost 20% are due to non-indigenous plant pathogens and associated control costs. These figures may underestimate the problem (Perrings et al. 2002).

17.2.3 Estimating Impacts

A comprehensive assessment of impacts of pest risks under global change requires a conceptual framework that encompasses the pest and its interactions with physical and biological factors, including other species in the same or different trophic levels. It also needs a balanced program of field observations to help identify variables that affect species populations, experimental studies to elucidate mechanisms, and models to synthesize and test knowledge and understanding. Networks of researchers are also invaluable in the context of global change in order to facilitate sharing of information and comparative regional studies (Scherm et al. 1999; Hijmans et al. 2000). Some examples illustrate how these activities can contribute to ecological research to form the basis for the design of adaptation strategies for global change.

17.2.3.1 *Field Observations to Detect Population Changes*

Field observations are the grist of ecology and yet there is reluctance to fund such efforts due to the open-ended commitments necessary to obtain long time-series of observations. Many important revelations have been obtained by analysing such data. For example, long-term monitoring of the wheat stem rust pathogen (*Puccinia graminis* f. sp. *tritici*), initiated in the early 1900s in the central United States, clearly documented the effects of the deployment of specific host resistance genes and of the eradication of the alternate host, barberry (on which sexual reproduction occurs) on the pathogen's virulence dynamics (Roelfs 1982).

In community ecology, the changing correlations in rankings of abundance of each species and drifts in species compositions in communities over time provided insights into the natural behavior of species communities (Lawton 2000). Species in higher trophic levels were more sensitive to climate change (Voigt et al. 2003) suggesting that some communities may break down under global change.

There is increasing global scientific interest in developing Long-Term Ecological Research (LTER) sites and programmes, most of which are concerned with species of conservation interest. The most enduring long-term, standardised network for monitoring arthropod pest species is the suction trap network operated by the Rothamsted Insect Survey for studying aphids (Woiwod and Harrington 1994). The long run of data has enabled statistical relationships to be established between aphid phenology (e.g., annual time of first capture) and a range of climate and land-use variables. The time of first flight was strongly correlated with temperature for some species at some sites, with earlier first flights after higher winter temperatures. In the case of the important pest species *Myzus persicae* at Rothamsted, the relationship accounted for 80% of the variance.

Within the United States, several LTERs are now being used to study pest populations. In a 12-year warming experiment at a site in the Rocky Mountains of Colorado, Roy et al. (2004) documented an overall trend of increasing damage from herbivores and plant pathogens in plots with warmer temperatures and earlier snowmelt, although some pathogens and herbivores preferred the cooler plots. Results support the idea that the community composition within a particular area is likely to change with global warming. Other LTER sites in Alaska are currently being used to study how climate warming may impact pest occurrence under various temperature/moisture combinations (Mulder and Roy 2003). It would be prudent to include more climate impact studies in LTER sites in the future; assessing the effects of pest control will add to the value of biodiversity information being collected without significantly increasing the cost of maintaining these research sites.

Regardless of the species being monitored, there is a need for much more spatial distribution data coupled with geophysical measurements, including soil types, topography, vegetation type and cover and land use. Such measurements are particularly valuable if they are spatially explicit, cover a wider range of parameter values than measurements at any single location, and contain multiple combinations and permutations of environmental conditions (Sutherst 1998). In addition, spatial information is becoming valued due to the trend towards landscape-scale management of non-indigenous species (Jules et al. 2002).

17.2.3.2 *Empirical Data from Experimental Manipulations*

Reductionist experiments are traditionally employed to isolate each component of a system and examine its relative contribution. Such an approach has been used to dissect the effects of elevated CO_2 on the dynamics and intensity of anthracnose disease on the tropical legume *Stylosanthes scabra* (Chakraborty et al. 2000a; Chakraborty and Datta 2003; Pangga et al. 2004). Elevated CO_2 was found to reduce disease in growth chamber experiments by delaying pathogen spore germination, germtube growth and appressorium production and by inducing host resistance to anthracnose. In the field under elevated CO_2, however, these disease-reducing effects were counterbalanced by increased pathogen fecundity and by an enlarged canopy of *Stylosanthes* which trapped more pathogen spores and provided a more humid microclimate, leading to increased lesion numbers. Follow-up studies should include additional treatment levels in order to detect possible non-linear responses (Körner 2000).

In general, it is difficult to predict field responses from experiments involving changes in a few selected variables. For example, although the intrinsic growth rate of populations of the pest aphid *Aulacorthum solani* was enhanced in elevated CO_2 (Awmack et al. 1997a), a decrease in the insect's response to alarm pheromone could make it more vulnerable to attack by natural enemies, thus potentially offsetting the population increase (Awmack et al. 1997b). Experiments are needed to show how these and other changes interact.

Artificial ecosystems in controlled conditions, such as the Ecotron (Jones et al. 1998), can act as a useful intermediate step between laboratory experiments and the field and assist in the scaling-up process. Whole-system studies in controlled ecosystems provide insight into the complexity of simplified synthetic communities and so help to elucidate patterns and mechanisms behind specific responses of those communities to changes in environmental variables (Lawton 2000).

