CLIMATE-RELATED TRANSBOUNDARY PESTS AND DISEASES

TECHNICAL BACKGROUND DOCUMENT

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CLIMATE CHANGE AND PEST DISEASES

The movement of plant pests, animal diseases and invasive alien aquatic organisms across physical and political boundaries threatens food security and creates a global public concern across all countries and all regions. Countries allocate large resources to limit the spread and control of transboundary pests and diseases[1] such as avian influenza, foot-and-mouth disease and locust. They also adapt animal and plant health services and activities and cooperate regionally and globally for prevention, early warning and control.

There is clear evidence that climate change is altering the distribution, incidence and intensity of animal and plant pests and diseases such as Bluetongue, a sheep disease that is moving north into more temperate zones of Europe. Cannon (see Annex 1) found examples of plant pests whose distribution is shifting in the United Kingdom and other parts of Europe, most likely due to climatic factors. For example, migrant moths of the Old World bollworm (*Helicoverpa armigera)* had a phenomenal increase in the United Kingdom from 1969-2004 and there have been outbreaks at the northern edge of its range in Europe; cottony cushion scale (*Icerya purchasi)* populations appear to be spreading northwards perhaps as a consequence of global warming; and cottony camellia scale (*Pulvinaria – Chloropulvinaria – floccifera)* has become much more common in the United Kingdom, extending its range northwards in England and increasing its host range in the last decade or so, which is almost certainly in response to climate change. In Sweden this species was previously only known as a greenhouse species, but is now established as an outdoor species. The range of the oak processionary moth (*Thaumetopoea processionea)* has extended northward from central and southern Europe into Belgium, Netherlands and Denmark.

Evans (see Annex 2) found that the oak processionary moth's northward progression was due to improved synchrony of egg hatch and reduction of late frosts. He also found that the massive population buildup of mountain pine beetle (*Dendroctonus ponderosae)* and its northward progression in the North American Pacific Northwest has most likely been due to a combination of warmer winter temperatures, reduced episodes of underbark mortality and increased drought which weakened the trees. Kiratani (2007)[2] reported on the polar extension of several plant pests in Japan over the period 1965 to 2000. Yukawa has found that about 40 of the 250 butterfly species in Japan have exhibited northward range extensions in recent years (see Annex 3). A particular case study reported by Yukawa showed that *Nezara viridula*, a tropical and subtropical crop pest, is gradually moving northward in

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[1] Transboundary animal and plant pest and diseases and relevant aquatic species refer to organisms that spread across national or geographical (physical) boundaries, indicating that disease or pest events in one country may have direct effects or potential effects in another country).

Transboundary Animal Diseases (TADs) may be defined as those epidemic diseases that are highly contagious or transmissible and have the potential for very rapid spread, irrespective of national borders, and can have serious socio-economic and public health consequences (OIE, FAO).

Transboundary plant pests refer to quarantine pests. These include pests of potential economic importance to the area endangered, even if they are not yet present, pests that are present but not widely distributed and officially controlled, and migratory pests, in particular locusts, which have the ability to change from individual to collective behaviour in swarms that easily cross boundaries.

For aquatic species, the term primarily refers to invasive alien aquatic species.

[2] Kiritani, K. 2007. The impact of global warming and land-use change on the pest status of rice and fruit bugs (Heteropthera) in Japan. Global Change, 13, 1586-1595.

southwestern Japan, possibly due to global warming, replacing the more temperate species *Nezara antennata*.

Major drivers for the spread of transboundary animal and plant pests and diseases and alien invasive aquatic species are international trade and traffic (except for migratory pests). Animal and plant pest and diseases are not evenly distributed over the globe, often because they are limited by physical barriers such as mountains, seas and deserts. The increase in movement of people, animals, plants, goods and conveyances has accelerated the redistribution of animal and plant pests and diseases and alien invasive aquatic species and climate change will create new ecological niches allowing for the establishment and spread of pests and diseases into new geographical areas and from one region to another. This expansion will continue to result in huge financial losses and require large eradication programmes and control measures. Among the major occurrences are foot-and-mouth disease in Northern Europe and South America, classical swine fever in Europe, Rift Valley fever in Africa, and the spread of coffee leaf rust throughout the world, soybean rust into the Americas, and citrus tristeza virus in South and Central America and now in the Mediterranean.

In addition, unforeseen emergence of “new” diseases and pests has been relatively common. New vectors, selection and recombination of disease genotypes may occur when animal species and breeds and plant species and varieties mix or when insect pests and vectors are introduced without their natural enemies. Change in climate resulting in changes in species composition and interactions will augment the emergence of unexpected events, including the emergence of new diseases and pests.

Climate change will especially impact vector-borne animal diseases due to the effects of climate change on the arthropod vectors and macro-parasites of animals due to the climate effects on the free stages of these parasites. Climate change may also result in new transmission modalities and different host species. Although developing countries are already subject to an enormous animal disease burden, both developing and developed countries will be subject to increased incidence or newly emerging diseases that are difficult to predict. Temperate countries will be particularly vulnerable to invasions by exotic arthropod-borne virus diseases and macroparasites.

Diseases caused by arthropod-borne viruses (arboviruses) include a large number of arthropod vector-borne (mosquitoes, midges, ticks, fleas, sand flies, etc.) that are often zoonotic, predominantly RNA viruses, that can cause hemorrhagic fevers or encephalitis in humans. They mostly spill over from natural reservoirs such as bats, birds, and rodents or other wild mammals. Emerging arbovirus disease complexes (particularly those in evolutionary flux) are by far the most important (climate change is only one factor altering disease ecologies). This group includes dozens of relevant disease complexes, which may be broken down into at least half a dozen subgroups, of which a number are chiefly animal diseases, others are of mixed animal and public health concern, while a third consists of mainly human diseases with an animal health dimension.

Animal disease distribution that will be strongly influenced by climate change includes bluetongue and Rift Valley fever as well as tick-borne diseases. In Europe, bluetongue is now transmitted by autochthonous temperate midge vectors. Rift Valley fever is a mosquito-borne animal and human disease with climate-influenced vectors. The effects of climate change on internal parasites (gastro-intestinal parasites and liver fluke) may include changes in the distribution of the parasites and the intermediate hosts. In areas that become wetter, these will become of greater importance.

Thornton (see Annex 4) also noted that the changes wrought by climate change on livestock infectious disease burdens may be extremely complex. Apart from the effects on pathogens, hosts, vectors and epidemiology, there may be other indirect effects on the abundance or distribution of the vectors' competitors, predators and parasites. For example, in the pastoral areas of East Africa, drier conditions may mean fewer water points and thus more intense interactions between livestock and wildlife.

While drivers of plant pest change include increases in temperature, variability in rainfall intensity and distribution, change in seasonality, drought, CO_2 concentration in the atmosphere and extreme events (e.g. hurricanes, storms), intrinsic pest characteristics (e.g. diapause, number of generations, minimum, maximum and optimum growth temperature of fungi, interaction with the host) and intrinsic ecosystem characteristics (e.g. monoculture, biodiversity) also affect change. Emerging pests are often plant pests of related species known as "new encounter" pests, which come into contact with new hosts that do not necessarily have an appropriate level of resistance, or are plant pests introduced without their biological control agents (in particular, insect pests, nematodes and weeds).

For example, the expansion of maize production driven by climate change will make more areas vulnerable to entry, establishment and spread of the corn root worm *(Diabrotica)*. The range of tephritid fruit flies will alter considerably with climate change with corresponding changes in phytosanitary regulations and international trade opportunities. Mountain pine beetle (*Dendroctonus ponderosae*), a pest of North American forests, is expected to decrease in generation time and winter mortality, which will increase the risk of range extension into vulnerable ecosystems. Conversely, some pests will be less damaging because climate suitability will decrease and through interactions with natural enemies and plant defences (see Cannon, Duveiller, Evans, Yukawa, Hendrichs, in Annexes 1, 5, 2, 3, 6).

Migratory plant pests, in particular locusts, are totally dependent on rain, temperature and vegetation and their habitats change rapidly. The desert locust *(Schistocerca gregaria)*, like other locusts, can change its behaviour and physiology from solitary grasshoppers to gregarious stages that form swarms. Solitary desert locusts occur at low density in the recession area, which covers North Africa, the Sahel, the Red Sea countries and parts of India, Pakistan, Iran and Afghanistan. The outbreak area reaches from Mauritania to India and from southern Europe to Cameroon and Tanzania. Outbreaks and plagues originate in the recession areas when there are several cycles of good breeding conditions. Although the effects of climate change on this system are difficult to judge, climate scenarios with more winter rain in the Sahel may provide better breeding conditions.

Aquatic animals are very vulnerable as water is their life-support medium and their ecosystems are fragile. Hine (see Annex 7) found a number of fish diseases that may be susceptible to climate change. Temperature and rainfall are critical ecological factors for epizootic ulcerative syndrome (EUS), a fungal disease of cultured and wild fish in fresh and brackish water that affects more than 60 host species, which recently expanded its distribution to southern Africa. *Perkinsus olseni*, a major mollusk pathogen, affects more than 100 host species and is also temperature dependant. Red tides (harmful algal blooms), influenced by climate change, are being spread into new locations by ships' ballast water.

Contributors to transboundary pests and diseases

Factors that affect the entry, establishment and spread of animal and plant pests and diseases and invasive alien aquatic species include:

- globalization,
- human population growth,
- ecosystem diversity, function and resilience,
- industrial and agricultural chemical pollution,
- land use, water storage and irrigation,
- atmospheric composition, CO_2 and oceanic acidification by carbonic acid,
- species interactions with hosts, predators and competitors, and
- trade and human movements.

These factors are not independent of each other and climate change interacts with each of them.

In terms of vulnerability and risk analysis, Sutherst (see Annex 8) found that production of crops, livestock and aquatic animals will vary according to their exposure to climatic hazards, such as droughts, floods, extreme temperatures, oceanic acidification and sea level rise. The *sensitivity* of each production system to those hazards will depend on the crop varieties, pest and disease species involved and their geographical locations. Response options will be determined by the local biodiversity which can act as a regulator of the pest population by varying degrees.

There is a need for a better impact assessment of climate change on animal and plant pests and diseases and invasive alien aquatic species. In the Fourth Assessment Report of the IPCC[3] these risks are insufficiently addressed.

Methods exist for risk analysis. However, the application of methods within the context of climate change to assess risks of entry, establishment and spread of threats is resource intensive and requires a large extensive and reliable data. These risk analyses will have to be re-evaluated and updated as climate continues to change. Considerations of cost effectiveness and limits to resources demand that approaches to risk analysis exploit minimum data sets and generic modeling tools to answer questions related to numerous pest species on a global scale.

Cost effectiveness and availability of resources will determine the depth of the analysis, through a hierarchy of expert opinion, rule-based assessments, analogous climates, species-specific climate envelopes, process-based simulation models, and crop-pest models linked to macro-economic analyses of the vulnerability of industries or regions. In view of the large number of animal and plant diseases and pests and the large number of potential invasive aquatic species, it is clear that, in most cases, detailed risk assessment is unlikely to occur, especially since invasive species ecology is in its infancy. Nevertheless, in principle, it is possible to estimate the area that is climatically receptive to a species, with the usual caveats on genetic homogeneity, biotic interactions at both the source and destinations, and human-modified microhabitats, such as irrigated crops.

[3] IPCC, 2007: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E.Hanson, Eds., Cambridge University Press, Cambridge, UK, 976 pp.

To understand the contribution of climate change to outbreaks, there is a need to: i) establish benchmarks of current biosecurity status and impacts and costs of biosecurity; and ii) monitor indicators of change in biosecurity in relation to rates of invasions by foreign species, rates of crop, livestock, forest and fish losses, and changes in costs of biosecurity. However, the costs associated with such may be prohibitive.

Impact on Food Security

Food security is defined as "When all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life" (World Food Summit, 1996). Components of food security are food availability, food access, food utilization and food stability.

Availability of food. Animal and plant pests and diseases and alien invasive aquatic species reduce the availability of quantities of food of appropriate quality, whether supplied through domestic production or imports. Overall quantifications of losses and potential losses due to animal and plant pests and diseases and alien invasive aquatic species are limited. Entry and establishment, emergence and outbreaks of animal and plant pests and diseases have historically resulted in major food problems either directly through yield reductions of food crops and losses in animal production, or indirectly through yield reduction of cash crops (e.g. rinderpest, potato blight, locusts). Climate change will result in a higher volatility and, therefore, is likely to cause additional crises in local agricultural production, in particular for small farmers and those involved in subsistence agriculture and aquaculture with different consequences for socio-economic groups and genders.

Access to food. Plant and animal pest and disease regulations are designed to facilitate trade while reducing the risk of international movement of restricted organisms whose introduction could require expensive eradication or control operations. Animal and plant pests and diseases and alien invasive aquatic species reduce food access through reduction of income from animal production, reduction of yields of food and cash crops, reduction in forest productivity, changes in aquatic populations as well as increased costs of control. Indirect effects are reduced access to international markets due to the occurrence of quarantine for animal diseases or plant pests.

Utilization of food. Food utilization in relation to animal and plant diseases and pests, chiefly concerns food safety. Climate change may result in food-borne zoonoses and increased use of veterinary drugs, while redistribution of plant pests and changes in pest incidence and intensity may result in additional and inappropriate pesticide use. New aquaculture diseases also could result in increased pesticide use. Consequently, there may be higher and even unacceptable levels of pesticide and veterinary drugs in food. Mycotoxins in food are a growing problem. Changes in rainfall, temperature and relative humidity may favour the growth of fungi that produce mycotoxins and thus may make food such as groundnuts, wheat, maize, rice and coffee unsuitable for human and animal consumption.

