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Climate-change impacts on plant pests: a technical resource to support national and regional plant protection organizations

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Preface

Climate change is having an impact on ecosystems and agricultural production systems throughout the world. It influences international trade flows of plants and plant products and it will change the infectivity, severity and distribution of plant pests throughout the world. Preventive, mitigation and adaptation measures by national plant protection organizations (RPPOs) and regional plant protection organizations (RPPOs) are essential to limit the international spread of pests adapting to climate change.

Climate-change impacts on ecosystems, pests and vectors also threaten the international trading system, as international trade provides a pathway for pests and vectors to spread into new areas of the world. To facilitate safe international trade in plants and plant products, it is therefore imperative to strengthen national, regional and international phytosanitary capacities regarding climate change (IPPC Secretariat, 2021a).

Assessment and management of climate-change impacts on plant health present a major challenge to national, regional and international plant protection organizations. Improved forecasting and modelling tools, harmonized surveillance and monitoring systems, accessible pest information and knowledge systems, and epidemiology and pathogenicity research can impact plant health.

The aim of this document is to provide technical and operational advice to NPPOs and RPPOs on how to effectively assess and manage the pest risk that is a consequence of climate change.

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Contents

Acknowledgements

This document has been developed by experts of the Commission on Phytosanitary Measures (CPM) Focus Group on Climate Change and Phytosanitary Issues, with oversight from the CPM Bureau. This document was also open to consultation to contracting parties of the International Plant Protection Convention (IPPC) through the IPPC Online Commenting System.

Abbreviations

CABI	Centre for Agriculture and Bioscience International
CPM	Commission on Phytosanitary Measures
EPPO	European and Mediterranean Plant Protection Organization
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GCM	global climate model
IPCC	Intergovernmental Panel on Climate Change
IPPC	International Plant Protection Convention
ISPM	International Standard for Phytosanitary Measures
NPPO	national plant protection organization
NRO	national reporting obligation
PRA	pest risk analysis
RCP	representative concentration pathway
RPPO	regional plant protection organization
SSP	shared socioeconomic pathway

Explanatory note

This technical document refers to relevant International Standards for Phytosanitary Measures (ISPMs) and other materials developed under the auspices of the International Plant Protection Convention (IPPC) Secretariat. To the extent that is reasonably practicable, the terms used are consistent with ISPM 5 (Glossary of phytosanitary terms) as at May 2024.

Further information can be found on the dedicated CPM Focus Group Climate Change and Phytosanitary Issues web page of the IPPC website. [1]

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[1] Focus group webpage: www.ippc.int/en/commission/cpm-focus-group-reports/climate-change-and-phytosanitary-issues/

1. Introduction

The aim of this document is to provide practical and relevant advice to national plant protection organizations (NPPOs) and regional plant protection organizations (RPPOs) on how to strengthen both national and regional phytosanitary systems to better assess and manage the pest risk that is a consequence of climate change.

The document also provides technical advice on incorporating climate-change considerations into regular phytosanitary activities. The advice has been developed by reviewing relevant literature and considering how it applies to the role of NPPOs.

Detailed factsheets about the impacts of climate change on plant pests are provided by several organizations, including the Food and Agriculture Organization of the United Nations (FAO), the Centre for Agriculture and Bioscience International (CABI), the Standards and Trade Development Facility and the Intergovernmental Panel on Climate Change (IPCC), among others. In addition, a video is provided by FAO (FAO, n.d.): www.youtube.com/watch?v=xaK7CWtcNh4

Why is climate important for determining pest risk?

Climate change and extreme events can have significant impacts on pests by influencing their distribution and life cycle and hence their pest status and the associated level of pest risk.

Climate has a direct effect on invertebrate pests by influencing their rate of reproduction, development, survival, longevity and dispersal. Climate can also have an indirect influence on insect pests by its effect on plant hosts, natural enemies and competitors. With some exceptions, insects are ectothermic, meaning that they rely on external heat sources and sinks to regulate their body temperature. Small changes in temperature can have dramatic effects on the rate of biochemical reactions in insects, pathogens and vectors (Prakash *et al.*, 2014). Therefore, any changes to the climate in a particular location or a period of extreme weather can have major impacts on insect pests.

Climatic factors are one of the three elements of the conceptual plant-disease triangle that explains the likely impact of plant pathogens. For an infection to take place, specific conditions must align: a susceptible host, a plant pathogen and an environment conducive to the pathogen's proliferation. An example of this can be seen in the case of *Xylella fastidiosa*, which is a vector-transmitted bacterial plant pathogen of which some subspecies affect grapevines, *Prunus*, olives and a range of other plants. It is native to the Americas but has spread to parts of southern Europe as a result of host-plant availability and a conducive environment for its spread and establishment. The distribution of *X. fastidiosa* has been shown to be limited by cold conditions in the winter and, in the case of grapevines, temperatures above 37 °C have also been shown to limit its distribution (Godefroid, 2019).

All plants, including plants as pests, are also directly affected by climatic factors such as temperature, precipitation, humidity, radiation and carbon dioxide levels. These climatic factors affect the ability of plants to grow, establish, resist infection and spread. Although responses are variable and complex, in many cases anticipated climate changes are expected to favour plants as pests (Clements, DiTommaso and Hyvönen, 2014).

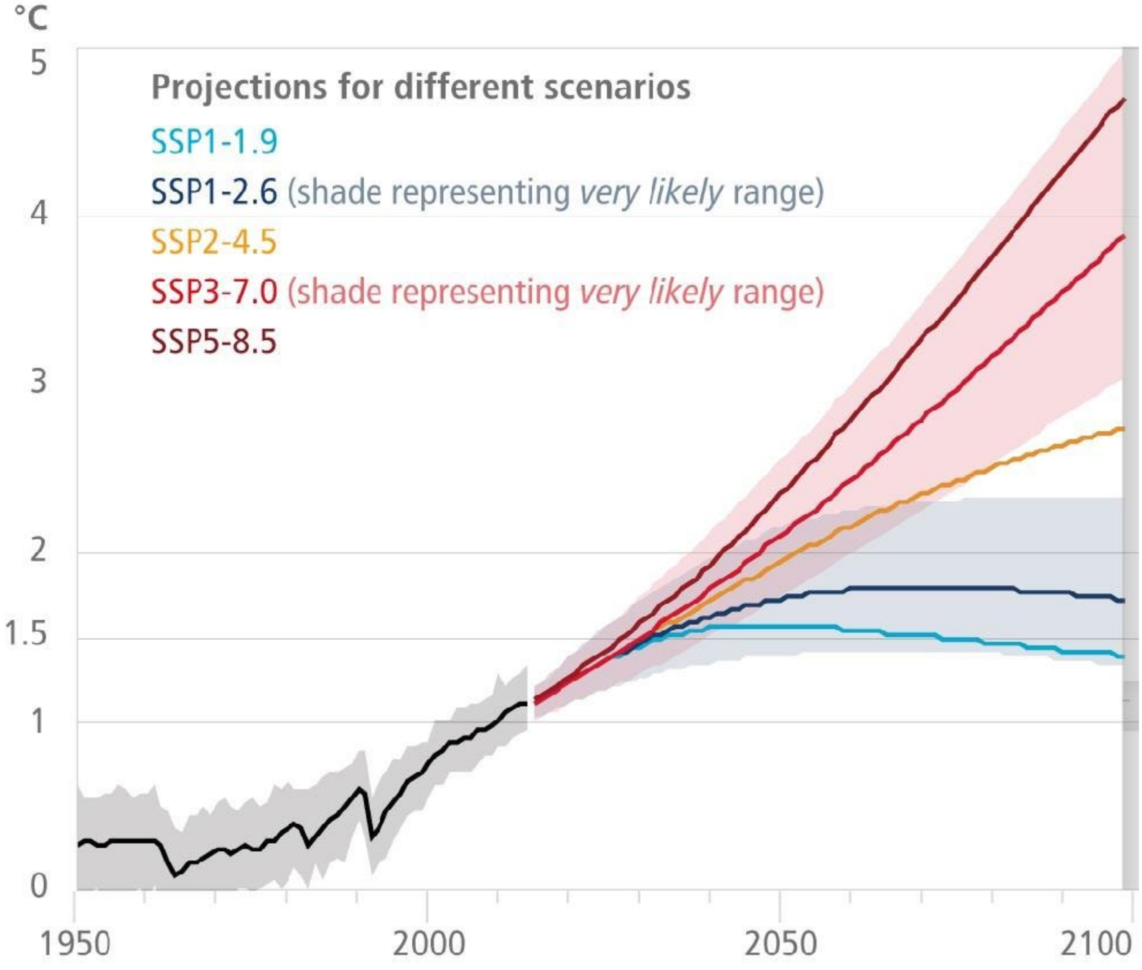
Trade offers a way to resolve challenges such as regional food shortages that result from climate-change impacts (Liu *et al.*, 2014). However, climate-change impacts on pests and pest vectors also threaten the international trading system, as international trade provides a pathway for pests and pest vectors to spread into new areas of the world. Pest pressure resulting from increasing pest abundance may pose a challenge, as existing phytosanitary measures may not be sufficient to mitigate the risk of pests entering new environments. To reduce the potential negative impacts of international trade, it is therefore imperative to strengthen phytosanitary measures in response to climate change (Hulme, 2021).

Since pest and plant distribution, pest epidemiology and pest impacts may change considerably as a result of climate change, robust surveillance and monitoring systems are vital at national, regional and international levels. Knowledge about the potential changes in pest life cycles, epidemiology and pathogenicity that may be induced by climate change is essential when undertaking pest risk assessments to determine how to manage pest risk effectively and economically. Greater attention needs to be paid to phytosanitary issues in general policy considerations on climate change. It is essential that phytosanitary policies and strategies are adequately reflected in the work of the IPCC. Political influence, resourcing, and funding for phytosanitary needs at a national, regional and international level will only be available when phytosanitary issues are recognized as an important component of the climate-change debate.

Recent and projected changes in climate

It is unequivocal that human activities have resulted in a warming of the atmosphere, ocean and land over recent decades (IPCC, 2021). Widespread and rapid changes in the whole climate system have been observed, and the scale of some changes are unprecedented over thousands of years. By the 2010s, global surface temperature had risen by 1.1 °C above pre-industrial temperatures. Extreme weather and climate events, including heat waves, droughts, heavy precipitation and tropical cyclones have become more frequent and severe, and these have led to some irreversible impacts on ecosystems and people as natural and human systems are pushed beyond their ability to adapt (IPCC, 2022a).