In one such laboratory-based study, interactions between three species of *Drosophila* fruit flies (*D. melanogaster*, *D. simulans* and *D. subobscura*) were studied in temperature clines with dispersal, with or without a hymenopteran parasitoid (*Leptopilina boulardi*) present (Landsberg 1989). As with other similar experiments, e.g., Davis et al. (1998), each of the treatments altered the balance of species numbers. The latter authors criticized the use of climatic mapping techniques (see below) on the basis of these laboratory results, and called for inclusion of population sinks and species interactions when trying to predict ranges under climate change. However, while recognising that species interactions are important in the field, Hodkinson (1999) and Baker et al. (2000) argued that experiments in confined spaces may overestimate species interactions since they do not provide species with the heterogeneous habitats that allow fauna such as these *Drosophila* spp. to coexist (Jenkins and Hoffmann 2001). A protocol has been described for ensuring that climate-based projections of species ranges do not overlook the roles of non-climatic variables (Sutherst 2003). Regardless, community-level impacts of global change will remain very uncertain due to their inherent complexity and multiple linkages.

Manipulation of whole systems in the field offers opportunities to study species interactions in more natural conditions. Free-Air CO_2 Enrichment (FACE) experiments (Hendrey 1992) have been particularly popular in global change research, but few have included pest components. A recent exception is a study on the interactive effects of CO_2 and ozone (O_3) on aspen trees infected with the rust fungus *Melampsora medusae* f.sp. *tremuloidae* (Percy et al. 2002; Karnosky et al. 2002). The results showed that O_3 predisposed the host to rust infection and that elevated CO_2 was unable to compensate for this effect. Exposure to O_3 or CO_2 increased the amount of hydrocarbons in leaf surface waxes, which aid host recognition by certain herbivorous insects; as a result, aphids were more abundant in trees treated with O_3 and/or CO_2 (Percy et al. 2002).

A complicating factor in controlled experiments is the potential for genetic adaptation to climate change. This is difficult to mimic in laboratory experiments that generally utilize populations of single strains or of a few strains with limited genetic diversity and do not investigate how populations may adapt as climate changes over long time periods with many generations. Indeed, there is now increasing evidence from field studies that some organisms can evolve rapidly in response to the strong directional selection pressures exerted by global change. For example, genetic adaptation to elevated temperature (Rodriguez-Trelles et al. 1998) and increased length of the growing season (Bradshaw and Holzapfel 2001) associated with global warming have been documented for certain insect species. The potential for genetic adaptation will be particularly important for host-parasite interactions, for which a changing climate could lead to temporal asynchrony between pest phenology and the availability of host tissue (Visser and Holleman 2001). In such cases, there will be a very strong selection pressure to maintain that close temporal synchrony (Dixon 2003).

17.2.3.3 *Modeling Tools*

Many modeling approaches have been applied to the assessment of risks from pests under global change because opportunities for large-scale experimentation are so limited. One group of models simulates the detailed population dynamics of species at a point scale. These tools have focused on software engineering to create modular and generic simulation models (Reynolds and Acock 1997; Sutherst et al. 2000). However, comprehensive, process-based models are inevitably complex and expensive to parameterise and so will be applicable only to the most intensively studied species or systems.

Simplified, inferential and dynamic simulation models (Sutherst and Maywald 1985; Sykes and Prentice 2004) can avoid the inherent problems of complex and over-parameterized models. They are also amenable to investigation of competitive interactions between species across geographical distributions. For example, in some cases where the CLIMEX model was used to project the potential range of a pest species in exotic habitats, strong evidence was found for biotic interactions truncating their ranges (Sutherst et al. 1985; Kriticos and Randall 2001; Wharton and Kriticos 2004). Inferential simulation tools that exploit the richness of spatial climatic data (Sutherst 1998) to infer the climatic responses that drive and limit species populations are highly informative, offering insights into the climatic factors that limit species distributions in different parts of their ranges (Yonow and Sutherst 1998; Kriticos et al. 2003a,b). Inference is less certain than deduction but complements mechanistic studies using traditional reductionist approaches. To date, models of combinations of species have only included species in additive form, such as the need for conditions to suit a weed and its biological control agent (Julien et al. 1995), crop tree and its arthropod pest (Wharton and Kriticos 2004), pathogen and host plants (Yonow et al. 2004), or both pathogen and vector in vector-borne disease transmission (Sutherst 2004). Recent progress has now included explicit species interactions within and between trophic levels (Sutherst et al. In press). This has allowed predation, competition and facilitation to be simulated on geographical scales. These advantages have been partially offset by the extra operational demands in estimating parameter values, a lack of probabilistic outputs, and difficulty in handling GCM climate change scenarios.