Stability of food. To be food secure, populations, households or individuals must have access to adequate food at all times. They should not risk losing access to food as a consequence of sudden shocks such as economic or climatic crises or cyclical events such as seasonal food insecurity. The concept of stability refers to both the availability and access dimensions of food security. Introduction or emergence of new animal and plant pests and diseases, and plagues of migratory pests may have substantial effects on the stability of food supply through direct losses as well as through the reduction of income and will also influence the stability of the production system.

Possible technical and policy responses: national, regional and international

Climate change will result in a higher probability of entry, establishment and spread of vector-borne diseases of animals, parasites of animals with free-living life stages, and pests of plants, diseases of fish and invasive alien aquatic species for the following reasons:.

- Climate change will create winners and losers. For some animal and plant pests and diseases and invasive alien aquatic species, the climate will become more conducive and for others the meteorological conditions will become less favourable. This will result in unstable situations with a high probability of entry and establishment in areas that are presently protected by unsuitable conditions.
- Meteorological and related environmental circumstances may change the geographical distribution of host species, putting them in contact with animal and plant pests and diseases of related hosts to which they do not possess resistance.
- New animal and plant pests and diseases may emerge due to evolving selection and adaptation to new situations.

Data for projecting risk. Projections of future distribution, severity and incidence can be made for animal and plant pests and diseases that are presently of quarantine significance, using various risk analysis methods and tools. However, the combination of climate change, new environments and new ecological conditions and limited data that pertain to these situations make the assessments of future situations less reliable. Emergence of animal and plant pests and diseases and invasive alien aquatic species rarely can be foreseen, and lack of reliable data will make projections of the potential spread of such animal and plant pests and diseases and invasive alien aquatic species highly unreliable. Changes in rainfall, very complex to foresee, will have a major impact on outbreak and plague patterns of migratory plant pest species, in particular on locust species which are totally dependent on moisture and temperature.

Early warning and prevention strategies. The strategy to address transboundary animal and plant pests and diseases and alien invasive aquatic species is prevention, early warning including forecast, early detection, early control and research. Investments in early control and detection mechanisms will be critical, to avoid higher costs of eradication and control. Prevention and early warning requires a reduction of the possibilities of entry and establishment and can be accomplished through better border control and rapid diagnostic tools for better surveillance of animal and plant pests and diseases and invasive alien aquatic species. To be successful, surveillance systems require monitoring and input from farmers as well as government services. Prevention and early warning also requires cooperation of countries within the same geographic/eco-climatic region to ensure better monitoring of animal and plant health in the region. FAO's Emergency Prevention System for Transboundary Animal and Plant Pests and Diseases (EMPRES) provides support to governments in all of these areas.

Eradication, containment, impact reduction. Once animal and plant pests and diseases and invasive alien aquatic species establish, an immediate decision is required on follow-up action. Where possible and economically feasible, eradication and containment should start as early as possible. Countries need appropriate emergency capacity to take action as well as regional infrastructures that can support and coordinate action among countries. Joint action of countries in the same region is an absolute necessity. Where eradication and containment is judged not feasible, actions should be undertaken that will reduce the impact of the introduced animal or plant pest or disease, or the invasive alien aquatic species. These actions can include changes in agronomy and animal management, introduction of new varieties, species or breeds, carefully considered introduction of biological control agents and Integrated Pest Management, all of which are within the framework of overall autonomous and planned adaptation as identified in the Fourth Assessment Report of the IPCC.[4]

In forestry, adaptation responses include: reforestation choices that take a long-term ecological view, increased monitoring and data sharing, enforcement of wood packaging standards, funding for emergency control operations and control of spread after introduction, and capacity building for better compliance by trading partners.

The trade in ornamental fish and other ornamental aquatic species is a major pathway for the introduction of fish diseases and invasive alien aquatic species. Legislation and national systems to prevent the entry and establishment of alien aquatic species and fish diseases only exist in a limited number of countries. There is great concern about the largely unregulated movement of ornamental fish species and aquatic organisms that spread diseases or become pests that impact aquatic systems. Governments should legislate and seek to establish capacity to implement systems that prevent the entry and establishment of alien aquatic species and fish diseases.

Information options. The effects of climate change on migratory pests will most likely require that new areas have to be surveyed in different time periods with control capacity available at different periods of the year and more locations than at present. Addressing changing locust situations will require better surveillance and monitoring, and earlier control.

Additional information is required on distribution of animal and plant pests and diseases and invasive alien aquatic species, and on their epidemiology. In particular, there is need for better surveillance methodologies; fast and cheap identification methods; epidemiological knowledge; and information on biological control organisms and mechanisms and resistant crops and animal breeds and species. Coordinated research, including the Consultative Group on International Agricultural Research (CGIAR) programmes related to climate change and food security, will be needed to improve the range of options available to countries. Better accessibility and analysis of existing historical data and more detailed data for all regions in relation to different climate change scenarios will improve the baselines needed to assess adaptation.

Food trade industry. The introduction of diseases and pests will result in higher costs to national food industry in relation to inspection, treatment and compliance with obligations of the importing trading partners. Trade disputes in the WTO systems could become more frequent. Information exchange mechanisms exist at global and regional levels. At national level, there are many national databases as well as those maintained by non-governmental organizations (NGOs) and universities. However, data are of varying quality and are often incomplete or out of date. As provision of data on distribution of animal and plant pests and diseases and invasive alien aquatic species can be perceived as harmful to trade interests, provision of such data needs cooperation and commitment of all parties. To enable risk assessment, prevention, monitoring, early detection and warning, and control, there is a need for an

[4] IPCC, 2007: Climate Change 2007 (op.cit.)

overall global data exchange mechanism covering the distribution of diseases, pests, invasive alien aquatic species and correlated ecological conditions including climate. In order to improve information exchange, it will be necessary to increase cooperation among national, regional and global organizations, specifying the data required and the safeguards that should be applied to protect national interests. Government agencies and relevant stakeholders should come together and discuss specifications and sustainable systems for practical use.

Government constraints. The national animal and plant protection infrastructure, in particular in developing countries, is often unable to execute the range of activities required for prevention, early warning and early control of transboundary animal and plant pests and diseases. National systems are often fragmented among agencies and ministries. The high level of uncertainty and the concomitant requirements for better legislation, increased risk analysis, better border control and the increase in requirements for eradication, containment and adaptation are beyond the possibilities of most plant and animal health services, in particular those of developing countries. Learning and sharing lessons from failures as well as from successes is especially important at national level. Governments also need to be aware of the importance of maintaining capacity for dealing with new animal and plant pests and diseases. Those that reduce funding when there is no crisis often suffer later from failure to maintain capacity.

At present most countries have insufficient enabling legislation and resources allocated to:
- surveillance and monitoring
- border control and inspections
- expertise in risk assessment
- diagnostic tools for early detections
- expertise in diagnosis (taxonomy)
- data collection and access to information
- tools for rapid response to entry, establishment and spread
- control measures at the source of the produce.

Government priorities. A top priority for dealing with animal and plant pests and diseases is strengthening national veterinary and plant health services and animal and plant health systems through capacity building. This includes improvement of infrastructure, border control, better legislation and enforcement, and better surveillance. Other priorities include improving the ability to respond to movements of animal and plant pests and diseases through increasing preparedness, ensuring maintenance of expertise and adopting rapid diagnostic tools and forecasting models. Investment in capacity building will contribute to reduction of emerging animal and plant pests and diseases at source. Basic sciences such as climate change science, taxonomy, modeling, population ecology and epidemiology should be given highest priority by governments.

Resources to address animal health, plant health and invasive alien aquatic species are often distributed among national ministries and agencies. In a number of countries, there is a move to establish "biosecurity" agencies that bring several of these functions together. In view of the additional strains climate change puts on these systems, governments may wish to design and implement national strategies that capture synergies across the agencies and entities responsible for managing animal plant pests and diseases and invasive alien aquatic organisms, and consider moving towards biosecurity approaches.

Ecosystem processes. Climate affects both local and regional ecosystem processes and production. Many threats are transboundary and countries will not be able to address these issues individually. Regional cooperation is a high priority for risk analysis, regional standard setting, exchange of information and coordinated action. Countries should examine and, where appropriate, strengthen their regional organizations and cooperation in animal and plant health and on alien invasive aquatic species. Regional and sub-regional organizations and cooperation exist but coverage, functions and efficiency vary among regions. In such cooperative frameworks, issues such as standard setting, joint risk assessment, joint action and access to information should be carefully considered and, where required, organizations should be strengthened.

Global frameworks. Global regulatory frameworks are provided by the World Trade Organization (WTO), the World Organization for Animal Health (OIE), the FAO International Plant Protection Convention (IPPC) and the Convention on Biological Diversity. OIE and IPPC also provide standard setting mechanisms for animal and plant health. IPPC and OIE have the structures to serve adequately under climate change scenarios, but their resources are limited. Concerning invasive alien aquatic species, the International Maritime Organization (IMO) International Convention on the Control of Harmful Anti-fouling Systems on Ships entered into force in 2008 while the International Convention for the Control and Management of Ships' Ballast Water and Sediments, was adopted in 2004 but is not in force yet. However, an overall global framework to adequately address invasive alien aquatic species and be prepared for the additional effects of climate change does not exist.

Relevant global organizations should seek further cooperation in appropriate fields through information exchange and capacity building. The Standard and Trade Development Facility, a WTO-hosted joint programme of FAO, OIE and World Health Organization, is a good example.

Main findings and recommendations

The spread of plant pests, animal diseases and invasive alien aquatic organisms across physical and political boundaries threatens food security and represents a global public “bad” that links all countries and all regions.

There is clear evidence that climate change is altering the distribution and potential distribution, incidence and intensity of animal and plant pests and diseases.

Climate change creates new ecological niches allowing for the potential for establishment and spread of animal and plant pests and diseases and invasive alien aquatic species to new geographical areas and from one region to another. It will also result in the emergence of new animal and plant diseases and pests. Change in climate resulting in changes in species composition will augment the emergence of unexpected events, including the emergence of new diseases and pests. The additional opportunities for entry, establishment and spread will result in higher uncertainty.

The impact of climate change on migratory plant pests is difficult to foresee. However, climate scenarios predict more winter rain in some Sahelian areas which may provide better breeding conditions for the desert locust *(Schistocerca gregaria).*

Transboundary plant pests, animal diseases and invasive alien aquatic species are a constraint to food security due to their impacts on food availability, food access, food safety and food stability.

Impact assessment and cost-benefit analyses of adaptation measures at national and regional levels and methods that take a wide range of factors into account should be developed and used in strategic planning.

The introduction of diseases and pests will result in higher costs to the national industry in relation to inspection, treatment and compliance with obligations of the importing trading partners. Trade disputes in the WTO systems could become more frequent. Investments in early control and detection mechanisms will undoubtedly be valuable, to avoid higher costs of eradication and control.

Adaptation to the increased potential of spread of transboundary plant pests, animal plant pests and diseases and invasive alien aquatic species under different climate scenarios requires higher levels of forecasting, prevention, early warning and early reaction. Early detection and identification, including through genotypic characterization, preparedness for and rapid response to new and emerging pests are critical elements.

Prevention needs cooperation of countries in the same geographic region to ensure better monitoring of animal and plant health in the region.

To meet the likely increase in entry, establishment and spread of animal plant pests and diseases and invasive alien aquatic species, countries need appropriate emergency capacity to take action and, where appropriate, regional infrastructures should support and coordinate action among countries. Joint action of countries in the same region is an absolute necessity.

To enable risk assessment, prevention, monitoring and control, there is a need for global data exchange mechanisms covering the distribution of diseases, pests, invasive alien aquatic species and correlated ecological conditions including climate. In this respect, it will be necessary to increase cooperation among national, regional and global organizations and specify better the data required and the safeguards that should be applied to protect national interests. Government agencies and relevant stakeholders should come together and discuss specifications and sustainable systems for practical use.

Where eradication and containment is judged not to be feasible, actions need to be undertaken that will reduce the impact of the introduced animal or plant pest or disease, or the invasive alien aquatic species: Changes in agronomy and in the management of animals, new varieties, new species, new breeds, carefully considered introduction of biological control agents and Integrated Pest Management. The general autonomous and planned adaptation measures listed in the in Fourth Assessment Report of the IPCC[5] should be considered when formulating local, national and regional strategies for adaptation to plant pests, animal diseases and aquatic organisms under climate change scenarios.

Adaptation responses in forestry include: reforestation choices that take a long-term ecological view, increased monitoring and data sharing, enforcement of wood packaging standards, funding for emergency control operations, control of spread after introduction, and capacity building for better compliance by trading partners.

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[5] IPCC, 2007: Climate Change 2007 (op.cit.)

The impact of climate change on migratory pests will require that, possibly, new areas have to be surveyed in different time periods and control capacity be available at different periods of the year and different locations than at present. Locust situation will require better surveillance and monitoring, and early control to be able to properly address a changing situation.

The national animal and plant protection infrastructures, in particular in developing countries, are often unable to execute the range of activities required for prevention, early warning, early control, eradication, containment and adaptation of transboundary animal diseases and plant pests, and will be further strained due to the impacts of climate change.

The top priority for animal and plant pests and diseases is strengthening of national veterinary and plant health services and animal and plant health systems through capacity building including infrastructure, border control, better legislation and enforcement and better surveillance. Another priority should be to respond to movements of animal and plant pests and diseases through preparedness, maintenance of expertise, rapid diagnostic tools and forecasting models. Investment in capacity building will contribute to reduction of emerging animal and plant pests and diseases at source. Basic sciences (i.e. climate change science, taxonomy, modeling, population ecology and epidemiology) should obtain highest priority by governments.