Figure 1: Increase in global surface temperature change relative to the period 1850–1990.



Notes: Scenarios range from very low greenhouse-gas emissions (SSP1-1.9) to very high (SSP5-8.5). For a description of the scenarios, see IPCC (2022). SSP, socioeconomic pathway.

Source: IPCC (Intergovernmental Panel on Climate Change). 2022. Summary for policymakers. H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig et al., eds. In: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig et al., eds. Climate change 2022 – Impacts, adaptation and vulnerability, pp. 3–33. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, Cambridge University Press. 3056 pp. doi.org/10.1017/9781009325844.001

Recent increases in temperature are projected to continue in the near term, then diverge on trajectories that are dependent on future emissions, as characterized by the IPCC shared socioeconomic pathways (SSPs: see Box 1). The trajectory of projected future change in climate is modelled under different assumptions of future emissions of greenhouse gases. In Figure 1, the scenarios range from projections of very low emissions (SSP1-1.9) to the highest emission scenario of SSP5-8.5. The actual rate of emissions that will occur in the future is dependent on the degree to which countries are able to reduce emissions and when they make these changes. Under the two lowest emission scenarios, temperature is projected to stabilize by the middle of this century and start to decline before the end of the century. Under the medium- and high-emission scenarios, temperature is projected to carry on increasing to 2100 and beyond. However, the shaded areas around the SSP-2.6 and SSP-7.0 projections illustrate the very likely range of possible outcomes under each scenario. By 2100, the range in projected temperature increase is about 1.4–2.3 °C and 3.0–5.0 °C for SSP1-2.6 and SSP3-7.0, respectively, from an 1850–1900 baseline. Thus, there is still considerable uncertainty about potential changes in temperature by the end of the century, even with the same emissions scenario.

The volume of precipitation has also been changing and is projected to change further. The IPCC synthesis report (IPCC, 2023) shows how soil moisture is projected to change under different temperature-increase scenarios from 1.5 to 4 °C. Under all scenarios, northern and western parts of South America, central America and the central area of North America, southern Africa, the Mediterranean region and central east Asia are projected to get dryer. Northern Canada, tropical areas of Africa, the Arabian Peninsula, central and northern Asia and much of India are projected to get wetter.

In addition to trends in average conditions (climate change), the frequency and severity of extreme climatic events have also been increasing in response to human-induced emissions of greenhouse gases (IPCC, 2021).

Box 1 · Representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs).

Representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs) are scenarios that have been developed to help understand the outcomes of different levels of greenhouse gas concentrations.

RCPs are scenarios based on a measure of the level of radiative force (the difference between incoming and outgoing energy). They describe the amount of the sun's energy that is trapped by earth, measured in watts per square metre. Four scenarios have been developed: 2.6, 4.5, 6.0 and 8.5 (W/m2), where RCP 2.6 represents a pathway in which greenhouse gas emissions are strongly reduced, while RCP 8.5 is a pathway in which greenhouse gas emissions continue to grow. **SSPs**, on the other hand, broadly outline the socioeconomic conditions that lead to different levels of greenhouse gas emissions. Five SSPs have been described, ranging from SSP 1 (a world of sustainable growth and equality) to SSP 5 (a world of rapid and unconstrained growth in economic output and energy use). While SSPs elaborate five different world socioeconomic scenarios, RCPs describe the outcomes in terms of energy trapped for four different scenarios. RCPs were used in the IPCC Fifth Assessment Report (IPCC, 2014) and the SSPs in the Sixth Assessment Report (IPCC, 2022a).

Source: Authors' own elaboration.

Temperature fluctuations and extremes have increased around the globe, based on observations since 1950. Furthermore, heavy rainfall events are likely to have increased over many land areas, although complex interactions between hydrology, climate and human management make it difficult to assess if climate change is affecting the character of droughts and floods over recent decades. Warming in tropical oceans is likely to have resulted in the increase in intensity and frequency of tropical storms over the last 40 years (IPCC, 2021).

2. Climate-change impacts on plants and plant pests

Geographical distribution and population dynamics of plant pests

Globally rising temperatures, extreme weather events and altered rainfall patterns are predicted effects of climate change on the environment. These and other related variables may have anticipated and unanticipated effects on plant biology, the distribution and abundance of plant and pest species, and natural enemies.

Different populations of pest species can respond in different ways to climate change, with the range of some shifting, some contracting, some expanding and others disappearing. Poleward expansion of many pests and pathogens has been noted since 1960 (Bebber, Ramotowski and Gurr, 2013). These asymmetric distribution changes can lead to new suites of pests in combination with host plants. The consequences of changes in pest distribution on future crop production and food security are considered to be hard to predict (IPCC, 2022b), although there are some valuable assessments of potential scenarios in Europe (EEA, 2019), China and the Americas (Ullah *et al.*, 2023).

Ongoing rapid changes in community structure and species distributions directly linked to climate change have been widely documented both in natural communities and in invasive species. The expanding distribution of pine processionary moth (*Thaumetopea pityocampa*) in Europe has been linked to increased winter temperatures (Battisti et al., 2005). Numerous pests, such as the plant redroot pigweed (*Amaranthus retroflexus*), are also expected to expand their geographical range in association with climate change (Hyvönen, Luoto and Uotila, 2012). Examples of changing phenology include those described by Gordo and Sanz (2005), who showed how the phenology of Colorado potato beetle (*Leptinotarsa decemlineata*) and olive fly (*Bactrocera oleae*) had changed over the second half of the twentieth century as a result of climate change and described how these changes have the potential to influence the pest status of these pests. Changes in the phenology of pests or plants can lead to changes in the synchronization between the susceptible stage of the plant and the abundance of the feeding or infective stage of the pest. Such changes have the potential to increase or decrease the impact of the pest.

Evolution of plant pests

Some pests are thought to have evolved in response to climate change, leading to more virulent lineages. For example, *Puccinia striiformis* f. sp. *tritici* causes wheat yellow (stripe) rust and was previously found predominantly in cold areas. Since 2000, however, novel strains that are more aggressive and thermotolerant have been recorded spreading into new regions (Mboup, 2012).

Climate-change impacts on agriculture (crops or horticulture)

Temperature is one of the most important factors affecting the distribution and abundance of plants, because of the physiological limits of each species. It limits the geographical areas in which different crops can grow and also affects their development rate, growth rate and yields. Increased carbon dioxide levels are also likely to affect plant physiology by increasing photosynthetic activity, resulting in better growth and higher plant productivity. This in turn indirectly affects insects by changing both the quantity and quality of plants (Skendžić *et al.*, 2021).

Although overall agricultural productivity has increased, climate change has slowed this growth over the past 50 years. Globally, related negative impacts have mainly been in mid- and low-latitude regions, but positive impacts have occurred in some high-latitude regions (IPCC, 2022a). The climate impacts for the past 20–50 years differ by crops and regions. Positive effects have been identified for wheat in northern Africa and northern Europe, rice in Australia and New Zealand, cereals in central Asia and maize, and soybean in northern America. The effects are mostly negative in sub-Saharan Africa, South America and the Caribbean, western and southern Asia, western and southern Europe, and at the overall global level (IPPC 2022c). Climate change has also impacted the productivity of vegetable and fruit crops in Nepal; for example, shifting climatic zones are reducing fruit production (Subedi, 2019).

Climate change is also opening new agricultural frontiers around the globe. Models suggest that the new frontiers will be most extensive in the northern hemisphere and in mountainous areas worldwide. Cold-tolerant temperate crops such as potatoes, wheat and corn have some of the greatest potential for expansion into these new areas. In addition, crops sown in existing agricultural areas are expected to shift their distribution in response to shifting climatic suitability. Shifting crop cultivation has the potential to cause major economic (e.g. food production) and environmental (e.g. biodiversity, ecosystem services) impacts. The environmental consequences of shifting crop production to new areas can include impacts on water, wildlife, pollinator interaction, carbon storage and nature conservation, on national to global scales (Hannah *et al.*, 2020). Pests are likely to accompany their host crops into new areas unless appropriate risk mitigation is in place, and they have the potential to cause harmful impacts beyond those to the crops themselves.

Extreme events can damage crops and natural vegetation. These disturbances, in addition to the changing atmospheric conditions, provide ideal opportunities for invasive species to enter and spread. Some of the key features of invasive species give them the ability to colonize new disturbed areas (Orbán *et al.*, 2021).

Climate-change impacts on trees, forests and the environment

Climate change will have positive and negative effects on forests, with varying regional and temporal patterns. Increasing productivity has been recorded in high-latitude forests such as those in Siberia, while in other regions negative impacts are already being observed, such as increasing tree mortality as a result of wildfires and droughts. Large pulses of tree mortality have been consistently linked to warmer and drier-than-average conditions for forests throughout the temperate and boreal biomes. Long-term data relating to tropical forests indicates that climate change has begun to increase tree mortality and alter regeneration. Climate-related dieback has also been observed, resulting from novel interactions between the life cycles of trees and pest species (IPPC, 2022c). For example, the incidence of sooty bark disease of sycamore trees (*Acer pseudoplatanus*) has been linked to drought conditions in Germany (Schlößer *et al.*, 2023). Further information about the impacts of climate change on forest systems is provided in Chapter 5 of the IPCC Sixth Assessment Report (IPPC, 2022c): www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FullReport.pdf

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3. Assessment of climate-change impacts on plant health

Climate and forecast modelling

Simulation models are a useful tool to assess the establishment, spread and damage potential of plant pests. For long-term crops such as forests, simulation models can help to quickly determine optimal management options, as well as suitable tree species and their performance under future climate conditions, to produce resilient and sustainable forest stands that are equipped for the future (Fontes *et al.*, 2010. Models can also be a great asset for studying climate change and assessing its impacts on pests in the future.

To model climate change, scientists use the results of global climate models (GCMs; also referred to as general circulation models). These models are used to examine the effects of climate change under different greenhouse-gas-emission scenarios several decades into the future (NOAA, n.d.). Modellers can use GCM outputs to forecast how pests could be affected by changes in variables such as temperature or precipitation during future time periods and climate-change scenarios.