Another modeling approach consists of a heterogeneous collection of statistical, rule-based and simulation approaches with variations, such as neural networks (Berry et al. 2002) or genetic algorithms (Peterson et al. 2002), designed to predict potential changes in geographical distributions of species (Kriticos and Randall 2001; Scott et al. 2002; Cocu et al. 2005). Potential geographical distributions tend to be based on ecological (realized) rather than physiological (fundamental) niches and so involve assumptions about the extent of specific and non-specific biotic resistance. This is a pragmatic approach that demands caution in the selection of appropriate tools, in the ability to detect significant biotic interactions and in choice of predictive variables. It has been claimed that species distributions are usually limited by fewer than ten factors (Brown et al. 1996); thus the use of descriptive, pattern-matching of meteorological data to create 'climate envelopes' has become very popular (Sutherst 2003). Descriptive species distribution models often do not have predictive capability and need validation against independent geographical distributions before being used to predict effects of global change.

17.2.3.4 *Networks*

International, interdisciplinary collaboration is crucial in order to accelerate progress by creating synergy, capitalising on existing infrastructure and pooling data (Scherm et al. 1999). This involves activities such as the compilation and standardisation of input data sets and models, the development of metadata (information describing the data and data collection methods), as well as formal model comparison experiments to identify the appropriateness of specific models for global change assessments. The potato late blight disease simulation network established jointly by the IGBP Global Change and Terrestrial Ecosystems (GCTE) Programme and the Global Initiative for Late Blight (GILB) is an example of a formal research network designed to conduct such activities. The aim of this group is to develop an operational platform for simulating the effects of selected global change drivers on late blight intensity and potato yields on a global scale (Hijmans et al. 2000).

17.3 Impacts

Several examples of the effects of selected global change drivers on plant pests have been given in the previous section, and we now consider the evidence for changes in the impacts more systematically. Rather than repeating what has already been summarised and synthesised in previous comprehensive reviews (Teng et al. 1996; Sutherst et al. 1996; Coakley et al. 1999; Chakraborty et al. 2000b; Bale et al. 2002; Scherm and Coakley 2003), we focus on selected examples from the most recent literature. All the environmental changes considered here are global in nature, but their intensity may vary on a regional scale; thus, the degree of exposure of each pest system will vary with both the driver involved and with geographical location. In the absence of a unifying principle, the risks associated with each type of change need to be addressed on a pest-by-pest and location-by-location basis.

17.3.1 Atmospheric CO_2 and Climate

The widespread pattern of upward shifts in the freezing isotherm and retreat of glaciers in the tropics, changes in the geographical ranges of species at higher latitudes, earlier spring migration and breeding by birds, and earlier seasonal activity of insects have been cited as examples of impacts of gradual global warming (Root et al. 2003; Parmesan and Yohe 2003). These surveys provide strong evidence that the recent climatic changes have already affected up to 50% of the species examined in a survey of the literature.

There has been difficulty in attributing the relative magnitude of causal effects because factors other than climate are often involved and observations cannot easily be verified experimentally. We urgently need to establish baseline data on abundance and geographical distributions, benchmarks to assess their consistency with physiological processes, and monitoring data to track the changes (AtKisson 1999). In addition, the implications of the asymmetrical increases of temperature with global warming (Karl et al. 1993) for the ecology of species and species interactions need to be clarified. For example, increased cloud cover at night coupled with higher minimum temperatures could lead to reduced dew formation which, in turn, could lead to less favourable conditions for infection by foliar plant pathogens. As another example, plants are often limited by a lack of sufficient thermal accumulation or by extreme temperatures. There are several cardinal temperatures (Woodward 1987) below which specific sets of adaptations are required for survival (e.g., deciduous or coniferous leaves, thick bark, ability to adjust osmotic concentrations, etc.). As these climatic limits shift pole-ward in response to global warming, some plants will be able to migrate with them, applying increasing competitive pressure on species that presently occupy hitherto unsuitable habitat.

17.3.1.1 *Weeds*

Temperature drives the development of plants, changing their seasonal phenology and geographical distributions. Moisture affects survival and growth, while CO_2 acts as a fertilizer for plants when other nutrients are not limiting.

Ziska (2003b) reports on a recent comparison of six non-indigenous weed species in the continental United States in three levels of CO_2. They used concentrations roughly similar to those that existed at the beginning of the 20th century (284 μmol mol^{-1}), currently (380 μmol mol^{-1}), or are anticipated for the end of the 21st century (719 μmol mol^{-1}). Results indicate that there has already been a stimulation of growth of these species (average of 110% increase) and that there is likely to be a further increase by about 50% on average. This research is notable because the overall CO_2-induced growth associated with the increase of 285–382 µmol mol^{-1} was about three times greater than in earlier studies of other species. It also provides support for the hypothesis that many organisms have been evolving with the increase in CO_2 concentration.

CO_2 reduces water loss in plants as they close their stomata in response to higher concentrations (Körner et al. 2007, Chap. 2 ofthis volume). One consequence of the increase in water use efficiency may be the spread of woody weeds into lower rainfall zones (Farquhar 1997; Kriticos et al. 2003a; Kriticos et al. 2003b). We can expect changes in the balance of C_3 vs. C_4 plants, legumes vs. non-nitrogen fixing species, and woody plants vs. grasses to occur on a wide scale (Farquhar 1997; Gavazzi et al. 2000). Thus there is likely to be a shift in the importance of different weedy species. An increase in the frequency of extreme climatic events will alternately aid dispersal and establishment of woody weeds in the case of floods, and reduce productivity in the case of droughts. Rangeland habitats currently support extensive pastoral activities, and the cost of weed control typically exceeds the productive value of the land. The evidence for relative competitiveness of temperate C_3 crop species against their C_4 weeds is equivocal. Increased competitiveness due to increases in CO_2 may be offset by reduced competitiveness due to increased temperatures (Fuhrer 2003).