Resources to address animal health, plant health and invasive alien aquatic species are often distributed among national ministries and agencies. In view of the additional strains on these systems by climate change, governments may wish to design and implement national strategies that capture synergies across the agencies and entities responsible for managing animal plant pests and diseases and invasive alien aquatic organisms, and consider moving towards biosecurity approaches.

There is great concern about the largely unregulated movement of ornamental fish species and aquatic organisms that spread diseases or become pests that impact aquatic systems. Governments should legislate and seek to establish capacity to implement systems to prevent the entry and establishment of alien aquatic species and fish diseases.

Climate affects ecosystem processes and production at local and regional scale. Many threats are transboundary and countries will not be able to address these issues individually. Regional cooperation is a high priority for risk analysis, standard setting, exchange of information and coordinated action. Countries should examine and, where appropriate, strengthen their regional organizations and cooperation in animal and plant health, and alien invasive aquatic species.

Global regulatory frameworks and standard setting mechanisms for animal and plant health are provided respectively by the OIE and the IPPC. These organizations have the structures to serve adequately under climate change scenarios, but their resources are limited.

An overall global framework to adequately address invasive alien aquatic species and be prepared for the additional effects of Climate Change remains unavailable.

Additional information and research is required on distribution of animal and plant pests and diseases and invasive alien aquatic species, and on their epidemiology. In particular there is a need for better surveillance methodologies; fast and cheap identification methods, epidemiological knowledge; and information on biological control organisms and mechanisms; resistant crops and resistant animal breeds and species. Coordinated research, including the CGIAR programmes related to climate change and food security, will be needed to improve the range of options available to countries. Better accessibility and analysis of existing historical data and more detailed data for all regions in relation to different climate change scenarios will improve the baseline studies needed to assess adaptation.

ANNEXES

Annexes 1 to 8 contain summaries of informed opinions of invited experts on major pests and diseases referred to in the document as well as abstracts of some of the expert presentations.

ANNEX 1	Raymond J. C. Cannon, Central Science Laboratory, Sand Hutton, York
ANNEX 2	Hugh Evans, Health Tree Division, Forest Research, United Kindgom
ANNEX 3	Junichi Yukawa, Kyushu University, Fukuoka, Japan
ANNEX 4	Philip Thornton, International Livestock Research Institute, ILRI
ANNEX 5	Etienne Duveiller, International Maize and Wheat Improvement Centre, CIMMYT
ANNEX 6	Jorge Hendrichs, Joint FAO/IAEA Division
ANNEX 7	Mike Hine, Independent Consultant
ANNEX 8	R.W Sutherst, School of Integrative Biology, University of Queensland, Australia

ANNEX 1

Raymond J. C. Cannon, Central Science Laboratory, Sand Hutton, York

Examples of plant pests whose geographical distribution and pest incidence and/or intensity will be substantially influenced by climate change and of which economic (including environmental) consequences will be substantial.

1) Name of plant pest
2) Present distribution (approximate)
3) Anticipated effect of climate change (i.e. change in ecological conditions will substantially widen the area where the plant pest could be introduced and/or could substantially increase its (potential) economic importance).

Indicative species

Colorado beetle

1) Colorado beetle, *Leptinotarsa decemlineata*
2) North America, Europe (except Denmark, Finland, Norway, Sweden and the UK), and much of Asia, to the Pacific Ocean.
3) Baker, *et al.* (1998) estimated that for an average warming of 2.3°C, the Colorado beetle, *Leptinotarsa decemlineata*, could expand its potential range in the UK by 120%. This would extend the potential northern limit of the species by 400 km, thus posing a potential risk to more than 99% of potato producing areas.

Western corn rootworm

1) Western corn rootworm, *Diabrotica virgifera virgifera*
2) North America and spreading throughout Europe.
3) *D. virgifera* was introduced into Europe near Belgrade, c. 1992, and has since been spreading eastwards and northwards. This major pest has not yet spread to its potential limits under existing climatic conditions, but global warming has the potential for increase its range considerably northwards. Baker, *et al.* (2003) showed that under current climate conditions, *D. v. virgifera*, appears to be at the edge of its range in the UK, but by 2050, under global warming, a large area of SE England will be [much more] suitable for this species.

Liriomyza leaf miners

1) South American leaf miner, *Liriomyza huidobrensis*
2) Cosmopolitan, but absent from a number of countries in Europe including UK, Denmark, Finland, Germany, Ireland and Sweden.
3) Warmer winter temperatures are likely to increase the probability of the non-indigenous, South American leaf miner (*Liriomyza huidobrensis*) overwintering outdoors in the UK (Baker, *et al.* 1996).

Diamondback moth

1) Diamondback moth, *Plutella xylostella*
2) Probably of European origin, now cosmopolitan in distribution.
3) At the northern extremity of its range, this species generally occurs at relatively low population densities and it does not usually overwinter. If however, as a result of global warming, overwintering occurred more frequently, the pest status of this species would increase dramatically (Dosdall 1994).

European corn borer

1) European corn borer, *Ostrinia nubilalis*
2) Central and southern Europe, North America, northern India and western China.
3) The effect of climate change for multivoltine species such as the European corn borer will be that it may be able to produce additional generations, relative to current conditions, in a given locale, with a potentially greater impact on their host plants. For example, *O. nubilalis* is predicted to become bivoltine – i.e. to produce two generations per season rather than one – in the Czech Republic as a result of predicted increases in temperatures during the period 2025-50 (Trnka, *et al.*, 2007). This species is at present near the northern limit of its range in southern England. A 3º C increase in mean annual temperature would advance the limit for maize (*Zea mays*) providing an opportunity for a substantial northward shift in the distribution of *O. nubilalis* (Porter, 1995).

Old World bollworm

1) Old World bollworm, *Helicoverpa armigera*
2) Widespread throughout the tropics, subtropics and warmer regions of the Old World, including southern Europe and the Mediterranean.
3) Migrant moths, such as *H. armigera* have also shown a "phenomenal increase" over the period 1969-2004, penetrating inland more frequently (Parsons & Davey, 2007), although this has not (yet) led to an increase in its pest status in the UK. However, there have been outbreaks in areas at the northern edge of its range in Europe, including the first finding in 2003, of *H. armigera* in Austria; and a damaging outbreak, also in 2003, in Baden-Württemberg, Germany, on a great diversity of plants grown outdoors (EPPO Reporting Service, 2004/012 and 2004/013).

Cottony cushion scale

1) Cottony cushion scale, *Icerya purchasi*
2) Cosmopolitan throughout the warmer regions of the world
3) Outdoor populations appear to be naturally spreading northwards perhaps as a consequence of global warming. In 1999, a severe infestation was reported in the Jardin des Plantes, Paris and it has also recently been found breeding outdoors in London (Watson & Malumphy, 2004).

Cottony Camellia Scale

1) The Cottony camellia scale, *Pulvinaria (= Chloropulvinaria) floccifera*
2) Cosmopolitan

3) *P. floccifera* has become much more common in the UK, extending its range northwards in England and increased its host range in the last decade or so. This is almost certainly a response to climate change. In Sweden, *P. floccifera* was previously only known as a greenhouse species, but is now established as an outdoor species (Gertsson, 2005).

Laurel scale

1) Laurel scale, *Aonidia lauri*
2) Mediterranean
3) *Aonidia lauri* has been found breeding outdoors sporadically in the London area since about 1996 (Malumphy, 1997). It is likely to respond to climate change and become more common.

Cabbage White butterfly

1) Cabbage white butterfly, *Pieris brassicae*
2) Europe, NW Africa and Asia. Introduced into N. America and Australia.
3) Most butterflies are predicted to increase in diversity, range and abundance in the UK under a warmer climate, but according to Roy, *et al. (2001) P. brassicae* would likely decline.

Cabbage root fly

1) Cabbage root fly, *Delia radicum*
2) Widespread throughout Europe, N. Africa, W. Asia, and N. America
3) A 3ºC increase in mean daily temperatures would cause cabbage root fly (*Delia radicum*) populations to become active about a month earlier in the UK (Collier et al. 1991), which may translate into increased pest severity.

Gypsy moth

1) Gypsy moth, Lymantria dispar
2) Europe to Asia; introduced to North America in the late 1860s and has been expanding its range ever since.
3) Increases in the populations of forest Lepidoptera have been linked to increased temperatures (Wulf, & Graser, 1996) and there has been an increase in outbreaks in areas previously unaffected by this pest, including an on-going outbreak in Jersey, Channel Islands. In mainland GB, the gypsy moth was confined to an area in NE London from 1995-2003 (Cannon, *et al.*, 2004), but in 2005, a second and much larger population was discovered in Aylesbury, Buckinghamshire[2]. Climate change scenarios also show an increase in probability of establishment of the gypsy moth throughout New Zealand, particularly in the South Island (Pitt, *et al.*, 2007). The performance of gypsy moth (*Lymantria dispar*) larvae on host plants grown under elevated CO_2 depends on the species, being reduced on some hosts and increased on others, such as oak (see references in Cannon, 1998).

Oak Processionary moth

1) Oak processionary moth, *Thaumetopoea processionea*
2) Central and southern Europe to Asia Minor.
3) The range of this species appears to be extending north: *T. processionea* re-appeared, at high densities, in Noord-Brabant in the southern half of the Netherlands (Stigter and Romeijn, 1992); it was caught for the first time in Denmark in 1996 (Skule & Vilhelmsen, 1997); it was found at several locations in London in 2006; is present in the provinces of Antwerp and Limburg in Belgium (Vandenbussche, 1997); and is now resident in the Channel Islands (Kimber, 2008).

Pine processionary moth

1) Pine processionary moth, *Thaumetopoea pityocampa*
2) *Mediterranean countries*
3) The pine processionary moth is expanding its geographical range in Europe, as a consequence of enhanced winter survival under a warmer climate (Buffo, *et al.*, 2007). Increasing winter temperatures will also affect the severity of this species on relic pines in upland regions of southern Europe (Hodar, *et al.*, 2003).

Firebug

1) Firebug *Pyrrhocoris apterus*
2) They are widespread in southern and central Europe.
3) *P. apterus* has become much more abundant in Guernsey in the last ten years[2].

Winter moth

1) Winter moth (*Operophtera brumata*)
2) Temperate Europe and N Africa; Japan and Siberia; introduced into eastern Canada.
3) Synchrony between the date of budburst and that of larval emergence greatly affects larval survival, so this species could be disadvantaged by global warming (Dewar & Watt 1992), i.e. become less severe as a pest.

Ragweed

1) Ragweed, *Ambrosia artemisiifolia* L.
2) An invasive North American annual (Asteraceae), which occurs in many European countries.
3) Ragweed plants, *Ambrosia artemisiifolia* L., produce highly allergenic pollen. A doubling of the atmospheric CO_2 concentration stimulated ragweed-pollen production by 61%, which suggests that there may be significant increases in exposure to allergenic pollen under global warming (Wayne, *et al.*, 2002). Rogers, *et al.* (2006) also showed that ragweed pollen production is expected to increase significantly under predicted future climate conditions. Rogers, *et al.* (2006) also showed that ragweed pollen production is expected to increase significantly under predicted future climate conditions.

Nematodes

There is a close correlation between soil temperatures and the distributions of some plant-parasitic species, such as *Longidorus caespiticola* (Boag & Neilson, 1996). A 1ºC rise in temperature would allow this species to become established further north in Great Britain. *Meloidogyne incognita* was recently found in The Netherlands (Dr. S. Hockland, *pers. comm.*), a species that previously was considered as limited to the Mediterranean area.

Plant Diseases

According to Chakraborty, *et al.* (2000), "Climate change could have positive, negative or no impact on individual plant diseases" and more research is needed to obtain base-line information on different disease systems. These authors concluded that despite the significance of weather on plant diseases, a comprehensive analysis of how climate change will influence plant diseases in agricultural systems is presently unavailable. Some discussion of the impact of climate change on both indigenous and non-indigenous diseases in the UK is contained in Hardwick, *et al.* (1996). Increased rainfall correlated with a high incidence of canker (*Leptosphaeria maculans*) in oil seed rape, whilst temperature was an important factor in the development of brown rust (*Puccinia hordei*) in cereals.

There are a number of quarantine diseases, which might become more serious under global warming, including brown rot (*Ralstonia solanacearum*) and sudden oak death (*Phytophthora ramorum*). Incidences of brown rot in Europe are primarily caused by *R. solanacearum* race 3 biovar 2A, which is reported to have strains adapted to cooler conditions. There are also other phylotypes of *R. solanacearum,* originating from Asia and South America, which would have a greater likelihood of establishment under predicted changes in climate, thereby threatening a much wider range of host plants. Wright & Woodhall (2006) considered that the impact of *P. ramorum* might increase through climatic changes producing more optimal conditions for the pathogen.

Dickeya dadantii (syn. *Erwinia chrysanthemi*, *Pectobacterium chrysanthemi*) is a phytopathogenic *Enterobacteriaceae* that can cause soft rot diseases in a wide range of economically important crops. Laurila, *et al.* (2008) report for the first time that *Dickeya*, originally known as a pathogen in tropical and warm climates, may cause diseases in potato in northern Europe.

Waage, *et al.* (2006) identified a substantial increase in the rate of new disease reporting over last decade, possibly as a consequence of globalization, although the influence of global climate change could also be a contributing factor. In another of the UK Government's Foresight project studies, 'The Effects of Climate Change on Infectious Diseases of Plants' Chancellor & Kubiriba (2006) concluded that whilst the 'geographical distribution of some plant hosts and disease pathogens will alter as a result of future changes in climate and, especially in Africa, this effect is likely to be strongest in areas of significant water stress'. However, they emphasised that the absence of reliable epidemiological information 'makes predictions hazardous'.

Barker, *et al*. (2006) suggest that plant diseases 'will continue to be characterized by the extreme variety of hosts and the extreme variety of pathogens', which they suggest means there will be a need for generic broad-spectrum diagnostic tests. Such devices will need to screen larger numbers of plant products than at present, and be faster and cheaper than current methods.