Integrated climate models

Climate models provide the data basis for most simulation models and are therefore very important. The development of the Earth's climate is hard to project and depends on complex interactions that require enhanced climate models. With the help of these models, different pathways of climate development for different magnitudes of human emissions can be estimated. The resulting projections of future climate data can be used by other models to simulate a suite of possible outcomes of plant and pest dynamics.

Where climate models are used for phytosanitary purposes (e.g. to develop pest models for pest risk analysis (PRA)), recommendations include the following:

- Where possible, use multiple GCMs and compare the results to quantify the agreement (see Case study 2). The models are created by different institutions and have different foci and assumptions. Use an expert to design, run and interpret the output.
- Use region-specific models where regional climate data are available (noting that these types of data are difficult to obtain).
- When regional climate data are not available, use downscaled global-climate models (noting that manipulation of climate data away from the scale at which it is gathered involves additional, often unacknowledged uncertainty). Leaving climate data at coarser scales reduces the inferences that need to be made and results in fewer assumptions; it may be more fit-for-purpose if the desired outcome of the model is to determine whether a pest will survive anywhere in an area rather than where in an area it will survive.
- Use multiple emission scenarios, SSPs or representative concentration pathways (RCPs: see Box 1) as described by the IPCC to better understand the range of potential futures based on greenhouse-gas emissions (see Case study 1 and Case study 2).
- Use two sets of climate data (i.e. baseline and projected) to provide risk managers with a sense of the potential changes in risk over time and geography (Government of Canada, 2008). Select a time frame for the climate projection that will make a useful comparison: for example, 20 or 30 years (Government of Canada, 2008; NAPPO, 2011).

Species-distribution models for plant pests potentially affected by climate change

Simulation models are used to assess the establishment and spread of pests under different conditions, including climate change. These models can be based on current species distribution (e.g. correlative statistical models) or physiological properties (e.g. mechanistic or process-oriented simulation models). They can help improve monitoring, surveillance planning, preparedness, and the determination of countermeasures, and can provide estimates of expected damage under different climate scenarios. Especially in the context of climate change, it is very important to estimate when, for instance, a (temperature) threshold is reached that will allow a pest to build long-term viable populations. In the case of species that are already present, the models can be used to estimate the pest abundance and number of generations per year.

Models can be used to predict and analyse different scenarios considering various climatic, political, and socioeconomic conditions. The main advantage of modelling is the ease with which individual parameters can be adjusted, as well as the rapid analysis of large, future time periods (Heß *et al.*, 2020). Such a modelling approach also involves some assumptions and limitations, which need to be considered when interpreting the results (Elith and Leathwick, 2009; Kearney and Porter, 2009). For example, it is possible that effects that have not been considered influence the distribution of a pest. The calculated result can thus be under- or overestimating the actual potential distribution.

Where species-distribution models are developed for phytosanitary purposes (e.g. PRA), recommendations include the following:

- Use the best, most recent biological and climate information and data available. The data may be obtained through sources such as literature searches, experimental research, expert judgements, the knowledge systems of Indigenous Peoples, and online or internal databases.
- Edit the pest occurrence data (e.g. remove old data points, centroids, data for misidentified pests, transient populations and interceptions, and, for plants, records from herbaria, botanical gardens, and planted populations).
- Validate the model or models by running previous time frames and known occurrence locations and compare modelling results with empirical data.
- Describe the critical assumptions, limitations, and level of uncertainty associated with models used in PRA (NAPPO, 2011).

Cultural assessments for plants and plant pests

Cultural assessments used in the modelling of impacts (damage) of pest spread and establishment on communities should recognize the rights of Indigenous Peoples under the United Nations Declaration on the Rights of Indigenous Peoples. In addition to issues of food or economic security, there are potential impacts on the identity and assets of Indigenous Peoples.

Impacts can occur through damage or loss of culturally significant plant species and includes (but is not limited to) those used in medicine, healing or well-being, ceremonies or belief systems, crafts, building and construction, or food for indigenous animals of cultural value.

Where there has been redress by governments or other agencies to address historical and socioeconomic inequalities, the impacts of climate-driven changes affecting culturally and economically important plant species that form part of any redress also need to be considered.

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Climate-change pest forecasts and data sources

Climate-change pest forecasts can be useful for showing the effects of climate change on the geographical distributions of pests and characterizing future economic and environmental impacts. Potential uses for climate-change pest forecasts include strategic planning, trade discussions, modelling of long-term spread, and cost–benefit analysis (Fowler and Takeuchi, 2022).

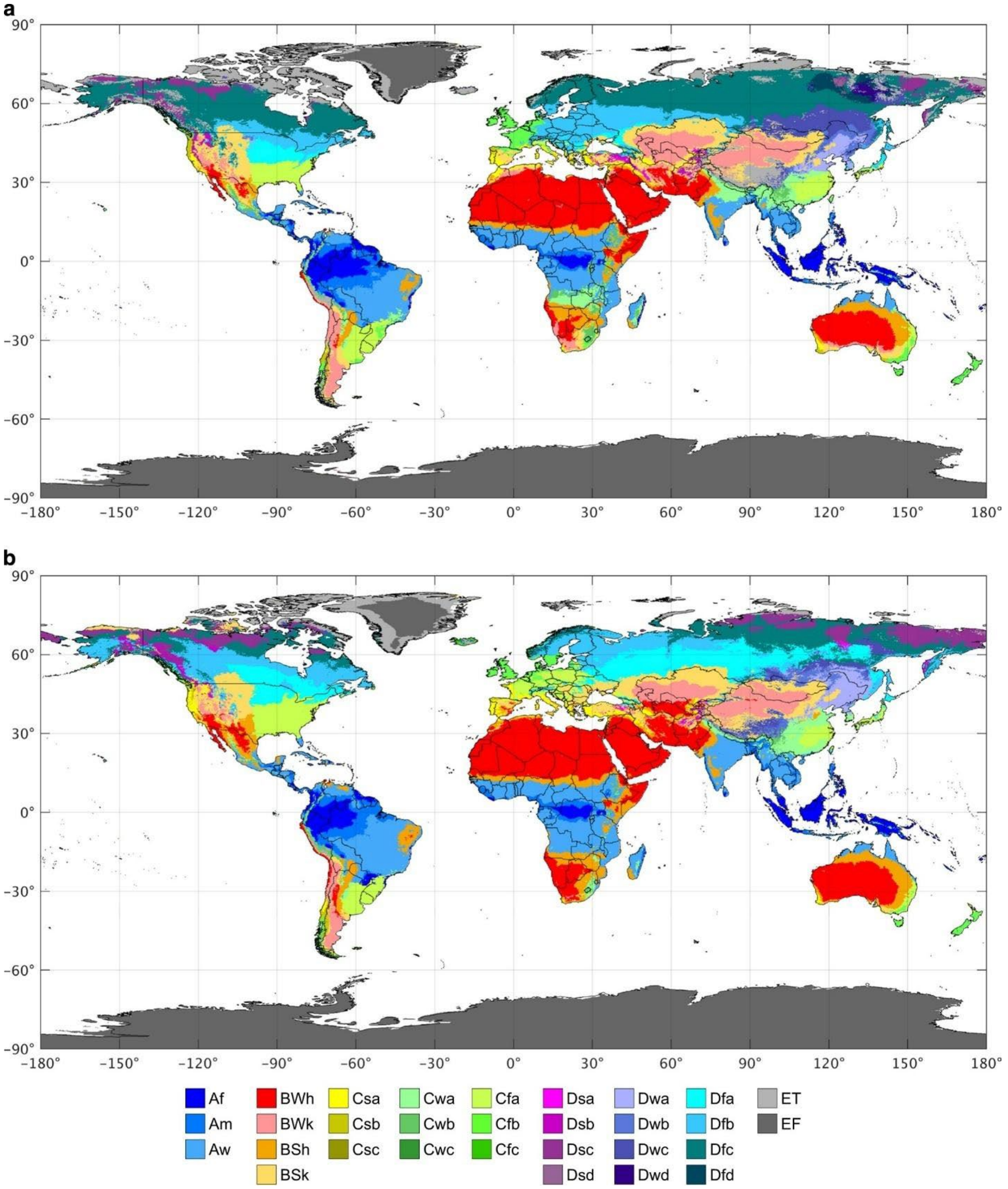
Several climate-change datasets with future and historical baseline information are publicly available, including Köppen-Geiger (Figure 2), Multivariate Adaptive Constructed Analogs (MACA), and WorldClim (see “Additional resources” in the Bibliography). These datasets include climate parameters such as temperature and precipitation that can be used in climate-change, pest-forecasting models. Some methods for characterizing changes in pest distributions under climate change do not require complex models. For example, such changes could be estimated using suitable Köppen-Geiger zones based on where the pest occurs (see MacLeod and Korycinska (2019) for information on pest–climate matching using Köppen-Geiger zones). These approaches could be useful for NPPOs with limited resources to inform their strategic planning for future pest impacts and spread.

Horizon scanning for plants and plant pests

Horizon scanning for new and emerging plant-health threats is an important component of preventive phytosanitary activities (EFSA *et al.*, 2021). Horizon scanning usually involves regular scans of literature, databases, pest alerts, media or any combination of these to mine new information on pests that may impact a country’s plant resources. Citizen-science platforms may also be included in scanning activities and are proving to be a useful source of information on new pest detections. Horizon scanning may be expanded to include considerations of climate-change impacts on pests (e.g. by adding new search terms in a literature search). Information of interest includes, but is not limited to: pest detections in areas that were previously climatically unsuitable; detections in neighbouring geographical areas (e.g. from the CABI Horizon Scanning Tool, the European and Mediterranean and Plant Protection Organization (EPPO) reporting service, or Pest Lens published by the NPPO of the United States of America (United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine)); new pest pathways arising as a result of climate change; new research on pest response to climatic factors; and species-distribution models that include future climate-change scenarios. By including climate change in horizon scanning, an NPPO can better identify and prepare for both new pests that are more likely to enter the country as a result of climate change and existing pests that, as a result of climate change, may pose a greater risk to plant health than they did before.