The invasion of ecosystems by weeds will also have important second-order effects such as the alteration of fire cycles (D'Antonio and Vitousek 1992) or soil nutrient conditions that can facilitate additional weed invasions (Ramakrishnan and Vitousek 1989). Plants can be constrained from spreading into cooler habitats either by insufficient thermal accumulation to grow and reproduce or by extreme low temperatures that cause stress or mortality by damaging tissues. If introduced beyond their thermal accumulation limits, perennial weeds can sometimes persist as 'sleeper' populations in marginally cold climates where they frequently fail to reproduce. There may also be microhabitats, e.g., with favourable combinations of altitude, slope, aspect and proximity to water bodies enabling founder populations to colonize very small areas from where they can expand as temperatures rise. Increasing temperatures are likely to shift heat-sum limits on tropical and sub-tropical weeds such as *Acacia nilotica* and *Cryptostegia grandiflora* toward the poles allowing them to invade areas that currently lack sufficient heat for them to reproduce (Kriticos et al. 2003a,b). Following climate warming, these established sleeper populations may form nascent foci for potentially rapid increase in abundance.

Assuming movement is possible, montane and alpine communities are likely to shift pole-ward as temperate species invade upward in altitude and the limits of minimum growing season length shift pole-ward (Fig. 17.1). Weeds will likely be able to disperse pole-ward across inhospitable habitats more effectively than other species with which they currently share habitat. These weed species typically have little reliance upon specialized pollinators, in addition to having effective dispersal methods (frequently human-mediated).

The focus on weeds has been in terrestrial ecosystems. Equally important, however, is the likelihood of climate change impacting pest species in aquatic ecosystems. Specifically, research in a marine ecosystem along the Dutch coastal zone shows that an increase in temperature of 4 °C results in increased harmful dinoflagellate and raphidophyte blooms (Peperzak 2003). It is likely that the rise in water temperature in fresh water bodies may also result in an increase in weedy species including numbers and growth of phytoplankton. Toxic algal blooms are likely to increase in frequency as a result. Additional research on biodiversity and the functioning of marine and freshwater ecosystems will be needed to protect valuable ecosystem services such as fisheries.

Recent research has shown enhanced growth of weed species that produce allergenic reactions, contact dermatitis, mechanical injury, or internal poisoning in elevated CO_2. Common ragweed (*Ambrosia artemisiifolia*) produces more pollen in elevated CO_2 (Ziska and Caufield 2000; Wayne et al. 2002; Ziska et al. 2003). Various weeds responsible for contact dermatitis, including stinging nettle, may also increase in vegetative biomass in increased CO_2 (Ziska 2003d), and nitrogen availability is unlikely to limit this response (Ziska 2003c). Ziska (2003a) also reviewed a number of plant species producing poisonous compounds (such as ricin from castor bean) and concluded that both laboratory and field studies indicate significant growth response to CO_2 and increased temperature. There is also the possibility that increased CO_2 and temperature reduce the effectiveness of herbicides, requiring an increase in frequency of application and concentration of herbicide to obtain adequate control (Ziska 2003a).

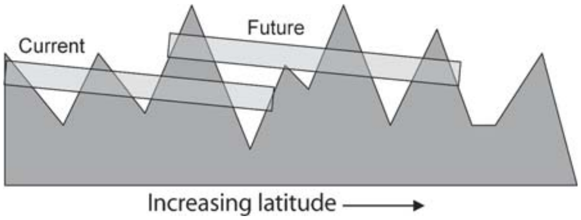

Fig. 17.1. Simplified schematic representation of the effects of a warming climate on alpine or montane vegetation (ignores topographic shading effects. The climatically suitable zone is represented by the lightly shaded parallelograms superimposed over a mountain range in the darker shading. A warmer climate will shift the suitable zone upward in altitude and toward higher latitudes. This may require dispersal across climatically unsuitable valley habitats. The climatically suitable zones are tilted to represent the compensating factors of decreased insolation at higher latitudes taking into account the effect of slope and aspect, and decreasing temperatures with increased altitude due to the adiabatic lapse rate

17.3.1.2 *Arthropods*

As described earlier, aphids are expected to be particularly responsive to climate change because of their low developmental threshold temperature, short generation time and dispersal abilities. They are key pests of agriculture, horticulture and forestry throughout the world, but especially in temperate regions. A long-term monitoring system for aphids (Woiwod and Harrington 1994) has demonstrated advances in aphid phenology that are compatible with the expectation of climate change (Fleming and Tatchell 1995). Correlations between phenology and temperature are strongest for species which pass the winter in the active stages rather than as eggs (Harrington et al. 1990; Harrington et al. 1995), presumably because, although the active stages are far less tolerant of low temperature, they are better able to take advantage of warm winters for development and population build-up.