Non-specific indicators

There are a range of non-specific indicators, which could, and are being used as indicators of climate change, i.e. beyond the specific ones of increases in the geographical range or abundance of given species, in particular, phylogenetic changes. For example, the phenology of a range of agricultural and horticultural events in Germany, over the period 1951–2004, was estimated to have advanced on average by 1.1 – 1.3 days, per decade (Estrella, *et al.*, 2007). Some of the best evidence for climate change is provided by non-pests, e.g. dragonflies and damselflies, are expanding their flight period, flying both earlier and later in the season (Hassal, *et al.,* 2007). The same is true of a large number of butterflies, grasshoppers, bush crickets and wasps. Plants are flowering earlier, an average of 4.5 days earlier in the decade 1991-2000, compared to the previous 35 years (Fitter & Fitter, 2002). This presumably applies to crop plants as well, although the effects could be masked by varietal selection.

Aphids

Aphid flight phenology is thought to be a good indicator of climate warming and Fleming & Tatchell (1995) predicted that over the next 50 years, aphids will appear at least eight days earlier in the spring – as measured by their presence in suction traps. This may increase their severity as pests, although the extent to which this will affect their pest status will also depend partly on how the phenologies of their host plants (and natural enemies) change as well (Harrington, *et al.,*2007). The green spruce aphid (*Elatobium abietinum*) could be at an advantage, in that a longer period favourable for growth would be available (Straw 1995). Zhou, *et al.* (1996) concluded that climate change-induced changes would increase the severity of aphid outbreaks and extend the period of virus infection further into the growing season in the UK. The Green citrus aphid, *Aphis spiraecola*, is a sporadic, transient visitor to the UK, which survives in sheltered conditions and/or in warm years. It is possible that *A. spiraecola* may be expanding its range as a result of climate change.

Migrant pest species

In many northern European countries, populations of many migrant insect species occur seasonally, as a result of immigration from more favourable regions to the south. Migrants will be able to respond quickly to climate change and will be difficult to exclude if they move naturally. The numbers of migratory butterflies arriving in the south of England has increased steadily over the period 1992-2005 (Sparks, *et al.*, 2007), and moths, such as the important pest species, *Helicoverpa armigera* have also shown a “phenomenal increase” over the period 1969-2004, penetrating inland more frequently (Parsons & Davey, 2007).

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ANNEX 2

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Increasing global trade and climate change: co-factors increasing the international movement and establishment of forest pests.

Abstract

Global trade, both in variety and quantities of goods moved, is increasing year by year. For example, WTO statistics indicate that between 2000 and 2005, global sea and air freight rose by around 20 percent with volumes now exceeding 7 billion tons per year. Trends in eco-climatic variables under different climate change scenarios also show marked differences in key drivers such as temperature, rainfall, soil moisture, etc. This juxtaposition of dramatically increased trade-driven international pest movement and more gradual shifts in climatic suitability in previously unsuitable regions of the world is providing new opportunities for plant pests to enter and establish in new locations.

Within the dramatically increased trade statistics, it is possible to determine which commodities are the high risk pathways for international movement of pests of phytosanitary concern. While wood, wood products and wood packaging have been recognised as key pathways and are subject to stringent phytosanitary controls, it is now becoming increasingly apparent that it is the ‘plants for planting’ pathway that poses the greatest current and future risk. Trade in live plants, often complete with root balls and associated soil, is increasing rapidly and globally. Full circumnavigation of the globe is now normality for live plants and, while there are phytosanitary rules in place, they tend only to reflect known pests. Those pests not on the lists of recognised organisms will consequently tend to be missed.

Transport along a pathway does not, of course, always result in successful establishment of pests in new locations. Previously, many organisms could not establish because of climatic unsuitability, reflecting the ecological and climatic barriers that determine distributions of pests in their natural ranges. The fact that distributions of pests in their native ranges is now changing and has been linked to climate change, indicates that climatic suitability for pests moving along trade pathways is also changing. Particular examples include the pine processionary moth, *Thaumetopoea pityocampa*, which has moved northwards in Europe over the past 50+ years and mountain pine beetle, *Dendroctonus ponderosae*, which is causing devastation well north of its previous range in NW Canada. Both have climatic components in explaining their range shifts. Prediction of which pest will become damaging in new locations is not easy but lessons can be learnt from the ways in which pest organisms are adapting to climate shifts in their current locations. Overwinter temperatures, synchronicity of insect emergence with bud burst of hosts in the spring, reduced tree defences arising from climatic stress and warmer summers accelerating development are all aspects that provide insights into future pest adaptations to climate change. There is no doubt that the complex interactions between climate, pest and host tree will require detailed study to increase our understanding and allow development of pest management strategies for the future. However, it does seem inevitable that the increased opportunities for pests to encounter new and suitable eco-climatic zones for establishment will result in many new infestations and challenges in pest management.

Forestry pests (both insect and pathogen) likely to be affected by climate change

This list is linked to the lifestyle parameters/climate interaction effects most likely to be affected by changes in climate, particularly temperature, and which reflect the effects on the pests themselves, their host trees and the interactions between them.

Synchrony between insect life stage and host phenological stage and overwinter survival of critical life stages

The limiting factor for many insects, particularly defoliators, is synchrony with bud burst in the spring. Key drivers are late winter temperatures for insect emergence and bud burst.

Examples:

Winter moth, *Operophtera brumata*: oak bud burst is 20 days earlier than 1950s in Europe. Egg hatch of the moth has also advanced 20 days, keeping synchrony.

Pine processionary moth, *Thaumetopoea pityocampa*: northward progression due to reduced frequency of late frosts affecting overwintering larvae.

Oak processionary moth, *T. processionea*: northward progression due to improved synchrony of egg hatch and reduction of late frosts.

Nun moth, *Lymantria monachai:* predicted to spread northwards in Europe, driven by higher accumulated day degrees and improved overwinter survival.

Gypsy moth, *Lymantria dispar*: predicted to extend range in North America, driven by higher overwinter survival of egg stages (milder winters) and higher accumulation of day degrees for larval development.

Larch bud moth, *Zeiraphera diniana*: synchrony between egg hatch and bud burst is critical and asynchrony due to climate shifts appears to be reducing incidences of the moth in Switzerland.

Host defences in relation to bark and wood boring beetles

Bark beetles (Coleoptera: Curculionidae: Scolytinae), particularly those classed as aggressive tree killers (e.g. *Ips typographus* in Europe, *Dendroctonus ponderosae* in North America) are often limited by host defences in healthy trees. Shifts in range and in severity of some of the more aggressive bark beetles have been associated with climate change acting on the host tree and on the insects themselves (voltinism). Other groups of xylophagous beetles will also be affected.

Examples:

Mountain pine beetle, *Dendroctonus ponderosae*: warmer winter temperatures with reduced episodes of underbark mortality and increased drought (weakening trees) appear to have combined to allow massive population build up and northward progression in the Pacific North West.

Southern pine beetle, *Dendroctonus frontalis*: northward shift predicted based on both shifts in its pine hosts and in limits of lethal winter temperatures (based on <-16^{o}C). Tree defences also implicated.

Buprestid beetles linked to oak decline (the genus *Agrilus*). The incidences of buprestid beetles have increased globally (both in their countries of origin and by international movement), with their impacts being linked to host tree stress, potentially driven by climate change. *A. pannonicus (=biguttatus)* is regarded as contributing to oak decline in Germany and has increased in incidence in recent years.

Fungal diseases of trees

Warmer summers will favour thermophilic rust fungi, for example on poplars.

Example: Melampsora allii-populina is likely to spread northwards with increased summer temperatures.

Higher year round temperatures will favour those fungi with relatively high temperature optima for growth.

Example: Phytophthora cinnamomi is predicted to spread into colder regions and have increased severity with climate change scenarios of increased average temperatures.

Warmer winters may increase the activity of currently weak pathogens.

Example: Phacidium coniferarum is active only in the host tree dormant season and so there may be lack of synchrony between periods of dormancy and temperatures still high enough to support fungal growth.

Summer droughts and elevated temperatures may cause climatic stress to host trees, increasing their vulnerability to pathogens.

Example: Armillaria spp (honey fungus) can become much more aggressive and damaging when summer drought stress reduces tree defences.

Interactions of fungi with vectors may be affected by climate change.

Example: Scolytus scolytus and *S. multistriatus*, vectors of Dutch elm disease (*Ophiostoma novo-ulmi*) may be more active during periods of elevated temperature, thus increasing the spread of the fungus.

ANNEX 3

Junichi Yukawa, Kyushu University, Fukuoka, Japan

Northward distribution range extensions of plant pests, possibly due to climate change: examples in Japan

Abstract

The number of alien insect species that have established in the Nansei Islands, Japan has increased in recent years from 74 to 99 species resulting from natural invasion or accidental introduction. For example, natural invasion of the Nansei Islands by subtropical butterflies and their subsequent northward range extensions have been observed for at least 15 species in recent years. As a case study of plant pests, I refer to the distribution range shifts of *Nezara viridula* and *N. antennata* (Hemiptera: Pentatomidae), which are pests of various crops, such as rice, soybean, corn, tomato and eggplant. *N. antennata* is distributed in Japan, Korea, China, and southeastern Asian countries and *N. viridula* is widely distributed in the tropics, subtropics, and southern parts of the temperate zones. Intensive and successive field surveys on the relative abundance of *N. viridula* to *N. antennata* in Kyushu and the Kii Peninsula, Japan, together with scattered collection records of *N. viridula* in the past, clearly showed that *N. viridula* has been expanding its range northward since the 1960s. The present range of *N. viridula* in Kyushu coincided well with the areas where the mean temperature for January exceeds 5˚C that has been suggested to be the lowest thermal limit for *N. viridula* to overwinter successfully. The future range of *N. viridula* is predicted to cover a large area of Kyushu if the temperature rises by 1.4˚C by 2100. In some places, *N. antennata* seemed to have been replaced by *N. viridula* as a result of their interspecific mating that prevented *N. antennata* from intraspecific mating. This is because *N. antennata* was overwhelmed, in abundance, by *N. viridula*, which has a higher reproductive potential than *N. antennata* under warm conditions with a sufficient amount of food resources. In order to monitor and predict northward shifts of plant pests, it is essential to gather detailed biological information on the pests and on distribution records in the past and present. We also need to investigate factors limiting northward shift such as (1) winter temperature, (2) geographical barriers, (3) flight ability or other means of movement, and (4) presence or absence of host plants, effective natural enemies, and competitors.

Examples of direct effects of climate change on herbivorous insects

Direct effects of climate change on herbivorous insects can be divided into the following two main categories although there are many others plus and minus indirect effects: (1) distribution range shift and (2) increase of the number of generations per year. Distribution range shift is further divided into (1-1) natural expansion due to global warming and (1-2) accidental introduction. Accidental introduction is caused by the increase of world trade, resulting in the establishment of herbivorous insects outside of their natural distribution range. Some examples of pest insects are given below:

Natural distribution range shift

1) Name of plant pests: Fruit flies including the following species:
   Bactrocera cucurbitae (Coquillett, 1899) (Diptera: Tephritidae) ‘Melon Fly’

Bactrocera dorsalis (Hendel) (Diptera: Tephritidae) 'Oriental Fruit Fly'
Bactrocera latifrons (Hendel) (Diptera: Tephritidae) 'Malayasian Fruit Fly'
2) Present distribution: South of the Japanese Archipelago
3) Anticipated effect of climate change: Invasion of the Japanese Archipelago

1) Name of plant pest:
Nezara viridula (Linnaeus) (Hemiptera: Pentatomidae) 'Southern Green Stink Bug'
Leptocorisa chinensis (Dallas) (Hemiptera: Alydidae)
2) Present distribution: Tropical and subtropical countries in the world
3) Anticipated effect of climate change:
Northward range shift to the Temperate Zones in the world

1) Name of plant pest:
Orseolia oryzae Wood-Mason (Diptera: Cecidomyiidae) 'Asian Rice Gall Midge'
2) Present distribution: South of the Philippines
3) Anticipated effect of climate change: Northward range shift to the subtropical Asia

1) Name of plant pest:
Quadrastichus erythrinae Kim (Hymenoptera: Eulophidae)
2) Present distribution:
Tropical countries in Africa and Asia
(found in Australia, Hawaii, Florida, Japan etc. in recent years)
3) Anticipated effect of climate change:
Expanding its distribution range and causing serious damages to *Erythrina* trees (Fabaceae) by inducing galls on twigs and leaves

Accidental introduction

1) Name of plant pest:
Cylas formicarius (Fabricius) (Coleoptera: Curculionidae) 'Sweet Potato Weevil'
2) Present distribution: Tropical and subtropical countries in the world
3) Anticipated effect of climate change:
Accidental introduction to the Temperate Zones and establishment there under warmer conditions

1) Name of plant pest:
Euscepes postfasciatus (Fairmaire) (Coleoptera: Curculionidae)
West Indian Sweet Potato Weevil'
2) Present distribution: Tropical and subtropical countries in the world
3) Anticipated effect of climate change:
Accidental introduction to the Temperate Zones and establishment there under warmer conditions

1) Name of plant pest:
Contarinia maculipennis Felt (Diptera: Cecidomyiidae) 'Blossom Midge'
2) Present distribution:
Southeast Asia (accidentally introduced to Hawaii, Florida, and Japan)

3) Anticipated effect of climate change:
   Accidental introduction and subsequent establishment in green houses, expansion of host range from orchids to various sorts of crops

1) Name of disease and transmitting pest:
   Citrus Greening Disease transmitted by
   Diaphorina citri Kuwayama (Homoptera: Psyllidae) 'Asian Citrus Psyllid'
2) Present distribution: Tropical and subtropical countries in the world
3) Anticipated effect of climate change: Northward range shift to the Temperate Zones