A horizon scan can be conducted to find new potential problems affecting conservation efforts, natural resources, and ecosystem services worldwide (Sutherland *et al.*, 2011). Prediction and early detection of pests, as well as strategies of containment and eradication, are essential in preventing their further spread (Donatelli *et al.*, 2017). Horizon scanning makes it possible to compile data on risk and impact that might help in pest management. Since horizon scanning focuses on predetermined topics of interest to the organization for which the scanning is undertaken, it can be tailored

Figure 2: Köppen-Geiger maps for 1980–2016 (a) and 2071–2100 (b), which combine climate-change projections from 32 Coupled Model Intercomparison Project (CMIP) phase 5 models based on representative concentration pathway (RCP) 8.5.



Notes: The Köppen-Geiger system uses seasonality values of monthly air temperature and precipitation to classify climate based on five main classes (A = tropical, B = arid, C = temperate, D = cold, E = polar) and 30 subtypes, including Af = Tropical Rainforest and Aw = Tropical Savannah (Beck et al., 2018). For more information on the Köppen-Geiger system and the criteria for each climate class, see Beck *et al.* (2018) and Peel, Finlayson and McMahon (2007).

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A. & Wood, E.F. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5: 180214. doi.org/10.1038/sdata.2018.214

Peel, M.C., Finlayson, B.L. & McMahon, T.A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11(5):1633–1644. doi.org/10.5194/hess-11-1633-2007

Source: Beck *et al.*, 2018. Reproduced unchanged under Creative Commons Attribution 4.0 International Licence: creativecommons.org/licenses/by/4.0/

to items of interest for pest management. Additionally, the practice of horizon scanning often functions to pick up multiple pieces of information that are, in and of themselves, quite weak but collectively paint a picture that is larger than the sum of its parts. This is because such horizon scanning is managed in such a way that collected information is not assessed independently but rather aggregated and assessed alongside other topically relevant information. Such a process is carried out by the NPPO of New Zealand (Ministry for Primary Industries) and helps to inform situational awareness about multiple changes to the global biosecurity-threat environment (Marshall, forthcoming).

Horizon scanning is an approach that can be used to gather information on pests, predict their potential arrival in a country and support invasive-species management. In a study conducted in Ghana, the CABI Horizon Scanning Tool was used to establish a list of potential pests that are not yet considered present in Ghana and are likely to pose a threat to agriculture and the environment. Using this list, 110 arthropods and 64 plant pathogens were evaluated using a streamlined pest risk assessment tool. Prioritization was carried out using an adapted version of the consensus method developed for ranking invasive alien species (Roy *et al.* 2014; Sutherland *et al.*, 2011). At the time of assessment, 16 species had not been recorded in the African continent, of which 14 were arthropods, and two were plant diseases. Forty-six plant pathogens and 19 arthropod species were documented in Africa and found in the nearby nations of Burkina Faso, Côte d'Ivoire and Togo. In assessing the likely pathways of arrival, it was found that a large proportion of arthropod species were likely to arrive on commodities that are host plants while fewer were likely to arrive as stowaways (i.e. contaminating pests) and others were able to disperse over great distances on their own. Species with the highest scores in the prioritization exercise had a high potential for entry into Ghana because of their presence in neighbouring countries and their likelihood to establish and spread. It is possible that some of those species may already be present in Ghana but not yet detected or identified to the species level; others are probably not yet present. The main recommendations for high-scoring species included comprehensive pest risk studies as well as surveys in Ghana and neighbouring countries (Kenis *et al.*, 2022). With these predictions on pests that pose a risk to Ghana, preventive measures, including climate-change mitigation measures, can be employed to prevent their entry, establishment and spread. An important step is to develop a contingency plan for the different stakeholders involved in pest management to follow.

Pest risk analysis

Climate suitability is an important consideration in a PRA as described in International Standard for Phytosanitary Measures (ISPM) No. 2 (*Framework for pest risk analysis*) and ISPM 11 (*Pest risk analysis for quarantine pests*). [2]

As climate change has the potential to affect climate suitability for pests, it should also be considered for inclusion in PRAs. Depending on the pest, the inclusion of climate-change considerations in the PRA may not be necessary (e.g. climate in the PRA already suitable) and may not be advisable (e.g. obvious that the climate will not be suitable in the near future, especially in extreme climate-change scenarios – too hot for insect species to survive). In general, the decision to include climate-change considerations in a PRA should be in line with the need for PRAs to be fit-for-purpose in aiding timely decision-making on pests and phytosanitary measures (NAPPO, 2011).

Factors to consider when deciding whether to include climate-change considerations in PRAs (see NAPPO, 2011) include the following:

- Is climate change relevant to the phytosanitary issue at hand? (See Case study 2.)
- Is the current climate in the PRA area already near the limit of climatic suitability for the pest (i.e. is it close to becoming suitable or close to becoming unsuitable), and what are the potential implications of changes

in the frequency and magnitude of climate extremes on the pest?

- Could climate change increase the likelihood that the organism poses a pest risk, making such risk more certain?
- Could climate change lead to a change in the areas used to grow a particular crop or the distribution of another host that would change the pest risk associated with a particular pest?
- Is there sufficient scientific evidence to show a causal relationship between climate change and the pest risk being assessed?
- Will climate-change considerations help the NPPO decide if an organism is a pest and if phytosanitary measures are justified?

Additional guidance on when to consider climate change in PRAs for established, accidentally introduced and deliberately imported organisms is provided in section 5 of the report Integrating Climate Change into Invasive Species Risk Assessment/Risk Management (Government of Canada, 2008): publications.gc.ca/site/eng/9.691412/publication.html

The decision on whether or not to include climate-change considerations should be clearly summarized and documented in the PRA, and a brief explanation should be given to support that decision (NAPPO, 2011). In all PRAs that include climate data, information and references on the climate data and the time frame they cover should be clearly documented. Using the most up-to-date baseline climate data available is recommended in order to conduct the PRA based on current (or near current) climatic conditions, which will include changes in climate that have already occurred (see issues discussed in Case study 3). This recommendation highlights the need for regularly updated climate data. Depending on the phytosanitary issue at hand and the time frame for the risk assessment, using the most up-to-date data to represent current climate may be sufficient accounting for climate change (e.g. evaluating the potential of a pest to establish in the PRA area at the present time); otherwise, future climate scenarios may be included.

Current climate data can be represented by means of observational data from recent 10-, 20- or 30-year periods, but can also be represented by modelled data. Stating a default expiry date or time frame for PRAs is recommended to increase transparency and to ensure that the conclusions are not relied upon after their expected date of validity (NAPPO, 2011). Furthermore, it may be appropriate to add longer-term time horizons into the PRA process so that both current and long-term projections for pest impacts can be accounted for, while balancing the need to ensure that any phytosanitary measures taken are justifiable (NAPPO, 2011).

The type of risk assessment will affect how climate change is considered in a PRA. For a PRA initiated by the identification of a pathway (e.g. a commodity), a list of pests associated with the pathway is generated at the beginning of the assessment. At this stage, pests with marginal climate suitability (i.e. pests potentially affected by climate change) may be included in the list for further evaluation. Potential sources of information for generating the list are noted in ISPM 11 and may also include horizon-scanning activities as described above. For a PRA initiated by the identification of a pest, climate change may affect any, or even all, key elements of the PRA (entry, establishment, spread and consequences of a pest) (see Case study 1). It is important to keep in mind that climate may have different effects on the pest, its host and its vector. For details and case studies on the implications of climate change on specific elements of a PRA, see NAPPO Discussion Document DD 02: Climate Change and Pest Risk Analysis (NAPPO, 2011): nappo.org/application/files/5415/8341/5783/DD_02_Climate_Change_Discussion_DocumentRev-07-08-12-e.pdf

The inclusion of climate-change considerations in a PRA need not be unduly complex. Existing maps of climate-change scenarios (e.g. from the IPCC) may be combined with knowledge of the environmental requirements of a species to draw some basic conclusions. In other cases, species-distribution models that include climate-change scenarios

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[2] ISPM 2 and ISPM 11 are part of the *Reorganization and revision of PRA standards*, for which a new draft ISPM was submitted to first consultation in 2023. For more information: www.ippc.int/en/core-activities/standards-setting/list-topics-ippc-standards/reorganization-of-pest-risk-analysis-standards/

may already be available in the published literature and can be cited in the PRA. It may also be reasonable to use studies that include models on similar, surrogate species. For example, a model of a surrogate species that shows the rate of its northward or southward movement and the average distance moved could be used to predict when a species might arrive in a PRA area if it is close but not yet directly in it. Simple, cold-threshold boundary models (e.g. based on isotherms or plant-hardiness zones) may be preferable in some cases to more complex models built on numerous assumptions. For plants, for example, climate matching using plant-hardiness maps as a broad surrogate for potential plant distribution may be a simple alternative to more complex bioclimatic models (NAPPO, 2011). The use of single-factor models such as plant-hardiness zones will be appropriate if the single factor is thought to be a likely limiting factor for the pest if it were introduced to the PRA area. In cases where models are developed specifically for a PRA, recommendations are provided in section 3 of this document, under “Species-distribution models for plant pests potentially affected by climate change”.

Climate-change considerations included in PRAs need to be sufficiently robust to meet the requirements of international agreements (e.g. World Trade Organization Agreement on the Application of Sanitary and Phytosanitary Measures; International Plant Protection Convention (IPPC)) and international case law. As such, any resulting phytosanitary measures need to be based on sufficient scientific evidence and not be arbitrary, unjustified, or a disguised barrier to trade. “Sufficient” scientific evidence should allow for an adequate risk assessment that focuses on ascertainable risk, namely, what is “likely” rather than what could be “possible”. It should also demonstrate a rational or objective relationship between a phytosanitary measure and the risk assessment (NAPPO, 2011).