The aphid monitoring network is now co-ordinated throughout Europe (Harrington et al. 2004). Analyses using the pan-European network and involving 29 pest aphid species suggest that under the Hadley Centre climate change scenario A1FI (Nakicenovic et al. 2000), the phenology of these species will advance on average by 8 days over the next 50 years (Harrington et al. in press). How this affects the status of aphids as pests will depend partly on the extent to which crop phenology advances in parallel with pest phenology. Indications so far are that sowing or planting dates of spring crops in Europe are not advancing because they are more dependent on rainfall than temperature. Winter rainfall is expected to increase in Europe, especially in northern regions.

Due to the inability of trees to disperse rapidly, forests are particularly prone to long-term disturbances caused by herbivores or from pathogens vectored by arthropods. Ayres and Lombardero (2000) reviewed the effects of climate change on forest distribution and health. They point out that there may be feedbacks to climate change due to impacts on water and carbon flux in forest ecosystems that are heavily damaged by herbivores or pathogens. In addition, insect or disease outbreaks in boreal forests could increase the number of forest fires that would further exacerbate climate change. Any major forest disturbance may impact biodiversity, water quality, property value, recreation, and the forest industry in general.

Hódar et al. (2002) and Hódar and Zamora (2004) report evidence that the pine processionary caterpillar (*Thaumetopoea pityocampa*) is increasingly attacking relict population of Scots pine (*Pinus sylvestris nevadensis*) that existed where winter conditions previously were unfavourable for survival and feeding of this pest. Given that this pine has poor regeneration ability, human intervention may be necessary to prevent its elimination from the Mediterranean region. Moving the pine into higher altitudes could provide insurance against losses.

17.3.1.3 *Plant Pathogens*

Long-term time-series data for plant pathogens are rare, owing primarily to the difficulties in monitoring and identifying these microscopic organisms. In cases where such data sets do exist (e.g., the time-series on wheat stem rust mentioned above), changes in management practices that have occurred over the years tend to override climate-related trends. Coordinated efforts are therefore needed to initiate standardized long-term monitoring programmes for pathogens in unmanaged ecosystems in which the confounding effect of anthropogenic disease management is minimized (Scherm and Coakley 2003).

The incidence of the aphid-borne *Barley yellow dwarf virus* (BYDV) in the UK has risen in recent years with the increase in the frequency of mild winters which permit aphid survival, movement and hence virus transmission (Harrington 2003). Problems from BYDV in the UK are likely to become more severe due to (1) changes in cropping patterns (in particular increase in the area of maize); (2) increased survival of a vector species, *Rhopalosiphum maidis*, that prefers maize and requires warm winters; (3) increased prevalence of a BYDV strain transmitted efficiently by this vector species; and (4) increased efficiency of transmission of this and other strains of BVDV in all cereals at higher temperatures. The incidence of the virus is expected to increase most in the west of the UK where milder winters are expected to be accompanied by wetter summers than will occur in the east. Both of these factors aid aphid survival.

Another example of the spread of a vector-borne disease comes from Japan, where an increase in epidemics of oak dieback in the past 10 years appears to be associated with the movement of the insect vector into more northern latitudes and higher altitudes as a result of a warmer climate. The symbiotic ambrosia fungus *Raffaelea* sp., vectored by the ambrosia beetle *Platypus quercivorus*, is implicated in the dieback (Kamata et al. 2002). With the expansion of its range, the vector has encountered *Quercus crispula*, an oak species that did not co-evolve with the fungus. This has led to a mortality of about 40% of the oaks each year. The pattern is consistent with the hypothesis that absence of regulating factors (e.g., natural enemies) in the newly invaded area allows outbreaks to occur for an extended time. The pattern is consistent with the enemy release hypothesis (Colautti et al. 2004).

Apart from being the cause of severe epidemics, introductions of non-indigenous plant pathogens can be problematical as they may enable the rapid evolution of novel plant pathogens via interspecific hybridization when the introduction occurs in areas where related but allopatric species are already present. Such new pathogen hybrids can have a wider host range and behave more aggressively than the two parent species (Brasier 2001). Thus, when one considers the movement of pathogens and their hosts into new geographic regions, one needs to be alert not only to a potential increase in disease severity, but also to the types of pathogens that may occur.

17.3.1.4 *Integrated Impact Assessments*

Integration of impact assessments remains a challenge in global change science and involves a number of different dimensions. Within a crop, growth and yield responses need to be linked with changes in the incidence and severity of pests. A spatial dimension then needs to be added to enable extrapolation to assess regional or industry-wide impacts. Such studies invariably require both environmental and socio-economic measures of impacts.

Since previous syntheses (Teng et al. 1996; Gregory et al. 1999; Sutherst et al. 2000) there has been limited progress in integrating host and pest models with socio-economic models to investigate impacts on regional or industry-wide scales, particularly for plant pathogens and weeds. The following section will therefore focus on recent integrated assessments involving vertebrate and insects pests.