1) Name of pest:
   Nilaparvata lugens (Stal) (Hemiptera: Delphacidae) 'Brown planthopper'
   Sogatella furcifera (Horváth) (Hemiptera: Delphacidae)'White-backed planthopper'
2) Present distribution: Tropical and subtropical Asia and Australia
3) Anticipated effect of climate change:
   Northward range shift to the Temperate Zones (long distant migration)

1) Name of pest:
   Plautia crossota Stali (Hemiptera: Pentatomidae)
   Glaucias subpunctatus Walker (Hemiptera: Pentatomiidae)
2) Present distribution: Tropical, subtropical, and temperate zones of Asia
3) Anticipated effect of climate change:
   Range shift to further north and overlapping of generations

Increase of the number of generations per year

1) Name of plant pest: Various aphid species including:
   Aphis gossypii Grover (Hemiptera: Aphididae)
   Myzus persicae (Sulzer) (Hemiptera: Aphididae)
   Aulacorthum solani (Kaltenbach) (Hemiptera: Aphididae)
2) Present distribution: Worldwide
3) Anticipated effect of climate change:
   Increase of the number of generations a year due to lower developmental zero point and low thermal totals required for one generation, resulted in more infestation

1) Name of plant pest: Various lepidopteran species including:
   Helicoverpa armigera (Hübner) (Lepidoptera: Noctuidae)
   Mamestra brassicae (Linnaeus) (Lepidoptera: Noctuidae)
   Spodoptera litura (Fabricius) (Lepidoptera: Noctuidae)
   Spodoptera exigua (Hübner) (Lepidoptera: Noctuidae)
2) Present distribution:
   Worldwide
3) Anticipated effect of climate change:
   Increase of the number of generations a year, resulted in more infestation

1) Name of plant pest: Various species of mites:
   Particularly Rust mites
2) Present distribution: Worldwide
3) Anticipated effect of climate change:
   Increase of the number of generations a year due to lower developmental zero point and low thermal totals required for one generation, resulted in more infestation

Other effects

1) Name of plant pest:
   Zeiraphera diniana Guenée (Lepidoptera: Tortricidae) 'Larch bud moth'
2) Present distribution:
   Central European Alps
3) Anticipated effect of climate change:
   Disappearance of periodical outbreaks, resulted in continuous outbreaks
   (Baltensweiler, 1993, Oecologia 94 : 62-66)

1) Name of plant pest: Pests in green houses, such as whiteflies, aphids, mites, etc.
   In Japan, previously pests in greenhouses were all domestic species, but in recent years about 50% of them are alien species. They came to Japan and can overwinter in green houses. Some of them will be able to go into the field from the green houses in future.

1) Name of plant pest: Various herbivorous insects
2) Anticipated effect of climate change:
   Increasing of C/N ratio affects feeding habit and development of herbivorous insects such as leafhoppers, planthoppers, etc.

ANNEX 4

Philip Thornton, International Livestock Research Institute, ILRI

Tick-borne diseases: East Coast Fever (ECF), Anaplasmosis, Babesia, Cowdria (heartwater)

Present distribution: sub-Saharan Africa (SSA) has all the most important ticks and tick-borne diseases (TTBDs – cowdriosis, anaplasmosis and babesiosis). Asia lacks ECF but has tropical Theileriosis and other tick-borne diseases in many regions. Latin America and the Caribbean also have globally distributed TTBD.

Anticipated effects of climate change: changes in the spatial distribution of ticks, as a result of increases in temperatures and shifts in rainfall patterns and amounts, may cause considerable problems, in that if the ticks and the diseases they transmit moved into new areas, animal populations with little or no immunity would be exposed and suffer major disease impacts.

Otber vector-borne diseases: e.g. Rift Valley Fever

Rift Valley Fever - Present distribution: Countries with endemic disease and substantial outbreaks of RVF are Gambia, Senegal, Mauritania, Namibia, South Africa, Mozambique, Zimbabwe, Zambia, Kenya, Sudan, Egypt, Madagascar, Saudi Arabia, and Yemen.

A number of other vector-borne diseases will also be affected by climate change. Diseases such as bluetongue have expanded their range due to global warming.

Anticipated effects of climate change: as RVF is most commonly associated with mosquito-borne epidemics during years of unusually heavy rainfall, changes in patterns and intensity of rainfall could have considerable impacts on the disease, mostly in terms of shifts in the probabilities of extreme weather events.

New emerging vector-borne diseases

Present distribution: anticipated effects of climate change: similar to the above -- the basic problem is likely to be the introduction of disease into areas where animals have no immunity, and the impacts may be severe.

Internal parasites: gastro-intestinal parasites, liver fluke (fascioliasis)

Present distribution: widespread in developing countries, particularly in warm and humid conditions, but details on impact are limited in places.

Anticipated effects of climate change may induce changes in the distribution of the parasites and the intermediate hosts. In areas that become wetter, there will be greater importance. In drier areas transmission around focal water points may be important.

Trypanosomiasis

Present distribution: Tsetse flies and associated trypanosomiasis are restricted to Africa (West, Central, Eastern and Southern). East Africa has the highest number of cattle in tsetse areas, Central Africa the greatest proportion of cattle in tsetse zones.
Anticipated effects of climate change: Studies that have looked at possible impacts of climate change on cattle trypanosomiasis (McDermott et al., 2001; Thornton et al., 2006) indicate that while climate change will modify (generally decrease, but not everywhere) habitat suitability for the major groups of tsetse fly, the demographic impacts on trypanosomiasis risk through bush clearance are likely to outweigh those brought about by climate change.

General

The changes wrought by climate change on livestock infectious disease burdens may be extremely complex. There are several ways in which climate change may affect infectious diseases (Bayliss and Githeko, 2006): there may be effects on pathogens, on hosts, on vectors, and on epidemiology. There may be other indirect effects in addition, in terms of impacts on the abundance and/or distribution of the competitors, predators and parasites of vectors themselves, thus influencing patterns of disease. For example, in the pastoral areas of East Africa, drier conditions may mean fewer water points and thus more intense interactions between livestock and wildlife. The virus causing Malignant Catarrhal Fever (MCF) is carried by all wildebeest in the wild, and increased proximity of wildebeest to cattle could result in increasingly serious disease outbreaks (MCF is difficult to control). The same applies to buffalo strains of ECF that can be passed to livestock.

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ANNEX 5

Etienne Duveiller, International Maize and Wheat Improvement Centre, CIMMYT

Examples of pests and diseases that can be affected by climate change

1) Name
2) Present Distribution
3) Anticipated effect

Fusarium Head Blight

1) Caused by *F. graminearum*, *F. culmorum* and related species
2) Northern America, Southern Cone (Southern Brazil, Argentina, Paraguay), China (Yangtse River basin), Northern Europe.
3) More people subject to hidden mycotoxin infections. Reduction of incomes for some countries. With increasing rainfall at critical time of the growing season, more wheat areas will be subjected to mycotoxin infections (DON etc..) and this can affect trade since international regulations on authorized mycotoxin contents are becoming more stringent. Climate change expected to affect cropping systems with more maize being grown in some areas and pathogen surviving on a new crop in the rotation. Expansion of conservation agriculture and maize are also likely to change the pathosystem composition. In North Africa, unusual high rainfall are already showing more FHB outbreaks. Indian Sub-continent is currently spared from rains and thus of FHB during wheat growing season. If 'sporadic' rains occur more frequently with climate changes, as a result of mycotoxin contamination, FHB may turn-out as a huge problem for public health (food) and industry (feed). See risks in Bangladesh too. More fungicides will also be used.

Wheat Blast

1) Caused by *Magnaporthe grisea*, it emerged in Brazil in the mid-80's. The disease first considered related to rice blast appears originated probably from a grass. Host range is broad and it is seed transmitted.
2) Southern Brazil, Bolivia, Paraguay
3) Heavy losses due to absence of resistance. Adaptation of the pathogen in warm environments (i.e. South Asia) would be a disaster. Adaptation of the pathogen in warm environments. Increased yield losses, infestation in new areas due to ability/possibility of pathogen to survive in unknown alternate hosts.

Spot Blotch

1) Caused by *Cohliobolus sativus.*
2) Southern Brazil, Bolivia, Paraguay, Eastern India.
3) Heavy losses due to insufficiency of satisfactory resistance. Adaptation of the pathogen in warm environments (i.e. South Asia). More areas will be affected in South Asia as 50% of areas considered presently under favorable wheat growing conditions will become more subject to heat and water stress. Observations over 6 years in India, Nepal and Bangladesh have already shown that climate change is taking its toll as a result of the increase of average night temperature

penalizing grain filling and increasing the spot blotch severity. This effect is likely to increase in more optimum growing areas.

Yellow rust

1) Caused by *Puccinia striiformis*.
2) Cool wheat growing areas of Andean region, North America, western China, Northern Europe, Middle East and Central Asia.
3) New severe epidemics due to change of races. Indications exist that the pathogen has become more tolerant to heat. Heat average increase triggering races adapted to new thresholds of temperature requirements. More areas affected by epidemics or epidemics more frequent.

Leaf Rust

1) Caused by *Puccinia tritici*.
2) North and South America, Europe, North Africa, Russia, Middle East, Indian Sub-continent.
3) New epidemics due to change of races. In south Asia, the disease tends to appear late in the growing season when temperature is rising. Climate change can lead to disease spread in areas where its importance is minor at present, eg facultative and winter wheat growing areas of China, parts of Europe, Pacific Northwest of US, winter and facultative wheat areas of Central Asia.

Stem Rust

1) Caused by *Puccinia graminis*.
2) North and South America, China, Middle East, Indian Sub-continent, Australia
3) New epidemics due to change of races and lack of genetic resistance. Change in heat average and relative humidity may trigger races adapted to new thresholds of environmental requirements. There is a study done in the UK indicating where in Europe Ug99 can become important with global warming.

Indian Peanut Clump Virus

1) IPCV
2) Restricted to a few areas (i.e. Rajasthan, southern India) where wheat is grown on peanut fields.
3) Yield losses. Seed and soil fungi (Polymixa) transmission. No resistance in wheat or largely unknown. Climate change likely to affect cropping systems patterns. Changes in rotations or cropping sequences due to high cereal prices may induce new infections of field or spread of the disease.

Barley Yellow Dwarf Virus

1) BYDV
2) Northern America, Ecuador, China, Pakistan, Northern Europe.
3) Yield losses. Not enough resistance in wheat. Resistance on virus diseases in developing countries presently largely under-funded, delaying to capacity of reaction against the problem. Climate change (drought) will increase the survival and spread of the aphids. In Pakistan it has been observed that some years, dry air favors aphid flights.

ANNEX 6

Jorge Hendrichs, Joint FAO/IAEA Division

The list of potentially invasive *Tephritid fruit flies* can be quite long (see attached list, many of which are polyphagous species). However, as mentioned by others, we cannot really nominate species or groups of species without a context. One can see six broad situations (see table below), based on which there appear to be two main scenarios that are relevant for fruit flies:
a) without competition from resident species, where only abiotic factors largely determine establishment and/or range expansion, or
b) with competition from related resident species, where both abiotic and biotic factors determine establishment and/or range expansion.

Introductions, Natural Expansions or Interactions	No Competition	Competition
Man-caused Invasions without Climate Change (ongoing for many hundreds of years)	Introduction into climatically suitable areas and establishment in the absence of related resident species. Examples: introductions of *Anastrepha*, *Bactrocera*, *Ceratitis* spp. fruit flies into tropical/subtropical islands that had been fruit fly-free, or *Rhagoletis* spp. into temperate regions.	Introduction into climatically suitable areas and establishment in the presence of competing resident species. Examples: many cases of K-selected *Bactrocera* spp. outcompeting more-r-selected native fruit flies; but also examples where more r-selected good colonizers could not become established.
Climate Change-caused Natural Expansions (but also Contractions)	Natural expansion into previously climatically unsuitable areas and establishment in the absence of related resident species. Examples: *C. capitata* expanding its range in southern Europe (already a temporary occurrence after mild winters).	Natural expansion into previously climatically unsuitable areas and establishment in the presence of related resident species. Examples: *Bactrocera* spp. expanding into subtropical areas of China.
Interaction of Man-caused Invasions with Climate Change	Introduction into previously climatically unsuitable areas and establishment in the absence of related resident species. Increased risk of establishment of introductions in formely prohibitive areas. Examples: *Anastrepha* spp. in California and Texas.	Introduction into previously climatically unsuitable areas and establishment in the presence of related resident species. Examples: *B. zonata* establishment in cooler/dryer areas of Near East and Mediterranean region.

Evidence from many situations of fruit fly invasions/expansions indicates that in a majority of cases, particularly in the tropics or subtropics, there is competition with native or previously introduced species, and this determines success or failure of establishment. In this regard, one can broadly generalize that polyphagous *Bactrocera* spp. nearly consistently outcompete all other fruit fly pests, while polyphagous *Ceratitis* spp. outcompete *Anastrepha* spp. fruit flies. Therefore the focus should be on these species that have greater invasive/range expansion potential.

Major Tephritid Species of economic importance and their Attractants.