In general, there is a need to intensify PRA activities as a result of climate change and its effects on pests (IPPC Secretariat, 2021a). In addition to new PRAs, existing PRAs may need revision to take into account new scientific knowledge (including biology and pest distribution) as well as change in global trade and climate-change considerations (EFSA, 2008). To deal with this increase in PRA activities, a shift from pest risk assessments of individual organisms to more generic approaches, such as pest risk assessments of groups of organisms and pathway-initiated risk analyses may be more efficient resource-wise (EFSA, 2008). Furthermore, continuous risk management may be employed to help reduce uncertainty in the PRA over the longer term and permit the integration of adaptation strategies where suitable (Council of Canadian Academies, 2022; Government of Canada, 2008). Continuous risk management is an iterative and adaptive approach to risk management that involves re-examining the PRA every few years, taking into account past iterations, updating as necessary based on new knowledge and participants, evaluating the effectiveness of mitigation measures, and readjusting as necessary (Council of Canadian Academies, 2022).

Cost–benefit analysis of pest impacts

Cost–benefit analysis of pest impacts under climate change could be a useful tool for anticipating future economic losses and strategic planning. Cost–benefit analyses have been used by NPPOs to evaluate the effectiveness of pest-control programmes to determine if they are worthwhile investments. For example, the NPPO of the United States of America conducted a cost–benefit analysis for their pine shoot beetle (*Tomicus piniperda*) regulatory programme (Fowler *et al.*, 2015), which provided justification for deregulating this pest.

Similar analyses could be done using climate-change scenarios and the associated changes in pest damage over time. These types of analyses could be useful for planning and resource-allocation purposes. For example, cost–benefit analysis could be used to justify planting alternative crops or implementing safeguarding measures to reduce the likelihood of pest introduction into areas where pest impacts are expected to be high because of climate change.

Cost–benefit analysis provides a framework for gathering, assembling and presenting the data required to undertake an economic analysis of control strategies for use in a PRA. It can be used in climate-smart agricultural methods to determine how economically profitable particular methods of climate adaptation will be for smallholder farmers. A study conducted in the United Republic of Tanzania used cost–benefit analysis to investigate whether climate-smart agricultural practices would be profitable for small-scale farmers. Crop rotation and intercropping maize with early-maturing or late-maturing soybean varieties were the climate-smart agricultural techniques used. Results indicated that the techniques were financially successful (Ng'ang'a *et al.*, 2020).

For more information on climate-smart agriculture, see Synergies and Trade-Offs in Climate-Smart Agriculture – An Approach to Systematic Assessment (FAO, 2021): doi.org/10.4060/cb5243en

Assessment of threats to culturally significant plant species

Assessment of threat levels and the cultural significance of any threat should be guided by, and preferably conducted by, Indigenous Peoples themselves. Where this is not possible, it is preferable for those making the assessments to have the endorsement of the Indigenous Peoples.

Recognition of the governance and management rights of Indigenous Peoples makes it important to include their worldviews, values and principles in the prevention of pest risk associated with climate change and in pest risk assessment. This inclusion should be upheld at all levels of decision-making and the pest risk assessment and management continuum.

Pest reporting and alert systems

The shifting of agricultural production zones has changed trade flows. However, the increase in international agricultural trade volumes will, in combination with the limited knowledge of pest behaviour under new climatic and ecosystem conditions, result in a deficiency of reliable, scientifically verifiable information upon which risk assessors and regulators can base their assessments and mitigation measures. This deficiency could be alleviated through the establishment of a reliable, international, information-exchange network dedicated to providing official services with information about the occurrence of pests and potential pathways (IPPC Secretariat, 2021a).

The official reporting of international trade pathways, pest detections and pest status is critical and should be supported by scientific research about the impacts of climate change on plant health.

The main purpose of pest reporting is to communicate immediate or potential danger. Immediate or potential danger normally arises from the occurrence, outbreak or spread of a pest that is a quarantine pest in the country in which it is detected, or a quarantine pest for neighbouring countries that are trading partners. It is also critical that information on changes to pest distribution, host range, and the adaptability of pests and host plants is shared at bilateral, regional and international levels. The IPPC reporting system (national reporting obligations (NROs)), combining official reporting by contracting parties with other available and published information from other sources, is essential for assessing and managing climate-change impacts on plant health.

Pest reports can also be made through

existing RPPOs, particularly for pests potentially affected by climate change or pest-related information having impacts at a regional level.

For more information on pest reporting, see ISPM 17 (*Pest reporting*) — www.fao.org/3/y4224e/y4224e.pdf — and the IPPC NRO Guide (IPPC Secretariat, 2016): www.ippc.int/en/publications/80405/

For an IPPC NRO e-learning training resource, see www.ippc.int/en/publications/91831/

For an e-learning course on surveillance and reporting obligations, see: elearning.fao.org/course/view.php?id=824

The provision of reliable and prompt pest reports confirms the operation of effective surveillance and reporting systems within countries. Pest reporting allows countries to adjust their phytosanitary import requirements and actions to take into account any changes in pest risk. It provides useful current and historical information for the operation of phytosanitary systems.

Pest risk pathways

Increasing international trade in combination with climate change may pose major challenges and uncertainties for plant health. An increase in international trade (through regulated pathways) from countries with a warmer climate that could correspond to the future climate in importing countries means that the potential for the introduction and establishment of pests is increasing (Diez *et al.*, 2012; Hulme, 2017). The risk of these pests expanding their geographical range and impact is likely to increase as a result of the current and predicted climatic changes (IPPC Secretariat, 2021a).

Pest dispersal occurs through both natural and regulated or unregulated pathways, strongly facilitated during recent decades by the globalization of markets for plants and plant products including food, planting material and wood. Global travel and the trade of agricultural products have moved crops and pests away from their native environments to new ones. Newly introduced crops may expand pest distribution, and the introduction of new pests into a completely new ecosystem may cause damage because pests and hosts may not have co-evolved together. This co-evolution has been especially recognized for plants and their pests (Woolhouse *et al.*, 2002) and has created a stable balance between hosts and pests within their endemic ecosystems.

According to Anderson *et al.* (2004), half of all emerging plant diseases are spread by global travel and trade, while natural spread, assisted by weather events, is the second most important factor. In addition, there are also likely to be interactions between pest establishment and climatic or weather conditions. For example, global warming may facilitate the establishment of some pests that would otherwise not be able to establish (e.g. during an unusually warm winter under temperate climatic conditions) (IPPC Secretariat, 2021a).

When considering the potential impact of climate change on plant health and hence on plant distribution, it is therefore important to understand not only which conditions allow pests to thrive, but also the pathways by which they move from one place to another. An understanding of the pathways is also needed when determining what measures should be taken to mitigate and adapt to the changes in pest risk brought about by climate change.

Some ISPMs include guidance on how to conduct PRA to determine the risk of introduction (entry and establishment) and spread of pests and to select which measures to apply to prevent this occurring (ISPM 2, ISPM 11, ISPM 21 (*Pest risk analysis for regulated non-quarantine pests*)).

The main types of pest pathways are as follows:

- **Wood packaging** – Historically, wood, including packaging, has played a major role in spreading pests. Among the examples that show the significance of such a pathway is the movement of wood boring beetles.
- **Seeds, planting materials and growing media** – Globalization of seed and planting-material markets is one of the main causes of the recent and rapid spread of plant

pathogens. Some of the newly introduced pathogens and arthropod and nematode pests that are typical of warm areas are spreading easily in temperate regions, because of increases in temperature.

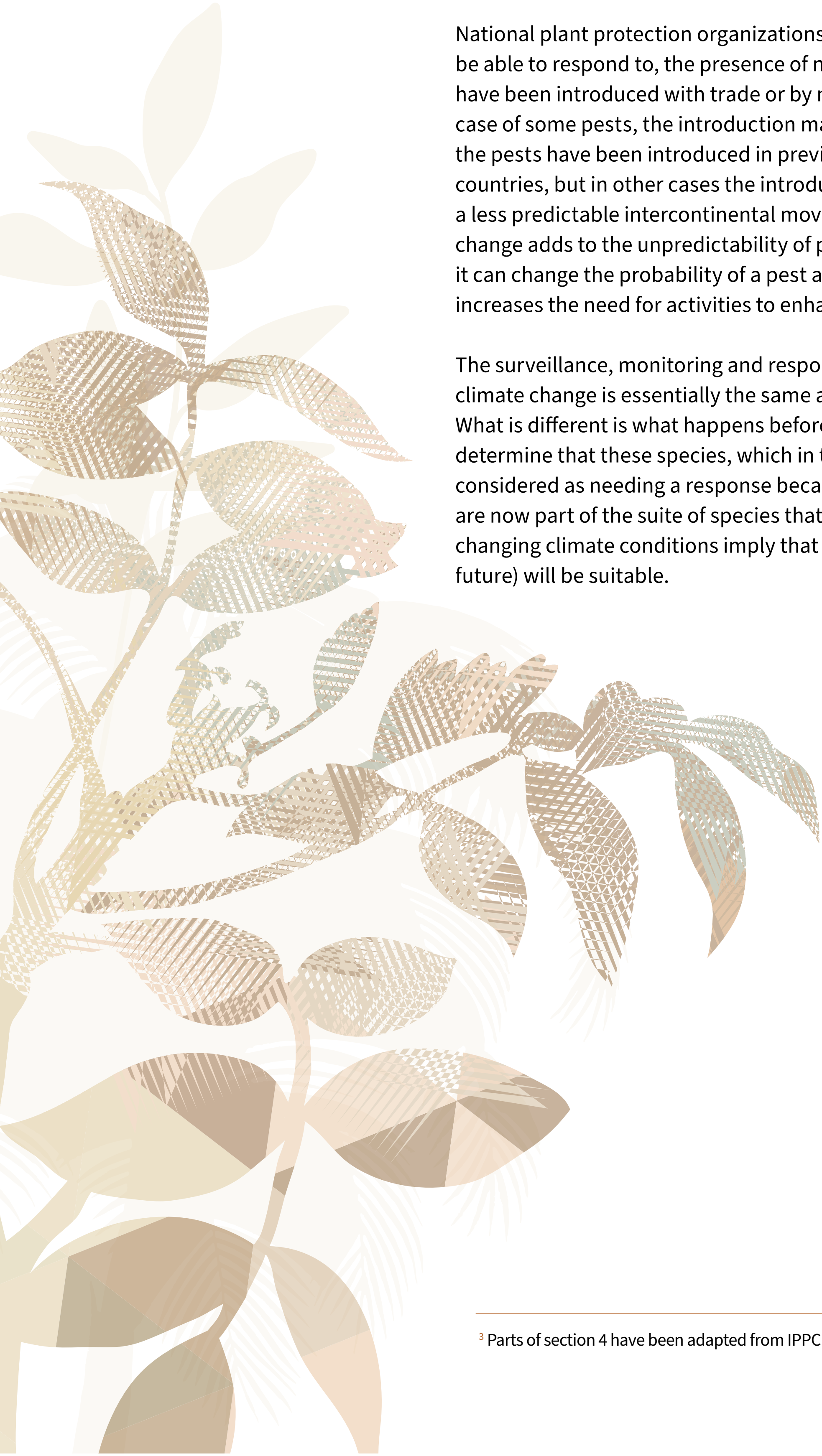
In general, seeds are vectors of pests. Mature plants are also frequent vectors of live insects, including mites, aphids, caterpillars, leaf miners and thrips. Particularly in the vegetable sector, the recent spread of new pathogens in different countries is clearly linked to the fact that, being seed-borne, their diffusion is favoured by market globalization; the effect of global warming on plants and their hosts has also contributed to this spread.