Rats and Plant Hoppers in Rice

In 1998, participants from seven countries were introduced to global change issues in a workshop under the auspices of the Biotrop-GCTE/Impacts Centre for South-East Asia (IC-SEA) (Sutherst et al. 1999). The effects of two key pests on rice yields, the rice field rat (*Rattus argentiventer*) and the brown plant hopper (*Nilaparvata lugens*) in the presence of a coccinellid predator were examined. Participants collaborated to build CLIMEX models for each species and an integrated DYMEX 'RatHopper' crop-pest population model to investigate likely changes in the population dynamics of the species and to explore long-term adaptation options. The CLIMEX model indicated a shift in the potential geographical distribution of the rat as the environment became too hot. Use of the RatHopper model showed the importance of fallow in reducing pest numbers and revealed a danger in trying to increase total yields by inserting another crop cycle each year.

Queensland Fruit Fly

The Queensland fruit fly, *Bactrocera tryoni*, is one of the most important pests of horticulture in Australia. It is excluded from a large area of south-eastern Australia by quarantine restrictions and treatments of local outbreaks. There is concern about the impact of global warming on its potential geographical distribution and resultant regional and industry consequences. The Murrumbidgee Irrigation Area is an important source of citrus exports that requires freedom from endemic fruit fly infestation to meet market specifications. An analysis of the potential risks to the horticultural industries in the region raised doubts about the long-term viability of the current containment program as the pressure from higher fruit fly populations and demographic performance increases at higher temperatures (Sutherst et al. 2000).

17.3.2 Land Use, Land Cover and Biodiversity

Global climate change may increase the rate of loss of ecosystem diversity (Hartley and Jones 2003). With a change of diversity of organisms at one trophic level, it is likely that there will be a resultant change at the next level. Two experimental systems (a long-term field study on heather moorlands and an Ecotron controlled-environment experiment) were used to determine whether plant species richness influences insect herbivores (Hartley et al. 2003). Despite the different scales and different ecological communities, the two systems showed certain similarities in response to environmental change. Site was more important than grazing regime in affecting the number of species that occurred in an insect herbivore community, and there were interaction-specific effects of environmental change, which varied with the specific plant and its insect herbivores as well as with the site. To complicate matters further, indirect factors, including below-ground processes, may ultimately impact on a particular insect-plant interaction in addition to the more obvious above-ground factors.

Disturbances resulting from climate change are apt to exert pressure on ecosystems and result in stresses on the organisms within them. For example, the analysis of aspen tree rings shows that there has been an impact of climate change that is likely to have been related to stresses including attacks by insects and pathogens. As with most crops, simulation models for growth in the net primary productivity of such forests do not currently include the potential impact of pests (Hogg et al. 2002).

17.3.3 Trade and Travel

Between 1940 and 1970, fewer than five non-indigenous plant pathogen species entered the United States per decade but that rate more than tripled during the 1990s. Simultaneously, the import value of floriculture and nursery products into the United States increased more than 17-fold between 1976 and 2000 (USDA-ERS 2002). Most of the recent plant pathogen introductions have been documented or are strongly suspected to have been associated with plant material (Scherm and Coakley 2003). This is a global phenomenon, tapping into new species pools as trade expands to new areas, e.g., eastern Asia (Levine and D'Antonio 2003).

17.4 Adaptation

The IPCC has developed general guidelines for the design of adaptation measures to climate change, and these are applicable to other drivers of environmental change. Responses can be either *autonomous* (part of everyday business) or planned (requiring a new policy) (IPCC 2001b). Adaptive measures have also been classified as behavioral, engineering or administrative/legislative (Parry and Livermore 1999).

Adaptation measures rely on application of innovative approaches or products to prevent or control pests in a changing environment. The attributes of management tools that make them more likely to be available for adaptation to global change in the decades ahead are evaluated against specific objectives using criteria such as effectiveness and constraints (Parry and Carter 1998) or sustainability and robustness (Sutherst et al. 1998). Their performance needs to comply with the concept of 'triple bottom-line' accounting, i.e., social and environmental considerations need to be included in addition to economic values.

Ideally, responses to changes in pest incidence and severity under global change would be proactive rather than reactive. Unfortunately, the Earth's climate system is so complex and non-linear that we can never be sufficiently confident of predicting climate change to avoid surprises. Examples of so-called climate flip-flops (Calvin 1998), changes in regional rainfall (Hennessy et al. 1999) and temporal variation in the correlation of the Southern Oscillation Index (SOI) with tropical rainfall (Cai et al. 2001) illustrate the extent of the uncertainties. Rather than only designing adaptation responses strategically and well ahead of time, there is an additional need to respond quickly to unanticipated environmental changes. This calls for managers to be 'nimble' and respond rapidly to changes as they occur. Such a capability will have to be based on a thorough understanding of the ecology of the target pest or community of species in an ecosystem at each location. The most likely pathway to developing such a capacity is to adopt a knowledge-based, rather than a product-based, approach to pest management (Lewis et al. 1997) with sophisticated decision support systems for our major agricultural enterprises.