Scientific Name	*Attractant*
Anastrepha fraterculus (Wiedemann)	Protein attractants (PA)
Anastrepha ludens (Loew)	PA, 2C[*] attractant
Anastrepha obliqua (Macquart)	PA, 2C[*] attractant
Anastrepha striata (Schiner)	PA
Anastrepha suspensa (Loew)	PA, 2C[*] attractant
Bactrocera carambolae (Drew & Hancock)	Methyl Eugenol (ME),
Bactrocera caryeae (Kapoor)	ME
Bactrocera correcta (Bezzi)	ME
Bactrocera dorsalis[****] (Hendel)	ME
*Bactrocera invadens (*Drew,Tsuruta&White)	ME, 3C[**]
Bactrocera kandiensis (Drew & Hancock)	ME
Bactrocera occipitalis (Bezzi)	ME
Bactrocera papayae (Drew & Hancock)	ME
Bactrocera philippinensis (Drew & Hancock)	ME
Bactrocera umbrosa (Fabricius)	ME
Bactrocera zonata (Saunders)	ME, 3C[**], ammonium acetate (AA)
Bactrocera cucurbitae (Croquillet)	Cuelure (CUE), 3C[**], AA
Bactrocera cucumis (French)	CUE, PB
Bactrocera tryoni (Froggatt)	CUE
Bactrocera tau (Walker)	CUE
Bactrocera latifrons (Hendel)	PA
Bactrocera citri (Chen)	PA
Bactrocera tsuneonis (Miyake)	PA
Bactrocera minax (Enderlein)	PA
Bactrocera oleae (Gmelin)	PA, ammonium bicarbonate, Spiroketal
Ceratitis capitata(Wiedemann)	Trimedlure (TML), Capilure, PA, 3C[**], 2C[***]
Ceratitis cosyra (Walker)	PA, 3C[**], 2C[***]
Ceratitis rosa (Karsh)	TML, PA, 3C[**], 2C[***]
Dacus ciliatus (Loew)	Protein attractants, 3C[**], AA
Rhagoletis cerasi (Linnaeus)	Buthyl hexanoate (BuH), ammonium salts (AS)
Rhagoletis pomonella (Walsh)	BuH, AS

Toxotrypana curvicauda (Gerstaecker)	2-methyl-vinyl-pyrazine (MVP)

[*]2C Two components synthetic food attractant mainly for female captures (Ammonium Acetate, Putrescine)
[**]3C Three components synthetic food attractant mainly for female captures (Ammonium Acetate, Putrescine, Trimethylamine)
[***]2C Two components synthetic food attractants mainly for female captures (Ammonium Acetate, Trimethylamine)
[****]Includes many species whose taxonomic status is uncertain.

ANNEX 7

Mike Hine, Independent Consultant

Diseases of aquatic animals

Name of animal disease: Oyster herpesvirus 1 (OsHV-1)

Present distribution:

Host	**Country**	**Reference**
Crassostrea virginica	East coast, U.S.A.	Farley et al. (1972)
Crassostrea gigas	New Zealand	Hine et al. (1992)
Crassostrea gigas	France	Nicolas et al. (1992)
Ostrea angasi	Australia	Hine & Thorne (1997)
Ostrea chilensis	New Zealand	Hine et al. (1998)
Saccostrea glomerata	Australia	Hine (1999)
Ruditapes philippinarum	France	Arzul et al. (2001a)
Pecten maximus	France	Arzul et al. (2001b)
Crassostrea gigas	Mexico	Vasquez-Yeomans et al. (2004)
Crassostrea gigas	West coast, U.S.A.	Burge et al. (2006)
Ostrea edulis	Spain	Da Silva et al. (2008)

C. virginica (Eastern oyster), C. gigas (Pacific oyster), O. angasi (Australian flat oyster), O. chilensis (Chilean flat oyster), O. edulis (European flat oyster), S. glomerata (Sydney rock oyster), R. philippinarum (Manila clam), P. maximus (European giant scallop)

It appears that OsHV-1 has been spread in C. gigas, moved extensively in and between Eurasia, the Americas, and Australasia since the 1980s, to replace flat oysters (Ostrea spp.) destroyed in large scale epizootics, due to other pathogens (Bonamia spp.). Infection of C. virginica (Farley et al. 1972), may have originated from C. gigas that were moved from the west coast to the east coast of the U.S.A. in the late 1950s. Apparently healthy adult (Arzul et al. 2002) and larval (Hine et al. 1998) C. gigas, harbor latent infections. OsHV-1 isolates within geographic regions are now more genetically similar to each other than between regions, irrespective of new regional host species.

Mass mortalities (>95%) occur among larval (Le Deuff et al. 1996, Renault et al. 2000) and juvenile (Friedman et al. 2005, Da Silva et al. 2008) oysters and other commercially important bivalves, both in hatcheries (Hine et al. 1992, Renault et al. 2000) and in the wild (Burge et al. 2006). Inter-species transmission readily occurs, particularly in hatcheries (Renault et al. 2000).

Anticipated effect: C. gigas accounts for ~80% of global oyster production, and for the past several years has had the highest annual production of any freshwater or marine organism (4.2 million metric tons, worth $3.5 billion US). Oyster farms obtain their stock from 1) hatcheries, and 2) collection of settled wild oyster spat. OsHV-1 is highly pathogenic to both.

Anticipated effect of climate change: OsHV-1 infected bivalves at normal ambient temperatures do not usually experience either disease or mortalities (Farley et al. 1972, Arzul et al. 2002). In hatcheries (Hine et al. 1992, Renault et al. 1995, Le Deuff et al. 1996), and in the wild (Friedman et al. 2005, Dégremont et al. 2006), epizootics are associated with elevated temperature. In the original study on oyster herpesviruses, Farley et al. (1972) showed that oysters held at 18°C-20°C remained healthy, while replicates held at 28°C-30°C experienced mass mortalities. Thus warming climate change will result in epizootics globally of the most cultured aquatic species.

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Name of animal disease: Perkinsosis (*Perkinsus olseni* – parasitic Dinoflagellate)

Present distribution: *P. olseni* occurs in the Pacific islands, Australasia (Goggin & Lester 1987, 1995), Southeast Asia (Hamaguchi et al. 1998, Choi et al. 1997, Liang et al. 2001), Uruguay (Cremonte et al. 2005), and has been introduced into Spain (Camino-Ordás et al. 2001), France, Portugal, and Tunisia. European and North African isolates are often identified as *Perkinsus atlanticus,* which is conspecific with *P. olseni* (Murrell et al. 2002).

It was originally described in association with epizootics among abalone (*Haliotis* spp.) in southern Australia (Lester & Davis 1981), but was subsequently found to infect (Goggin & Lester 1987), and to be infective to (Goggin et al. 1989), >60 bivalve species around mainland Australia, very seldom causing disease (Goggin & Lester 1995). However, it was subsequently reported to cause epizootic disease in temperate venerid clams in Japan (Hamaguchi et al. 1998), China (Liang et al. 2001), and Korea (Choi et al. 1997), and, following its introduction into Europe in the venerid Manila clam, *Ruditapes philippinarum,* in European venerid clams (*Ruditapes decussatus*) (Camino-Ordás et al. 2001).

Anticipated effect: Currently venerid clams occur in warm to cold temperate latitudes, but *P. olseni* is temperature restricted to warm temperate latitudes. Clam culture and harvesting mainly in Asia, North America and Europe constitutes 80% of world clam production. *P. olseni* causes variable mortalities of 60-80% among cultured and wild clams.

Anticipated effect of climate change: The original description of *P. olseni* was from epizootic mortalities among abalone during and following unusually high summer temperatures (Lester & Davis 1981). The current distribution of *P. olseni* is temperature limited. For example, a susceptible host, the venerid clam *Austrovenus stutchburyi,* occurs all around New Zealand, but *P. olseni* only infects and kills *A. stutchburyi* in the north of the country, north of 37°S (Hine & Diggles 2002). Similarly, susceptible hosts occur in Tasmania, which is south of 40°S, and there is movement of venerid clams between mainland Australia and Tasmania, but *P. olseni* has not established in Tasmania. Climate change resulting in warming will extend the range of *P. olseni* northwards in the northern hemisphere (as has occurred with another pathogen, *Perkinsus marinus* [Cook et al. 1998]), and southwards in the southern hemisphere, putting it into contact with currently unexposed wild and cultured venerid stocks. This is likely to result in epizootic spread and severe reduction in venerid clam production.

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Name of animal disease: Epizootic ulcerative syndrome (EUS) caused by *Aphanomyces invadans*

Present distribution: EUS occurs throughout Asia, Australia, Papua New Guinea, east coast U.S.A. It first broke out in Japan in 1971 (Egusa and Masuda 1971), then Australia, New Guinea, southeast Asia, southern Asia, and western Asia. A closely related species infects menhaden in the eastern U.S.A. (Blazer et al. 1999). EUS is non-host specific, and infects freshwater, estuarine and marine fish, but some species are more resistant than others. It occurs in the tropics, sub-tropics and warm temperate regions. Chronic to acute infections.

Anticipated effect: A reduction in fish populations, particularly estuarine and coastal species, but not sufficient to seriously affect populations overall. The infection is likely to spread into fish ponds, particularly if farms are stocked from the wild.

Anticipated effect of climate change: Warming trends are likely to see range extension into what are now temperate regions, because of movement of infected hosts. However, a cooling trend may also increase disease in enzootic regions, as EUS occurs during periods of low temperatures (18°C-22°C) and after periods of heavy rainfall (Bondad-Reantaso et al. 1992). These conditions favour sporulation of *Aphanomyces invadans*, and low temperatures delay the inflammatory response of fish to oomycete infection (Catap and Munday 1998).

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ANNEX 8

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Climate change and vulnerability to introductions by plant and animal pests and diseases

Abstract

The concept of vulnerability is described in the context of climate change and illustrated with worked examples. Risk assessments need rigorous analytical techniques, quality datasets and consideration of species interactions as well as linked pest-crop/livestock analyses. In addition, risk assessments for biosecurity must take international trade patterns and WTO rules into account. Internal movement issues in relation to pest-free zones also need to be assessed.

There are real difficulties in relying on climate change scenarios when designing adaptation options. Based on the IPCC 2007 scenarios biosecurity risks will increase in temperate areas with increasing temperatures and change in uncertain directions in tropical and subtropical zones, where rainfall changes will dominate. Most developing countries are ill-equipped to manage changing risks from climate change because they have such poor internal and international border controls. This makes them particularly vulnerable to new pests and diseases under climate change.

It is concluded that parsimonious approaches are needed to risk assessments of most transboundary pests and diseases due to data and resource constraints. Combined climate change scenarios and sensitivity analyses are needed. There is an urgent need to improve the quality of the field pest data and a new initiative towards that goal will be described. Risk assessments require globally applicable, generic modelling tools that link crop/livestock and pest/disease risks, and include triple-bottom line accounting methods to assess vulnerability. Such approaches need to be applied to source, transport and destination risk assessments.

Introduction

Rather be approximately right than precisely wrong

Much has been written about the well-established pest risk analysis (PRA) procedures supervised by the IPPC. Assessments involve defining the risks associated with the sources, pathways and destinations involved in international trade. These need to be made in the absence of perfect knowledge and with many frustrations in procedures and commodity-based risk assessments. The main effect of climate change is to alter the geographical sizes of sources and destinations, and change the climatic suitability of each location for local populations. This will also result in changes to the phenology of species. Of course, sources are also destinations so the issues involved are very similar at each end of the pathway. For this reason, I have not separated the three processes but I have tried to focus on the effects of climate change on transboundary pests and management of the changing ecology. This has been hampered by a lack of worked examples for each taxonomic group.

A wide range of stakeholders needs vulnerability analyses of pests, vectors and invasive species under climate change. It includes national agricultural enterprises, natural ecosystems, and public health agencies. Source, pathway and destination risks will all change in various ways depending on the pattern of climate change, the region, the crop and the pest or disease involved. Interaction between climate change and other global change drivers such as enhanced concentrations of atmospheric gases, trade patterns, irrigation practices and human health, for example, will affect the outcomes of risk assessments. In this paper a brief outline is presented of the most pertinent issues involved with risk assessments for transboundary pests (pests, diseases and weeds) as they are affected by climate change.

Definitions

In global change, the concept of vulnerability goes beyond the estimation of impacts to identifying the capacity of stakeholders to implement adaptation options. The aim of research on biological responses to climate change is to determine the vulnerability of taxa and either natural or managed systems to such change. Adaptation may be either natural, including ecological and genetic adaptations, or managed as in the case of policy or local management interventions. Vulnerability is defined thus:

Vulnerability = Impacts x Adaptation, where
Impacts = Exposure x Sensitivity

The degree of *exposure* to climate change depends on the region, with larger temperature changes expected in northern polar regions in particular and the least in the tropics. Minimum temperatures are expected to increase more than maximum temperatures due to the higher moisture content in the atmosphere. Changes in available soil moisture are more uncertain and some northern temperate regions are expected to get wetter and sub-tropical regions to get drier (IPCC 2007).

The impacts of climate change on global agriculture will be determined by both the particular hazard and context involved. Production of crops, livestock and aquatic animals will vary according to their *exposure* to climatic hazards, such as droughts, floods, extreme temperatures and rises in sea-levels. The *sensitivity* of each production system to those hazards will depend on both the crop and pest/disease species involved and their geographical location. These responses will be modified by the local biodiversity, acting as regulators of populations to varying degrees. The combination of exposure and sensitivity will determine the potential impacts in any given situation.

The increasing temperatures in the temperate latitudes will result in less cold stress from low minimum temperatures, longer growth seasons with more degree-days for development and more heat stress of temperate species from higher maximum temperatures. As these changes take place, day lengths remain unchanged so species with close linkages to day lengths will have their dormancy, diapause, migration or reproductive processes disrupted. In addition, they will be at risk of a loss of synchrony with other species of plants and animals with which they interact but which respond differently to temperature changes. All of these changes will contribute to shifts in the geographical distributions of pests. Temperate species will push further towards the polar regions while tropical and sub-tropical species will encroach on the temperate regions.