One additional reason for the movement of pests from one geographical area to another is the international response to weather and other events (floods, hurricanes, etc.), when pests may be inadvertently introduced into a country through humanitarian aid. Often, the necessary phytosanitary protocols are overlooked in an effort to get aid to a country quickly.

- **Conveyances, cargo and movement of animals** – Tractors, cars, trucks, trains, ships, aeroplanes, containers, re-sold used agricultural equipment, and other vehicles are common means by which pests are passively moved. Indeed, plant pathologists, entomologists and weed scientists often consider the speed of spread of pests as directly related to the speed of conveyances. The global shipping network is widely recognized as a pathway for vectoring invasive species. One insect species that is known to have spread throughout the world by shipping, including transportation by ships and shipping containers, is the spongy moth (*Lymantria dispar*). This species may be introduced into a new area when the port has a suitable climate for its survival and establishment. Khapra beetle (*Trogoderma granarium Everts*) is also a pest whose incidence in shipments of non-host products has increased considerably in recent years.
- **International passengers** – People, with their leisure or business travel, are perfect vectors of pests, particularly in the absence of strict controls at points of entry. Leisure travel, in particular, is often associated with people bringing back food, seeds or exotic plants, and these can be infested with pests or can themselves be a pest.
- **Natural dispersal pathways** – There are examples where native and non-native pests have significantly expanded their geographical ranges naturally (i.e. not assisted by humans). These are usually associated with major changes in host distribution or climate. Of the changes in climate, increasing temperatures have particularly facilitated range expansion in pests, especially at higher latitudes and altitudes (Gullino *et al.*, 2022).

For more information, see the Scientific Review of the Impact of Climate Change on Plant Pests – A Global Challenge to Prevent and Mitigate Plant Pest Risks in Agriculture, Forestry and Ecosystems (IPPC Secretariat, 2021a): doi.org/10.4060/cb4769en

4. Management of climate-change impacts on plant health[3]



National plant protection organizations need to prepare for, and be able to respond to, the presence of non-native plant pests that have been introduced with trade or by natural migrations. In the case of some pests, the introduction may be predictable because the pests have been introduced in previous years or to neighbouring countries, but in other cases the introduction may be the result of a less predictable intercontinental movement of a pest. Climate change adds to the unpredictability of pest introductions, because it can change the probability of a pest arriving or surviving, and this increases the need for activities to enhance preparedness.

The surveillance, monitoring and response to a pest affected by climate change is essentially the same as that to any pest of concern. What is different is what happens before: the previous steps that determine that these species, which in the past would not have been considered as needing a response because of unsuitable climates, are now part of the suite of species that need to be considered, as changing climate conditions imply that climates now (or in the near future) will be suitable.

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[3] Parts of section 4 have been adapted from IPPC Secretariat (2021a, 2021c).

Pest surveillance and monitoring

Plant-health surveillance and monitoring are important tools to detect the introduction of new pests or to monitor their status. Climate change means that there is a need for national, regional and international surveillance and monitoring activities for plant-health threats to be intensified. Consideration should be given to the development of model templates for multilateral surveillance programmes, especially for developing countries, to demonstrate how such programmes may be set up to offset phytosanitary threats (IPPC Secretariat, 2021a). One example of a survey template is found in Regulation (EU) 2016/2031 (Articles 22, 23, 24) of the European Parliament (European Union, 2016), but other templates may also contain model approaches that determine risk locations based on environmental, anthropogenic or other factors to determine optimal survey locations and time periods. Also, tools to ensure statistically sound surveillance can be of help, such as the European Food Safety Authority's Risk-based PEst Survey Tool – RiPEST (Bemelmans, 2023).

Surveillance and monitoring for pests potentially affected by climate change at the national and often regional level supports early detection of newly introduced pests as well as timely and effective control and eradication actions. The earlier a pest is detected after introduction, the greater the likelihood that eradication measures will be successful. Hence, surveillance and monitoring need to be key components of a strategy to assess and manage the introduction of pests potentially affected by climate change (FAO, 2008).

National plant protection organizations will need to consider climatic variability caused by climate change in the design and implementation of surveillance and monitoring programmes (IPPC Secretariat, 2021a). As stated in ISPM 6 (Surveillance), the suitability of the climate and other ecological conditions in the area for the pest is one of the factors that may determine the areas or sites selected for surveillance. The changing climate brings with it changing levels of risk of different pests; therefore, NPPOs and RPPOs need to keep under review the list of pests for which they survey.

Surveillance

Surveillance is an official process whereby information on pests in an area is obtained through general surveillance, specific surveillance or a combination of both (ISPM 5 (*Glossary of phytosanitary terms*)). Useful references on the requirements for surveillance include ISPM 6 and the IPPC *Surveillance guide* (IPPC Secretariat, 2021b).

A detection survey is a survey conducted to determine the presence or absence of pests (ISPM 5) in an area. Conducted regularly, detection surveys aid in the rapid identification of individuals or populations of pests that have been introduced through accidental means or natural spread or as a consequence of climate change. Detection surveys for pests potentially affected by climate change can be conducted by collecting samples by trapping, making visual inspections or sampling latent hosts.

Trapping surveys should be conducted in areas where the pest has not been detected before but might establish or in areas where migratory populations are expected to occur (IPPC Secretariat, 2021c). Research on pest biology and response to climate change, as well as modelling or forecasting to identify where the pest might establish, may be used to inform where and when to survey (e.g. Grünig *et al.*, 2020; Kean and Stringer, 2019; Taylor *et al.*, 2019). Surveys in such areas may be complemented by surveillance in areas with susceptible hosts. Where pest introduction is thought to be most likely to occur as a result of human action such as travel or trade, surveys should focus on points of entry of travellers and freight. Where natural spread or introduction of a pest as a consequence of climate change is thought to be most likely, surveys should focus on areas bordering or closest to any country known to be infested. One example of international guidance for surveillance is the European Food Safety Authority's series of pest survey cards. This advice is intended to help European Union (EU) member states plan surveys for quarantine pests (EFSA, n.d.).

Along with detection surveys, information on pests potentially affected by climate change may be gained through general surveillance. General surveillance is a process whereby information on pests of concern in an area is gathered from various official or non-official sources (ISPM 6). One of those sources might be a citizen-science initiative coordinated to encourage the general public and stakeholders (e.g. growers, importers) to look out for pests potentially affected by climate change. Other sources include scientific publications and websites and social-media sites, such as the Global Biodiversity Information Facility,[4] that collate records of the detection of pests. Simple pest factsheets and identification resources (e.g. on fall armyworm (*Spodoptera frugiperda*) or *Fusarium oxysporum* f. sp. *cubense* Tropical Race 4) may be distributed to encourage people to report suspected pest detections to plant-health authorities (see IPPC *Surveillance and reporting obligations* e-learning course: elearning.fao.org/course/view.php?id=824).

Protected natural areas typically have monitoring programmes that can be integrated into wider national programmes to broaden the likelihood of detection of new incursions (Dalton *et al.*, 2023).

Response plans

A response plan sets out the phytosanitary measures that are to be applied to contain or limit the spread of invasive pests once they are officially detected and confirmed. These include delimiting surveys, preventive measures, phytosanitary measures and measures to suppress the pest population and its spread (if feasible). A response plan should be implemented immediately once a pest that is potentially affected by climate change and poses an unacceptable pest risk is officially found in a new territory. The prevention and preparedness plan should also continue to be implemented for the parts of the country where the pest is still absent.

Key components of a response plan may include the following:

- **Delimiting surveys** – A delimiting survey is a survey conducted to establish the boundaries of an area considered to be infested by or free from a pest (ISPM 5).
- **Phytosanitary measures** – If the pest is detected in an imported consignment, the infested commodity should be immediately treated or destroyed to prevent its spread. All lots of the same consignment should be checked and, if necessary, treated or destroyed. The NPPO should notify the relevant national and international bodies of the pest interception.
- **Monitoring surveys** – It is important to check all plants present on the site that may have been infested by the pest. An accurate, specific surveillance programme should be implemented around the site to ensure that the pest has not already spread to the surrounding environment.
- If the pest is detected in places of production or in the wild, pesticide treatments or other control measures should be applied, and surveys should be intensified on other host plants throughout the country. A contingency plan should be developed by the NPPO on how the pest can be managed in the long term.
- If the pest is not yet widespread, the NPPO may officially establish a demarcated area (infested area plus buffer zone, the latter as defined in ISPM 5), in which phytosanitary measures are implemented, and the rest of the country may be considered a pest free area provided it meets the requirements of ISPM 4 (*Requirements for the establishment of pest free areas*) or ISPM 10 (*Requirements for the establishment of pest free places of production and pest free production sites*).

To ensure a rapid and effective response

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[4] Global Biodiversity Information Facility: https://www.gbif.org/

to an outbreak, it is advisable to carry out simulation exercises. These exercises, based on a hypothetical situation, are a preparation for real action in case of an outbreak. They help to improve workflows and are a good tool by which to identify important infrastructure, responsibilities, missing information, flaws in the system, necessary financial resources, and other important factors that should be considered.