17.4.1 Natural Adaptations

Species rely on dispersal, phenotypic plasticity and genetic selection to respond to environmental change. In human-dominated landscapes, pests tend to disperse and be moved by humans more effectively than many less numerous species and so are less likely to be constrained from moving to track changing climates than rarer or more sessile species. Phenotypic plasticity is an important strategy for coping with a variable environment, such as the timing of onset of low temperatures in autumn (Taylor and Spalding 1989). If ecological responses are insufficiently plastic or are too slow to keep pace with the rate of environmental change, there is the potential for micro-evolutionary adaptations that are better able to exploit the new conditions. This has been documented for plants (Geber and Dawson 1993), a plant-associated mosquito (Bradshaw and Holzapfel 2001), and *Drosophila* (Rodriguez-Trelles et al. 1998). In addition, as species move with climate change they may be exposed to a new set of abiotic factors (e.g., soils and topography), as well as a modified community of competitors and predators, which will also exert new selection pressures.

17.4.2 Adaptive Management Options

Without foresight into future technologies, we can only assess the suitability of currently available practices. However, technologies, including those used in agriculture and ecosystem management, are rapidly evolving (Giampietro et al. 1999) and are not predictable. This is a major limitation, as it requires the attributes of existing and new technology to be extrapolated into the uncertain physical and biological environments of the future. While global climate models are able to generate scenarios of climate change, they can not yet be used to make predictions.

Legislative

Legislative or administrative options to adapt to environmental change include strengthening of barriers to entry of non-indigenous species, improved detection procedures for incursions, monitoring of pest abundance and geographical distribution (Baker et al. 2000), as well as enhanced knowledge-management using a hierarchy of information technologies such as expert systems, simulation models, remote sensing and GIS (Sutherst et al. 1996).

Engineering and Behavioral

Preventative measures based on environmental management are robust but depend on ongoing management inputs, which are easily downgraded in times of economic stringency. Selecting for plant species that are tolerant of drought and resistant to pests could be considered 'engineering' to the degree that biotechnology is used for genetic modification. Classic tools of breeding will also be needed to ensure plant and animal adaptability to climate change. Based on the results of an assessment of the effects of future climate change on sugar beet production in Europe, efforts are being made to incorporate appropriate disease tolerance into species that will be used increasingly in northern parts of the growing range (Jones et al. 2003).

Effective responses to ongoing or accelerating invasions by non-indigenous species require a multi-pronged approach that addresses sources, pathways and destinations of potential pests (Baker et al. 2000). The chances of such species leaving their source area can be reduced by attacking the pest populations using biological control agents at their source (Sands et al. 1993), or by strengthening inspection procedures to prevent them from entering the pathway to other countries. Prevention of international trade in horticultural plants with potentially weedy or insect-harbouring attributes (Lok 2001) necessitates a greater understanding by industry. As part of the Montreal process (http://www.mpci.org), the temperate and boreal forestry sector has adopted sustainability protocols that include features such as reductions in pesticide use. This has seen an attitudinal change to pests as well as an interest in issues such as crop species becoming weeds (e.g., wilding pines) and managed forests as sources of weed invasions into adjacent areas.

Biological control using natural enemies can be valuable in adapting to new invasions or threats. Restoration of habitats around agricultural fields can rectify the loss of natural vegetation which shelters generalist predators. Some predators have low mobility and so do not find their way into fields fast enough after each new crop to provide useful contributions to pest management. Provision of artificial shelters for generalist predators can be a useful technique for managing pests in field crops (Halaj et al. 2000).

To address the potential impacts of woody weeds on rangelands effective quarantine procedures need to be implemented to prevent weed spread, establish education programmes to assist in the early detection of new invaders, and develop more effective biological control programmes aimed at vulnerable life-stages of the weeds (Kriticos et al. 1999). Biologically-based adaptation measures have the desirable characteristic of low implementation costs per unit area.

17.4.3 Adaptation of Control Measures in Response to Global Change

Following the processes developed for increasing the sustainability of cities (AtKisson 1999) we need to address three issues in relation to adaptation:

1. Indicators of change are required in order to track pest movements and feed information back to inform the decision-making process. We have addressed this issue in relation to measuring and monitoring impacts.
2. Steps need to be taken to accelerate development and strengthen guidance of the use of new technologies and approaches to pest management. This will include knowledge-based decision support systems that measure outcomes in terms of the 'triple-bottom-line' of environmental, economic and social benefits.
3. Processes have to be implemented to accelerate the adoption of new approaches because global change is accelerating and society needs to fast-track adaptive management responses if it is to keep pace with the changes.

The ever-present risk of researchers finding solutions in isolation from those who are expected to adopt the technology can be averted by pooling the efforts of scientists, policy-makers, managers, advisers, teachers and students to develop adaptation strategies jointly. The use of modular simulation modeling networks as a vehicle for facilitating such activities has been encouraging in both developed and developing countries (Sutherst et al. 2000). It can form the basis of measures to inform the community and ensure its involvement in and ownership of adaptive measures, leading to accelerated adoption. Scenario-planning is another useful tool for generating and evaluating options to enhance sustainability (Schoute et al. 1995). This approach is easier for groups with no formal technical training to follow (Sutherst et al. 1999).