In the tropics the most likely changes of biological significance will be related to changes in available moisture. With lower average rainfall scenarios, and more intense rainfall events dispersed between longer dry periods, the seasonal growth and stress patterns of many pests and their associated biota are likely to alter. More prolonged and intensive droughts are expected. Crop pests and pathogens may be affected by changes in the crop canopies as enhanced concentrations of CO_2 stimulate growth of foliage in situations where other nutrients are not limiting.

The *adaptive capacity* of any given agricultural system will depend on a number of biological, economic and sociological factors. While some crop species have high phenotypic or genetic plasticity and will be able to respond to climate change, others with a narrow genetic base will fail and need human intervention in terms of species switching or selective breeding. The extent of potential impacts and adaptive capacity determines the *vulnerability* of a species, agricultural enterprise or other local or regional system to climate change. The capacity of local communities to adapt their agricultural enterprises will depend upon their physical, social and financial resources, as measured by 'triple-bottom line' accounting methods. Resource-poor societies will be more vulnerable to climate change if their agricultural production systems are not biologically resilient to potential impacts.

The uncertainty and spatial heterogeneity of climate change scenarios means that they cannot be used as targets for designing adaptation strategies. Rather, a combination of scenarios and sensitivity analyses is needed. Adaptation strategies need to be designed to be resilient and insensitive to regional climate change.

Methods

A hierarchical and generic approach to assessment of vulnerability to climate change

The international global change community's approach to assessment of vulnerability to plant pests under climate change was summarized by (Sutherst, Baker et al. 2007). The basis of the biosecurity risk assessments is that it is not cost-effective to undertake in-depth analyses for the burgeoning imports. Similarly, detailed analyses of most pests to determine their potential impacts with climate change are not feasible. Limits to resources demand parsimonious approaches that exploit minimum data sets and generic modelling tools to answer questions related to numerous pest species on a global scale. To this end, a hierarchy of approaches with escalating demands and cost, based on resources and needs, was proposed (Sutherst, Yonow et al. 1996). Needs vary depending on how widely the impacts of the pest are likely to be felt in the industry or community. The nature of the industry sector and its reliance on overseas markets, which themselves may be affected by climate change, will contribute to the needs of a comprehensive vulnerability analysis. Such analyses therefore need multidisciplinary collaboration to address different industries, commodities and community interests.

The proposed hierarchy ranged from use of expert opinion, rule-based assessments, analogous climates, species-specific climate-envelopes, process-based simulation models, and linked crop-pest models (Teng, Heong et al. 1996) to macro-economic analyses of the vulnerability of industries or regions (Sutherst, Collyer et al. 2000; White, Sutherst et al. 2003).

A generic tool is one in which the computer code remains constant and the user assembles modules of processes and objects to describe the behaviour of any type of organism (Reynolds and Acock 1997; Sutherst 1998; Sutherst, Maywald et al. 2000). Such models are then parameterised to represent the biological relationships for a particular species. In the context of biosecurity, a specific model must function anywhere across the globe without reparameterisation. Genericness relies on identifying common themes, processes and events that affect different taxa, management practices and impacts. Process-based models have to avoid the site-specific drivers that make them so useful for field-scale applications if they are to be applicable on regional or global scales. There is a trade off between generality and simplicity. For cost reasons, such models will remain as niche tools for use on the most costly pests and for use in wealthy countries.
The following resources and characteristics are essential parts of any effective generic modelling package for use in climate change impacts:

- A pool of modularised biological processes including development, reproduction, survival, longevity and mobility etc. that can be coupled with any lifecycle stage.
- The ability to assemble life stages into lifecycles and to link them to attributes, to each other and

to other species.

- 'Inheritance' of properties from existing modules, to enhance or adapt them to new needs without the risk of damaging the original code.
- A spatial modelling platform to enable the storage and retrieval of geo-coded data and to display the results.
- A modelling paradigm that functions globally rather than only locally, using biologically meaningful climatic variables, with the capacity to handle radically different climatic patterns. Local models - usually static, GIS-based, statistical models - are rarely appropriate for this purpose.
- The ability to discriminate between climatic and non-climatic causes of changes in the population dynamics and geographical distributions of species. This requires the models to accurately capture the climatic response, so ensuring that residual variance can be confidently tested for other causes.

In Australia we have developed such an integrated, modular and spatial toolkit for conducting risk assessments of species for a range of needs. This DYMEX modelling toolkit (www.hearne.com.au) includes an inferential model, CLIMEX, to infer species responses to climate from their geographical distributions and seasonal phenology. DYMEX also includes a system for building process-based population models of animals and plants without the need to write any code. The CLIMEX spatial platform is available for use with the population models. Currently, the Bill and Melinda Gates Foundation-funded HarvestChoice project is enhancing and applying the DYMEX toolkit to facilitate the assessment of pest losses of food crops (with an initial focus on the current or potential pest problems of poor smallholders in sub-Saharan Africa and South Asia) in collaboration with several CGIAR centres. The aim of the HarvestChoice project is to incorporate pest damage information (see below) into an economic analysis for targeting funding to on-farm and post-farm productivity and profitability. One aim is to reduce the gap between potential and actual yields, as well as stabilizing yields. Experience with DYMEX/CLIMEX is expected to contribute significantly to the development of a valuable platform for integrated risk assessments for other purposes such as climate change in the future. Concurrently, PRATIQUE, a new EU Network initiative coordinated by Dr Richard Baker, is aimed at addressing the many outstanding issues involved with improving technology for conducting pest risk assessments or PRAs.

Global climatic datasets now exist for historical monthly averages for temperature, rainfall and evaporation with a resolution of 30' over the past 100 years. These are an invaluable resource for biosecurity analyses. The first step in any pest risk analysis is to define the climatic gradients in the region of interest to provide a template with which to estimate the biological responses. This is done using the 'climatic gradients' utility in the CLIMEX model, which provides relative values of the annual heat load, soil moisture and combined hydro-thermal indices. These indices alert the user to the biologically meaningful climatic features of the target area.

A lot has been written about the relative merits of different modelling tools but insufficient emphasis is placed on the quality of the species data that is used to parameterise and test models. Of particular importance is the need to distinguish between overwintering and summer ranges of species that have high mobility such as the plant hoppers, bollworms, aphids, midges and myiasis flies. If existing records do not adequately sample the environmental space that a species can potentially occupy, no model will be able to deliver safe projections of potential geographical distributions in other regions. One of the major components of the HarvestChoice project is a structured elicitation of regional expert opinion and data on actual pest distribution and damage in the developing world. It uses an innovative, geographically-enabled elicitation website.

Questions

Is invasive species ecology mature enough to address pest risks with climate change?

Invasive species ecology is in its infancy, despite the plethora of attempts to predict potential ranges of invaders in new environments. The most obvious symptom of its immaturity is the lack of consideration by modellers of the non-equilibrium nature of much of the data on invasions. The usual response in both the environmental and pest modelling sectors has been to use static, statistical models to describe the data. The chaotic results from different statistical models when applied to the same datasets has led to the use of a so-called consensus approach to the problem, with averaging or subjective selection of the best models with each application (Thuiller 2003). This is a giant step backwards. It evades the issue of why the models give such different results and hence does not address the root causes of the problems. In contrast the climatic envelope approach has demonstrated repeatedly that it is able to identify areas that are climatically receptive to invasions (Sutherst, Maywald et al. 2007). The challenge is to progressively include non-climatic variables.

Climate change is a corollary of transboundary movements in the sense that, in both cases, the target pest is exposed to a new environment. In the former case the environment evolves around the pest while, with transboundary movements, the pest may be introduced into environments with quite different climates (Baker, Sansford et al. 2000; Sutherst, Maywald et al. 2000). Translocations have much greater potential to expose the species to novel climates as well as novel biota. It follows that if we can define the risks from translocations we can be confident that, with the right tools, we can define risks from climate change. Of course, there is always the caveat that exposure to new species interactions are essentially undefinable *a priori.* Such novel interactions can have powerful effects and may mask any effect of climate change (Sutherst, Maywald et al. 2007). Pests, by their very nature, tend to have fewer inter-specific interactions than other species but even they are often strongly suppressed by predation as evidenced by the success of so many biological control programs.

Spatial environmental heterogeneity is often responsible for providing local *refugia* for invasive species that arrive during extreme climatic events. For example, during very wet years in the mid-1970s in Australia, *Haematobia irritans exigua*, the buffalo fly, expanded its range by some hundreds of kilometres, only to remain entrenched in some benign coastal pockets that provide shelter from severe winter temperatures (Williams, Sutherst et al. 1985). If expectations of an increase in the frequency of extreme climatic events with climate change are confirmed, such invasions may become more common. Indeed (Rosenzweig, Iglesias et al. 2001) found numerous examples in which human disease incidence was affected by such events. The resolution of most climatic datasets and models is usually insufficient to identify such local refugia but on occasions they have been detected The invasive climbing fern *Lygodium mircophylum* was discovered several hundred kilometres south of its known range in eastern Australia after the peninsular site was identified as being climatically suitable using the CLIMEX model (J. Goolsby pers comm.).

Sources

Risks associated with sources relate not only to established species but also to temporary introductions that may breed and escape in exports before dying out the following winter. This adds an extra dimension to PRAs. For example New Zealand blocked importation of fruit from Australia because it could have introduced Queensland fruit fly, even though it was acknowledged that the fly could not overwinter. Before the winter the fly could have undergone a generation and contaminated export fruit. The areal extent of sources of resident pests will expand polewards in temperate latitudes and retract in regions with temperatures that are already close to the upper limits for that species. To that extent one of the major risks involves protection of zones with 'area freedom' enjoyed by some crop and livestock producers outside the current range of major quarantine species. One such case is the Queensland fruit fly, *Bacterocera tryoni*, in south-eastern Australia (Sutherst, Collyer et al. 2000). Many other fruit and vegetable growing countries have similar problems with different species of fruit fly. A priority is to improve the quality of mapping of species occurrences around the world.

Pathways

One of the primary tools of biosecurity is farm hygiene to avoid the spread of pests with movement of livestock, machinary or plant material. Failure to implement rigorous procedures results in costly spread of pests such as livestock ticks in Africa, fire ants in North America, woody weeds in Australia, and plant pathogens such as the root rot fungus *Phytophthora cinnamomi* in many countries. As the potential ranges of these species expand with global warming, better management of pathways needs to become a vital part of any adaptation package.

Destinations

On *arrival* at a destination an exotic species has to establish and the spread. Williamson and Fitter (1996)'s 10s rule is a useful, general guide to the rates of success of such pest species being introduced, becoming established and then becoming invasive. *A priori*, it is possible to estimate the area that is climatically receptive to a species, with the usual caveats on genetic homogeneity, biotic interactions at both the source and destinations, and human-modified microhabitat such as irrigated crops. Such estimates allow a first-pass estimate of the areal extent of risks to target crops or other social or environmental features of concern. For example, the red imported fire ant, *Solenopsis invicta*, threatens summer rainfall areas of Australia and northern and western areas beyond the current boundaries of its introduced range in the USA. Road transport of horticultural produce provides an efficient vector while irrigation provides a receptive environment at the destination, even outside the natural climatic range.

The small chance of *establishment* of introduced species means that apparently small events may prevent establishment. For example, the Old World screw-worm fly, *Chrysomya bezziana*, was detected in Darwin harbour in northern Australia late in the wet summer season. An early end to the wet season that year may have contributed to its failure to become established (Sutherst, Spradbery et al. 1989). Climate change falls into this category of factors modifying the risks of establishment. The direction and strength of those changes will be species-, site- and time-specific as seasonal climatic patterns change.

Pests *spread* both naturally and with the aid of vectors of various types. The spread will be accelerated greatly by a receptive climate. Conversely, the spread of the red imported fire ant in Australia was almost certainly retarded by a prolonged drought soon after its initial containment.

Climate change is not occurring in isolation and any risk analysis of transboundary pests needs to take into account the concurrent changes in the other global change drivers like enhanced concentrations of CO_2. In addition changes are occurring in the patterns of trade, transport, crop species and varieties, pesticide resistance and technology etc. Each of these changes has the potential of causing shifts in species' geographical distributions that may appear to be caused by climate change. Or they may suppress the climatic signal. On top of this there may be interactive effects of combinations of global change drivers on species. Interactive effects of enhanced concentrations of CO2 and ozone on the growth of forest trees in North America have been reported (Percy, Awmack et al. 2002). They concluded that both gases need to be considered when assessing the risks from climate change. Increased transportation and human movement may act synergistically with temperature changes. In one of the most detailed analyses of a plant pathogen, (Bergot, Cloppet et al. 2004) predicted the geographic range expansion of *Phytophthora cinnamomi* in Europe in response to increased temperatures that would allow for overwintering of this oomycete in new areas.

Consideration of species interactions is another field which lacks rigour and sufficient field examples to allow us to generalize on their significance. Extrapolation from oversimplified laboratory experiments (Davis, Jenkinson et al. 1998) is dubious and such claims have not been supported with field data.

Very limited experience using the CLIMEX model has shown that, at least in certain classes of interactions, it is possible to infer their contribution to the potential geographical distribution of an invasive species (Sutherst, Maywald et al. 2007). Such interactions include competition and symbiosis, predation and host resistance. Genetic interaction causing hybrid zones are particularly powerful (Sutherst 1987; Sutherst and Maywald 2005). Many of these interactions are unstable and vary with host resistance, annual variation in climate and propagule pressure.

Interactions that rely on synchronised activity, such as bird migration and breeding on one hand and plant and herbivore phenology on the other, require process-based simulation models running on spatial platforms to identify the species and regions at risk of disruption with different amounts of global warming. The intense selection that such disruptions cause suggests that genetic adaptation will often occur. Techniques to explore the scope for genetic adaptation are needed by pest risk researchers.

Can we isolate climate change signals and define their impacts?