For more information, see Emergency Preparedness – A Guide for Developing Contingency Plans for Outbreaks of Quarantine Pests (IPPC Secretariat, 2023): doi.org/10.4060/cc4820en

Suppression

Suppression is the application of phytosanitary measures in an infested area to reduce pest populations (ISPM 5). Phytosanitary measures include legislation, regulation or official procedures. Improving host-plant resistance to pests and competitiveness with pest plants, along with adjustments to pesticide application, are considered effective ways of adapting plant protection to future climatic conditions (Juroszek and von Tiedemann, 2015).

Integrated pest management is the preferred overall approach for suppression, but different methods will be appropriate in different situations. Choosing which method to use, and where and when to use it, at national, local or farm level, is critical to effective integrated pest management. In order to meet the phytosanitary import requirements of trading partners, a systems approach may be appropriate, as detailed in ISPM 14 (*The use of integrated measures in a systems approach for pest risk management*).

Any suppression method being considered for use can be evaluated against several criteria: cost-effectiveness, effectiveness, safety, availability and scalability.

Adaptation

The application of many pest-management measures, such as the application of plant-protection products, is generally less viable in forestry than in agriculture because of costs, impacts to non-target organisms and practical considerations. Therefore, adaptation to respond to potential climate-change effects is most likely to involve preventive measures, such as removing infested trees to avoid further spread of pests (Bonello *et al.*, 2020; Liebhold and Kean, 2019). Another major preventive adaptation is the choice of suitable tree species, or pest-resistant or tolerant clones or cultivars if available, when new forests are planted (Bonello *et al.*, 2020; IPPC Secretariat, 2021a). Given that managed forests are generally planted for a number of decades, foresters need to consider factors including the suitability of the planting site, the species and clones planted and other silvicultural factors in the knowledge that there is likely to be considerable change in the climate over the lifetime of the trees.

Indigenous Peoples

Indigenous Peoples have a long history of adapting to challenges in changing environments and their resilience strategies can help enrich and strengthen other adaptation efforts. Indigenous People's knowledge provides a basis for the successful understanding of responses to, and governance, of climate change risks. For example, terrestrial and aquatic ecosystems in lands managed by Indigenous Peoples are often less degraded than other managed lands as a result of resource-use practices and ecosystem-stewardship strategies that protect and foster biodiversity (IPCC, 2022b).

Recognizing and engaging with Indigenous Peoples to integrate alternative worldviews and traditional knowledge is needed at all levels of a country's biosecurity system,[5] including preparedness.

Integration of Indigenous People's knowledge at all levels will enable

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[5] Biosecurity is a critical part of a government's efforts to prevent, respond to and recover from pests and diseases that threaten the economy and environment. To prevent pests and diseases from entering a country, the biosecurity risks of importing different types of goods and commodities are identified.

co-management of responses, recognizing the rights of Indigenous Peoples to protect their environmental resources and uphold their responsibilities towards the natural world and the use of traditional knowledge.

International cooperation and capacity building

As pest management by one country may affect another, and pests can cross borders, international cooperation will be essential to the success of countries in adapting pest-management strategies to climate change (IPPC Secretariat, 2021a). The cooperation can take the form of promptly reporting the presence of new pests (ISPM 8 (*Determination of pest status in an area*)), sharing PRAs and knowledge on the use of climate models to predict pest status, or sharing resources and expertise (e.g. the National Regulatory Control Systems published by EPPO (n.d.(a)) on how to combat a particular pest. National plant protection organizations that have experience of managing a novel pest are likely to have useful experience to share with countries that may have outbreaks in future years. International cooperation may be global (e.g. via IPPC mechanisms) or regional (e.g. via RPPOs). For example, Carvajal-Yepes *et al.* (2019) have proposed a global surveillance system for crop diseases. This system would extend and tailor established phytosanitary and networking practices to developing countries, enabling quick responses to unexpected disease outbreaks and ultimately stabilizing and enhancing global food production. The global surveillance system would consist of existing surveillance systems around the world, linking general and specific surveillance activities across countries, and increasing coordination in pest detection, response and control.

Countries may build their capacity to cope with, and adapt to, climate change in various ways. For example, an IPPC phytosanitary capacity evaluation may be used to assess a country's readiness to respond to plant diseases. Irrespective of whether or not climate change occurs as scenarios predict, enhancing capacity will have benefits and is likely to also result in cost–benefit improvements (IPPC Secretariat, 2021a). Enhancing adaptation capacity also means finding ways to manage financial risk under climate-change stresses. Crop insurance may be an option in some cases, but it does not necessarily protect productivity and may encourage continued production of crops where they are no longer suited to the environment (Di Falco *et al.*, 2014; IPPC Secretariat, 2021a).

For more information, see The Global Action for Fall Armyworm Control (FAO, 2022) — doi.org/10.4060/cb8910en — and Recommendations for an Effective Pest Outbreak Alert and Response System (IPPC Secretariat, 2022): https://assets.ippc.int/static/media/files/mediakitdocument/en/2022/03/POARS_All_Recommendations.pdf

Communication and awareness

Communication is a critical element in assessing effectively pests that are potentially affected by climate change, once their presence has been detected. The IPPC Guide to Pest Risk Communication (FAO, 2019) — www.ippc.int/en/publications/90623/ — and the IPPC guide on Managing Relationships with Stakeholders (IPPC Secretariat, 2015) — www.ippc.int/en/publications/90634/ — provide guidance to NPPOs on identifying and engaging with stakeholders and on developing pest risk communication strategies, including guidance on the key goals and concepts of pest risk communication, the factors that may influence its success and the principles of good pest risk communication.

National plant protection organizations are encouraged, even when pests potentially affected by climate change are still absent, to publish their pest prevention, preparedness and response plans on their websites and

communication platforms
(Facebook, LinkedIn, Twitter, etc.).

Stakeholder-awareness programmes, particularly for farmers and growers, are also beneficial. Such programmes should include information on how to identify pests potentially affected by climate change, what should be done if these pests are suspected, how to report to the NPPO, and other relevant information that might be required. For example, the NPPO of Australia (Department of Agriculture, Fisheries and Forestry) has developed communication and awareness materials to meet different stakeholder needs for the top 40 priority pests, including pests potentially affected by climate change. These materials include: NPPO information (e.g. on national-response); jurisdictional information to farmers and industry on surveillance, management and pest reporting; and industry information (resources and reference materials to support their specific activities). The EPPO region host an online platform for publicity material, with materials for many of the pests relevant to the region (EPPO, n.d.(b)), that NPPOs may also find useful when developing communication and awareness materials.

Examples of communication material related to the impact of climate change on plant health include:

- www.forestresearch.gov.uk/climate-change
- www.rhs.org.uk/science/gardening-in-a-changing-world/climate-change/potential-new-pests

5. Case studies

Case study 1: Use of climate-change projections by the European and Mediterranean Plant Protection Organization in pest risk analyses of invasive alien plants

Since 2016, with the initiation of the EU-funded project “Mitigating the Threat of Invasive Alien Plants in the EU through Pest Risk Analysis to Support the EU Regulation 1143/2014” (EPPO, n.d.), EPPO has considered climate change in PRAs for invasive alien species. Indeed, this is a requirement of EU regulation 1143/2014, Article 5(d): “a thorough assessment of the risk of introduction, establishment and spread in relevant biogeographical regions in current conditions and in foreseeable climate change conditions” (European Union, 2014). Within the project, PRAs including consideration of climate change were conducted for 16 plant species: *Ambrosia confertiflora*, *Andropogon virginicus*, *Cardiospermum grandiflorum*, *Cinnamomum camphora*, *Cortaderia jubata*, *Ehrharta calycina*, *Gymnocoronis spilanthoides*, *Hakea sericea*, *Humulus scandens*, *Hygrophila polysperma*, *Lespedeza cuneata*, *Lygodium japonicum*, *Pistia stratiotes*, *Prosopis juliflora*, *Salvinia molesta* and *Triadica sebifera*.

To estimate the effect of climate change on the potential distribution of these plants, the potential distribution of each species under current and future climates was modelled using the R software package (biomod2) (Thuiller *et al.*, 2016). Future climate conditions for the 2070s under intermediate (RCP 4.5) and higher (RCP 8.5) climate-change scenarios were obtained (the latter being considered as a worst-case scenario). The variables were obtained as averages of outputs of eight global-climate models (BCC-CSM1-1, CCSM4, GISS-E2-R, HadGEM2-AO, IPSL-CM5A-LR, MIROC-ESM, MRI-CGCM3, NorESM1-M), downscaled and calibrated against the WorldClim baseline.

Distribution maps for each scenario were produced and these were then used by expert working groups to assess the influence of climate change on entry, establishment, spread and impact. In addition, the effects of climate change that would be most relevant to the species (e.g. changes to temperature, precipitation, land use, risk of fire) were identified.

When the climate-change evaluation indicated an increased risk of entry, establishment, spread or impact in the PRA area, this was noted in the PRA as additional information. The conclusion of the PRA, however, was based on an evaluation that did not consider climate change, because of the high uncertainty related to the climate-change projections and the difficulty in capturing this uncertainty in the overall assessment.

Although the project has now ended, climate change is still included in EPPO PRAs for invasive alien plants. The models are updated along with the projected time frame: see, for example, the EPPO PRA for *Solanum carolinense* (gd.eppo.int/taxon/SOLCA/documents), where SSPs SSP1-2.6 and SSP3-7.0 were used to project the climate for 2041–2070.

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Case study 2: Blueberry maggot establishment – use of modelling to predict expansion of pest distribution

Blueberry maggot (*Rhagoletis mendax* (Diptera: *Tephritidae*)) is an obligate fruit-parasitic fly that is native to North America and is found locally in Canada across southern Ontario and Quebec, and generally more widely distributed in New Brunswick, Nova Scotia and Prince Edward Island, as well as in the eastern part of the United States of America, south to Florida. Originally not thought to be present in Ontario and Quebec (Bush, 1966; Neilson and Wood, 1985; Vincent and Lareau, 1989), regulations were put in place to try to prevent, or at least slow, its entry. In addition, regulations were put in place in Canada (and remain in force) to prevent its transfer to British Columbia. Quebec has long been a significant producer of high-quality fresh blueberries, and trapping programmes initially ensured the continued absence of the pest from the province (Vincent and Lareau, 1989). Fresh berries for export from infested provinces to other provinces were also tested for the presence of the maggot in the berries (Dixon and Knowlton, 1994). However, by the mid-1990s, managers of commercial fields in Ontario announced the arrival of blueberry maggot, which was possibly always locally present but on alternative hosts (Smith, Gavrilovic and Smitley, 2001). At approximately the same time, the fly arrived in southern Quebec (Vincent *et al.*, 2022; Yee *et al.*, 2014) and regulations for Quebec were now directed to preventing entry to the Lac St. Jean area, where pesticide-free and pest-free fresh blueberries were produced in an economically important industry (Vincent *et al.*, 2016). Over the next 10 years, the range of the pest expanded more broadly through southern Ontario, the southern shore of the St. Lawrence area of Quebec and out along the St. Lawrence River to the Gaspé region (albeit locally) and previously uninfested parts of New Brunswick, following a general northward movement. This northward movement suggests that the climate was becoming less limiting in areas where previously it was limiting.