17.4.4 Threats to Sustainability of Adaptation Options

Pesticide Resistance

Synthetic pesticides are used widely to reduce damage to agriculture, and there has been a long history of development of resistant strains of arthropods, plant pathogens and weeds. Loss of susceptibility of pests to pesticides has the potential to reduce the capacity of communities to adapt to global change.

Entomologists concerned with protection of crops (Georghiou 1994) or livestock (Sutherst and Comins 1979) pioneered the development of resistance management strategies, and such strategies are now used widely in all disciplines dealing with pest management (Russell 1999; Vaughn 2003). Sutherst and Comins (1979) used the terms '*saturation*' and '*moderation*' to describe strategies aimed at either intensive control or less aggressive measures designed to reduce selection pressures. Pesticide resistance needs to be managed by avoiding a high-risk 'magic bullet' (*saturation*) approach and adopting multi-pronged measures (*moderation*).

Human Safety and Non-Target Effects

The widespread use of pesticides has had detrimental effects on both humans and animals. The early effects of

DDT on bird life are well known but the replacement chemicals were also associated with significant risks (Marco et al. 1987). Very low concentrations of some agricultural chemicals can mimic the activity of estrogen and thyroid hormones in humans and animals (Colborn et al. 1996). They are referred to as 'endocrine disrupting chemicals' and include organochlorine pesticides and some synthetic pyrethroids and herbicides (Krimsky 2000). Their disruptive effects threaten their availability for adaptation to global change. In the United States, all registered pesticides are under review under the Food Quality Protection Act (Ragsdale 2000) with an initial focus on active ingredients that have high mammalian toxicity, pose a threat to ground water resources, or have shown carcinogenic or teratogenic effects in laboratory animals.

17.5 Vulnerability

The vulnerability of affected natural and managed ecosystems to pests is assessed by combining impacts and adaptation with the adaptive capacity of the affected ecosystem. Regions or industry sectors vulnerable to pests under global change will be those that are unprepared or do not have suitable options to respond to major changes in pest status. Such changes are more likely to occur in regions adjoining endemic areas, where they rely on freedom from infestation for market access. An example is the Murrumbidgee Irrigation Area in south-eastern Australia where the citrus industry is focused on exports but has an ongoing problem with exclusion of the Queensland fruit fly. Under climate change, pest pressure is likely to increase in the temperature-limiting region, making eradication of incursions more difficult (Sutherst et al. 2000).

Tropical rangelands, where invasions with leguminous woody weeds are expected to occur with rising temperatures and concentrations of CO_2, are located mostly in less-developed countries. As such weeds spread into semi-arid rangelands, the low economic value of these lands limits human capacity to undertake adaptation measures. Economic options are restricted to biological control and in some situations, hygiene measures to stop the spread of seed by livestock. As biological control options are often limited by fear of non-target damage (Thomas and Willis 1998; Brimnen and Boland 2003) and by an apparent shortage of suitable agents, there are few options available. The problem is magnified by resource shortages and the absence of government control over animal movements in many developing countries. Indeed, all industry and public health sectors in developing countries are vulnerable to increases in impacts because they do not have the resources or infrastructure to respond effectively.

17.6 Summary and Conclusions

Pests have major effects on both natural and managed ecosystems. Their impacts are expanding as more species are spread around the world and often become an irreversible extra burden on the affected systems. Environmental change creates disturbances and the many pest species involved ensure that there will be some species available to exploit opportunities arising from disruption of native communities or vacant niches. Climatic volatility is a concern and recent predictions of the increasing frequency and intensity of extreme events demand greater attention. Environmental change results in shifts in species' geographical ranges, seasonal phenology, host preferences, population densities and population genetics. To date, results from limited experimental studies have shown a wide range of negative and positive responses by different species to the same environmental changes. This limits our ability to make generalizations about likely responses to global change. The problem is compounded by interactions between species in the same or different trophic levels in communities.

The resources necessary to enable researchers to provide managers with the information needed to adapt to global change include: baseline data on driving variables, indicators of change, strategies and tools to analyze problems and design adaptive management responses, and information delivery systems to accelerate adoption of new technologies or approaches to keep pace with the accelerating rate of change. Among the available management options, biological approaches based on either host resistance or natural enemies tend to be more robust because they have built-in flexibility and, in the most successful cases, avoid the need for extra contributions by human management, which is so often the weakest link.

There is a conundrum where strategic decisions on adaptation need to be made, but they require a sound understanding of the environmental, social and economic consequences. We support evidence-based policy and yet we acknowledge the great uncertainties associated with both the scenarios of environmental change and the responses of ecological systems to these changes. Further, we recommend *nimbleness* in adaptive management responses in order to respond to unexpected changes, and yet that relies on having sufficient understanding of the systems involved to make sound decisions. The two long-standing questions 'How much knowledge is enough?' and 'Is that knowledge attainable given the complexities of natural systems?' still have not been resolved.

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