A key question is how to isolate the effects of climate change from the many other global changes that are taking place concurrently. Discrimination of the role of climate change from other global change drivers needs a whole-system, integrated monitoring program, plus reality checks against benchmarks. These benchmarks are needed to guide us in assessments of whether climate change could be responsible for observed changes in geographical distributions of invasive species. In relation to temperature, for each $1^{o}C$ increase there will be a potential for range expansions of ~ 200 km poleward. Similarly, spread of the species ~170 m higher in elevation can be expected for each $1^{o}C$ increase in temperature. Such benchmarks are only guides and greater amounts of spread are possible given favourable local microclimates, particularly in benign coastal habitats. Reported changes in species ranges need to be within this range in both direction and extent to have credibility, after consideration for relevant migration rates. There is a coherent global pattern of changes in the seasonal phenology and distribution of species that has been attributed to climate change (Parmesan and Yohe 2003). Changes in phenology are more readily related to climate change than are geographical distributions which are affected by other anthropogenic forces. Harrington, Clark et al. (2007) reported expectations of advances in first records of aphids in suction traps of 8 days on average over the next 50 years throughout Europe. They found strong discrimination between species with different lifecycles and between species feeding on herbs and trees. This led them to suggest that traits may be useful in predicting responses to environmental change. In contrast, no consistent advances were found in arrival times of wheat stem rust *Puccinia graminis* f. sp *tritici* in the USA, possibly due to less warming than the global average and the greater role of variation in moisture compared with aphids in the UK (Scherm and Coakley 2003).

Our approach has been to rely on our CLIMEX model to define the species response to climate and then to examine gross departures from the model predictions to direct a search for non-climatic explanations. This approach has identified numerous situations at risk where the species has later established or been found outside its current known range (Sutherst, Maywald et al. 2007). Ultimately, the climate change signal needs to be confirmed by physiological and ecological measurements. These include such variables as increased development rate, number of generations per year, decreased over-wintering mortality and both fecundity and survival that may also be strongly affected by moisture changes.

Past experience suggests that we can confidently anticipate the potential range of many potential invasive species if we have information on their home range and a sound climate response model. When changes are observed that are inconsistent with those expectations we need to look for other explanations such as restricted climatic heterogeneity at the source, biotypes, release from biotic resistance at the destination, new vectors etc. A CLIMEX checklist has been provided to encourage users to question the role of different factors in limiting geographical distributions (Sutherst 2003). Even when changes are consistent with expectations, caution is needed to ensure that other factors like resistance to pesticides or drugs may have allowed a pest or disease to escape suppression and expand into a new area. The spread of invasive species is very much related to propagule pressure at sources, pathways and destinations, so the rate of introductions is important.

In Europe, most of which is not moisture limited, the most likely effects of climate change will be related to increasing temperatures. This will extend the northern limits of species such as the tick, *Ixodes ricinus*, that transmits encephalitis viruses (Lindgren, Talleklint et al. 2000) in Scandinavia. Care is needed to take account of different effort in independent surveys. Likewise, bluetongue virus outbreaks have extended further north with warmer winters and apparently reached areas with other endemic, competent vector species, which in turn have extended the range of transmission purse (Purse and al. 2007). With the long dispersal range of *C. imicola* caution is needed in attributing this leap of transmission to climate change.

Interactive effects of climate change need much deeper analyses to detect and quantify. The major role that host resistance plays in the regulation of livestock parasites means that any climatically induced stresses on the hosts will have the potential to have magnified effects on their parasite populations. This has been found with nematodes in grouse in Scotland (Hudson 1974), the livestock tick *Boophilus microplus* on cattle in Australia (Sutherst, Kerr et al. 1983) and the winter tick, *Dermacentor albipictus* (Acari) on moose in Canada (Samuel 2004). In seasons of nutritional stress the numbers of ticks surviving on the hosts explodes even when the climate is detrimental to free-living stages of the ticks. Tick survival in Canada also increases with mild winters.

Drier subtropical zones will increase nutritional stress of cattle late in the dry season. While not considered to be a high risk transboundary pest, *R. B. microplus* is indeed a threat to cattle in Africa where few countries have either internal or interstate border restrictions on cattle movements. As a result the tick is expanding its range into highly receptive tropical regions (Sutherst 2001). It seems unlikely that climate change will play a significant role in such spread unless it is related to human migrations in response to increased drought or social upheaval as may be involved in the Sudan.

As noted above, interaction between increasing temperature and constant daylengths disrupts evolved relationships in species related to migrations, breeding and dormancy mechanisms. In the case of arthropods there may be sufficient genetic plasticity to facilitate rapid adaptation, so disruptions to lifecycles are likely to be shortlived. More data is required to support the outstanding example of the mosquito, *Wyeomyia smithii* in the New York area (Bradshaw and Holzapfel 2001). The authors found that with increasing temperature between 1972 and 1998 the critical photoperiod that triggers diapause decreased by over 30 min.

The likelihood that climate change will result in the emergence of new pests seems low unless it involves interactions between closely related species with resultant hybridization and the creation of new strains of pathogens with enhanced pathogenicity (Brasier 2000; Scherm and Coakley 2003). This occurred with Dutch elm disease *Ophiostima ulmi* and *O. novo-ulmi* on introduction to Europe. *Melampsora* spp, a fungal pathogen of poplar, hybrids inherited the host ranges from both parents. *Phythopthora cambivora* crossed with *P. fragariae* to produce a hybrid that attacked alder, which was not a host of either parent. Brasier (2000) concluded that the high frequency of new fungal hybrids indicates that many more such cases are likely in response to translocations by humans and environmental change including climate change.

Garrett, Dendy et al. (2006) reviewed the status of plant pathology in relation to climate change and made many useful recommendations that are consistent with those above. Wiedner, Rucker et al. (2007) analysed the population dynamics of the invasive cyanobacteria *Cylindrospermopsis raciborskii* and concluded that its invasion of temperate Europe was enabled by warming of temperate waters (Bourgeois, Bourque et al. 2004).

What role might pests have in affecting food security with climate change and where?

As species respond individualistically to climate change, it is difficult to generalize on likely threats to crops and livestock and specific analyses will be required. If we accept the general thrust of current climate change scenarios, and they are still very uncertain, we can anticipate that tropical regions will be more vulnerable to pests that are triggered by extreme rainfall events. On the other hand, sub-tropical and temperate regions are more likely to suffer from increased incidence of tropical and subtropical pests as these organisms migrate poleward with increasing temperatures. Migratory pests such as aphids, plant hoppers and midges appear particularly well adapted to exploit these emerging habitats. On the other hand, diminishing supplies of irrigation water from disappearing glaciers will reduce irrigated cropping in many regions, and so shift risks towards dry climate crops.

Authorities need to plan for greater interactive effects and annual variation in pest threats with climate change. I have referred to this as becoming more '*nimble*' and responsive to events rather than relying on our ability to anticipate them all (Sutherst 2004). Risks may increase from more frequent extreme climatic events but the average risk may reduce in the tropics with a drying scenario and intensified hydrological cycle.

The effects of global temperature change on rice leaf blast epidemics, caused by the rice blast fungus, *Magnaporthe grisea,* in several agroecological zones in Asia was studied with the CERES-Rice model coupled with BLASTSIM (Luo, Teng et al. 1998). Simulations suggested that the effect of temperature varied in different agroecological zones. In temperate Japan and northern China, higher temperatures increased the severity of blast epidemics while lower temperatures reduced them. Results in the humid tropics were opposite to those in cool areas.
In temperate rice systems, the main driving variables determining the size of populations of the brown plant hopper, *Nilaparvata lugens,* are the numbers entering the crop and the temperature during the growing season (Holt, Chancellor et al. 1996). Both of these factors are sensitive to global warming.

Analyses of food security issues need linked crop-pest models and economic models of global commodity trade.

Future research needs

We can distinguish between needs for routine risk assessments, based on current understanding, in support of biosecurity and those that are aimed at new understanding of the processes involved in changing risks from pests with global change. Adequate tools exist for the former needs and the task now is to conduct a sufficient number of integrated risk assessments of different classes of pests in different food production systems in different regions to enable researchers to generalise about likely patterns of vulnerability of different industries, commodities and regions, and hence trade pathways. Data and parameterisation issues are the main reason for delays in including non-climatic variables. Global drivers are easier to incorporate than local drivers because there is better access to harmonized global datasets. Thus we are restricted to global drivers for global scale risk assessments, with the lack of local detail that it imposes. At the other extreme, local drivers are usually needed to guide field-scale management decisions but they cannot be used to extrapolate results globally.

In relation to new knowledge, priorities are:

1) Gather data on states (eg. damage; geographical distributions – establish transects across climatic gradients) and processes (population dynamics).
2) Improve skills for detection of biotic interactions and characterise the role of biotic interactions across environmental gradients in the population dynamics of invasive species. Sound field and experimental data will be needed to clarify the mechanisms involved in interactions because they can be very subtle. Some projections may be possible for invasive species with a history of displacing related taxa, such as some fruit flies and ticks (Sutherst, Maywald et al. 2007). Tri-trophic interactions are difficult and logistically demanding to parameterise.
3) Increase focus on non-linearity of biological responses by including more than two treatment levels in all experiments (Sutherst 2001). In addition, include tests for interactions by including more than one environmental variable, such as temperature, moisture and CO_2.
4) The use of species traits offers promise of opportunity to generalise about responses to climate change. The choice of suitable attributes or traits to use in pest risk analyses centre on biotic potential, host type, mobility and species interactions (Harrington, Clark et al. 2007).
5) There is a need for an integrating, multidisciplinary framework based on (i) empirical data; (ii) qualitative evidence of underlying mechanisms; (iii) experimental validation; (iv) quantification of relationships within process-based, dynamic models and subsequent testing of the behaviour of the lifesystems concerned; and (v) integration of each process model into higher level physiological and economic models. The approach that is most appropriate will depend on consideration of the socio-economic resources available.
6) Develop methods for dealing with uncertainty in management of transboundary movements of pests. Incorporate climatic variability into risk assessments in order to overcome deficiencies in the use of long-term average data. This is now possible with the latest global climatic datasets but parameterisation and validation of models will require time-series data.
7) There is a continuing need to resolve the most appropriate amount of detail in simulation models to preserve their ability to apply globally. Such models are useful for improving our understanding of the responses of pests to environmental variables.
8) Linked crop-pest risk assessments, incorporating other global change drivers like: CO_2, climatic extremes; changing trade patterns; fuel costs; GMOs etc. are needed with output fed into macroeconomic models to assess food security issues as is being developed by HarvestChoice.

Adaptation

There is a major difference in the approaches to management of risk in the natural resources and commercial sectors. The former believe that they can explain and predict future outcomes of environment change, while the latter are more humble and believe that the world is too complicated to predict. The response of industry is to rely on scenarios of different futures and design their business models to withstand each of those scenarios. There is considerable merit in this approach in the current context.

A global change workshop in Nairobi discussed issues in common between vector-borne diseases of plants, animals and humans and the development of adaptation measures (Sutherst, Ingram et al. 1998; Sutherst, Ingram et al. 1998). Local adaptation measures will be required in response to changes in the dynamics of vectors, diseases and host populations, as well as to changes in habitats. Changes in the geographical distributions of vector-borne diseases will require further measures related to quarantine exclusion and regulation of movement of host material. The meeting placed importance on the sustainability of each adaptive tool and rated its robustness in the face of environment change. Robustness depends on the sensitivity of the method to changes in the timing, intensity and spatial movement of the target species under global change. Biological control methods and exploitation of host resistance through vaccination, selective breeding or genetically modified organisms ranked highly.

Not-withstanding the comments above in relation to assumptions about the ecological community's ability to fully understand problems, it is desirable to make evidence-based decisions on adaptive measures to the extent that it is possible. A biosecurity-focussed pest management decision support-system (DSS) would provide a solid foundation for a global response to disruptions imposed by climate change on the management of transboundary pests.

Will relevant agencies and organizations need to adapt to management of climate change effects on transboundary pests?

1) Climate change has changed the way in which the world has to view many decision-making processes because we can no longer rely on historical precedents to design future actions. Instead we need to follow trends in climate and track their effects on biological systems. Sound monitoring is essential to provide baseline data against which to measure the effects of climate change as well as to measure the effectiveness of response strategies.
2) The key to effective adaptation is to increase the capacity of management to cope with uncertainty. This means building in resilience and redundancy, as well as encouraging the adoption of robust biological solutions to pest problems where possible.
3) Strengthening of rapid response capabilities will be one necessary measure.
4) Acceleration of adoption of new technology and approaches will be essential as the rates of environmental change increase. The use of workshops built around exploration of future scenarios of change will be effective, with the assistance of simulation modelling tools when that is appropriate. The aims would be to design systems that are insensitive to spatial and temporal variation in the climate.

Some components of an effective adaptation strategy could include:

1) Establish *Benchmarks* of current biosecurity status
    1. Incursions
    2. Establishments
    3. Impacts
    4. Costs of biosecurity
2) Monitor *Indicators* of change in biosecurity
    5. Rates of introductions and invasions by foreign species
    6. Rates of crop, livestock, forest and fish losses
    7. Costs of biosecurity

3) *Accelerate Adoption* of new technology

8. Work-shopping tools including scenario analysis and simulation modelling
9. Internet-based data collection and dissemination of information

Conclusions

Climate change is ongoing and has changed the way in which the world will do business, with the loss of the ability to base decision-making on historical precedents. The rate of environment change is such that new processes and structures will be necessary to accelerate the adoption of new technology and ways of doing business. This will be particularly challenging at the international level where different countries and regions have vastly different needs and capacities to develop and adopt new tools and practices. The strong reliance on consensus-based decision making in international fora makes the need for tools to facilitate rapid evolution of processes and adoption of new paradigms particularly urgent.

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