Why the blueberry maggot was not in Lac St. Jean was a bit of a mystery. According to cold-tolerance thresholds and host availability, including the availability of wild hosts, it should have been found throughout southern Ontario and southern Quebec into the Lac St. Jean area long ago (Smith, Gavrilovic and Smitley, 2001; Vincent *et al.*, 2016; Vincent *et al.*, 2014). One possibility was that late spring frosts might have limited northward expansion of the fly by killing potential host fruits before oviposition could occur or before larval development was complete. Another was that unreliability of spring warmth could limit northerly expansion of the fly's range; this could explain why massive losses of berries caused by late frost were occasionally reported in Lac Saint-Jean (C. Vincent, Agriculture and Agri-Food Canada, personal communication to M. Damus, 2010).

In 2010, the NPPO of Canada (Canadian Food Inspection Agency) was still conducting surveys and imposing regulations to prevent the entry of blueberry maggot to the Lac St. Jean region, and it was curious to know when natural arrival and establishment might occur. To attempt to answer this question, the current range of blueberry maggot in North America was used to create a bioclimatic-envelope model with the machine-learning, maximum-entropy program Maxent (Phillips, Anderson and Schapire, 2006), using 1950–2000 climate norms as environmental data layers. The results were then extrapolated to climatic conditions forecast under four models of climate change (Australian CSIRO Mark 2, Canadian Centre for Climate Modelling CGCM2, Hadley Centre HadCM3 and Japanese NIES99) under two scenarios (A2a and B2a). These narrative storylines have been superseded by emissions-based scenarios, but the A2 scenario represented high human population growth and slow technological development, while the B2 scenario represented moderate population growth with more environmental protection (Nakićenović *et al.*, 2000). In addition, a climate-envelope algorithm (BIOCLIM, Busby 1991), implemented in DIVA-GIS (Hijmans *et al.*, 2001), was used to try to identify what the current climatic limitations to the fly's range might be.

The current climate dataset suggested that the Lac St. Jean area was unsuitable, while the rest of southern Quebec was suitable. The future climate scenarios all suggested that Lac St. Jean would become suitable by 2020, and that the Saguenay River, which leads northwest into Lac St. Jean, would form a bridge from the infested area into the (at the time) pest free Lac St. Jean region. BIOCLIM modelling of the factors limiting establishment north of the then-infested region suggested that it was not only cold air temperature that was preventing establishment, but also the stability of the temperature. North of the St. Lawrence River, the identified most-limiting factors were temperature annual range, isothermality and temperature seasonality. The conclusion, as predicted previously by Charles Vincent (personal communication), was that it was the unreliability of seasonal weather patterns that limited northward expansion of the fly, not extreme winter cold (CFIA, 2010).

In 2018, the first adult blueberry maggot specimens were caught in the Lac St. Jean area, but no larvae were found. In 2019, more adults were caught, and by 2021, 17 out of 40 survey sites in the Lac St. Jean region were positive for blueberry maggot (Vincent *et al.*, 2022) and the regulated area was adjusted to include the Lac St. Jean region of Quebec. While the correspondence between the predicted date of establishment and the presumed date of establishment can certainly be attributed to a great deal of luck, and modelling cannot be expected to so accurately predict arrival times, the information presented in 2010 was very helpful in managing the response of the NPPO to the finds later that decade in the Lac St. Jean area.

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Case study 3:

Choice of climate-data date ranges – use of 2030 climate data in species-distribution modelling by the national plant protection organization of Canada

The first restriction that non-specialists encounter when applying specialist techniques is the availability of information accessible to persons without specialist training. Many climate-data websites are available and provide detailed climate data to the user with skills in R or other forms of programming, full training in geographical information systems, the requisite software to apply it, and so on. However, although risk assessors tend to be generalists and rely on specialists when they are available, when they are not they need to use tools that are available and “canned” – that is, ready-for-use. One excellent website with such tools is the CliMond data hub (Kriticos *et al.*, 2012), where climate data are presented in raw format (monthly averages or totals of minimum temperature, daily maximum temperature, monthly precipitation total, daily average radiation), BIOCLIM format (35 core covariates commonly used in correlative species-distribution modelling) and CLIMEX format (location and meteorology files that are combined into a MetManager file for use in the proprietary software CLIMEX). On the CliMond website, data are provided as a baseline (historical) set, centred on 1975, and six future dates (2030, 2050, 2070, 2080, 2090 and 2100) created by two models (CSIRO and MIROC-H) under two storylines each: A1B and A2. These narrative storylines have been superseded by emissions-based scenarios (RCPs), but the A1B scenario presents a future condition after balanced emphasis on all energy sources, including fossil and renewable sources, while the A2 scenario represents high human population growth and slow technological development (Nakićenović *et al.*, 2000). Unfortunately, the CliMond website has not been updated since 2014, but it still contains a set of relevant data for modelling potential distributions of organisms of phytosanitary concern. Because of the site’s content stability, it has particular value when non-specialists need to access ready-to-use climate data in formats required by the modelling systems most commonly applied: CLIMEX (Kriticos *et al.*, 2015; Sutherst and Maywald 1985) and Maxent (Phillips, Dudík and Schapire, 2021).

But which data to choose? While awaiting international agreement on how to incorporate climate-change projections into risk assessment, it is nevertheless clear that it already has to be considered: projecting species-distribution models into historical climate norms (1975) no longer makes sense, and in particular for Canada, where winter cold is likely to be the major limiting factor preventing establishment of newly arrived organisms. Canada’s climate is, by virtue of its northern location and in common with other high-latitude countries, apparently warming at twice the global rate (Environment and Climate Change Canada, 2019), meaning that for these countries at least, 1975 norms no longer approach current realities. At the Plant Health Risk Assessment Unit of the Canadian NPPO (Canadian Food Inspection Agency), species-distribution models are built (trained) on data that most closely match the majority of the presence data. If the data are historical, then the baseline dataset (centred on 1975) is used and the results are projected onto another time frame. If the data are recent, and the

1975 climate norm seems too remote in time to capture the climate change that has already occurred, then both the training and projection are done with the 2030 climate dataset (all four models – both scenarios and both designs). The CliMond website unfortunately does not offer 2000, or 2010 or even 2020 data, even though these have all been observed. The closest future, most relevant dataset is then the 2030 projection, which for risk assessment of proximate near risks is the most useful and is also considered the most defensible. But the choice of 2030 is also practical: the further out one chooses, the greater the various models diverge in their predictions, and the more weight is placed on making an "accurate" guess of the future condition – that is, which climate scenario or RCP is considered most likely (Environment and Climate Change Canada, 2022). Therefore, to minimize uncertainty and match the fit-for-purpose nature of pest risk assessment, which is to address the immediate potential for harm with as little additional uncertainty as possible, a near-time future was chosen from the easily applicable and readily available data. Simply put – a pragmatic choice was made.

As the need to integrate climate change into its daily activities and planning progresses, the NPPO has added specialists to the science staff of its plant-health programme. It is expected that they will soon conduct species-distribution modelling for risk-assessment purposes in a way that the generalist risk assessors could not, but for the time being, the current approach seems to have been successful.

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Additional resources

AQUASTAT – FAO's global information system on water and agriculture: https://www.fao.org/aquastat/en/geospatial-information/global-maps-irrigated-areas/latest-version/index.html

Atlas of Living Australia: https://spatial.ala.org.au

CABI Horizon Scanning Tool: https://www.cabi.org/HorizonScanningTool

CliMond: global climatologies for bioclimatic modelling: https://www.climond.org/Default.aspx

EDDMapS – Invasive Range Expanders Listing Tool: https://www.eddmaps.org/rangeshiftlisting/

EFSA's ScanClim tool: **EFSA (European Food Safety Authority) & Maiorano, A.** 2022. SCAN-Clim: a tool to support pest climate suitability analysis based on climate classification. EFSA Journal, 20(2): e07104. https://efsa.onlinelibrary.wiley.com/doi/full/10.2903/j.efsa.2022.7104

Growing Degree Days throughout this century, in the conterminous US: https://usfs.maps.arcgis.com/home/item.html?id=08108855bf0741418f1799f9ed8a6639

IPCC (Intergovernmental Panel on Climate Change) Working Group I Interactive Atlas: https://interactive-atlas.ipcc.ch/

Köppen Geiger climate-change data: https://www.gloh2o.org/koppen/

Multivariate Adaptive Constructed Analogs (MACA) statistically downscaled climate-change data: https://toolkit.climate.gov/tool/maca-cmip5-statistically-downscaled-climate-projections

New Zealand Climate app – Climate Matching Tool: https://climate.b3nz.org.nz/

WeedFutures.net: https://weedfutures.net/

WorldClim – future climate data: https://www.worldclim.org/data/cmip6/cmip6climate.html

IPPC

The International Plant Protection Convention (IPPC) is an international plant-health agreement that aims to protect global plant resources and facilitate safe trade. The IPPC vision is that all countries have the capacity to implement harmonized measures to prevent pest introductions and spread, and minimize the impacts of pests on food security, trade, economic growth, and the environment.

Organization

- There are over 180 IPPC contracting parties.
- Each contracting party has a national plant protection organization (NPPO) and an official IPPC contact point.
- Ten regional plant protection organizations have been established to coordinate NPPOs in various regions of the world.
- The IPPC Secretariat liaises with relevant international organizations to help build regional and national capacities.
- The secretariat is provided by the Food and Agriculture Organization of the United Nations (FAO).

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