DOI: 10.1111/epp.12989

ORIGINAL ARTICLE

Including climate change in pest risk assessment: Current practices and perspectives for future implementation

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Abstract
The evaluation of the potential for newly arrived species to survive and the determination whether a founder population can become established and subsequently spread and cause negative impacts are crucial considerations when performing a pest risk assessment in plant health. Climate change has clear consequences concerning the potential range of pests, and their potential for spread and impacts. Despite its importance, no guidance exists to support the evaluation of whether and how climate change should be incorporated into pest risk assessment. This paper reviews how climate change has been considered so far, not only in the area of pest risk assessment but also in other domains and provides guidance on how its incorporation could affect the overall assessment. Furthermore, from this analysis, some possible solutions for incorporating climate change into pest risk assessment are provided, taking into account that its outcomes have profound political, economic, social and environmental implications.

KEYWORDS
climate change, pest risk assessment, plant health, plant pests, time horizon

Inclure le changement climatique dans l'évaluation du risque phytosanitaire: pratiques actuelles et perspectives
L'évaluation du potentiel de survie de nouvelles espèces; et la détermination de la possibilité d'établissement et de dissémination d'une population fondatrice et de ses impacts négatifs sont des considérations cruciales lors de la réalisation d'une évaluation du risque phytosanitaire. Le changement climatique a des conséquences évidentes sur la répartition géographique potentielle d'organismes nuisibles ainsi que sur leurs éventuels dissémination et impacts. Malgré son importance, il n'existe aucune directive pour évaluer la pertinence de l'intégration du changement climatique dans l'évaluation du risque phytosanitaire. Cet article examine comment le changement climatique a été pris en compte jusqu'à présent, non seulement dans le domaine de l'évaluation du risque phytosanitaire, mais également dans d'autres domaines, et explique l'impact de son intégration sur l'ensemble de l'évaluation. En outre, à partir de cette analyse, certaines solutions pour intégrer le changement climatique dans l'évaluation du risque phytosanitaire sont fournies, en reconnaissant que le changement climatique aura de profondes implications politiques, économiques, sociales et environnementales.

Включение изменения климата в оценку фитосанитарного риска: текущие практики и перспективы будущего применения

Оценка потенциала выживания новоприбывших видов и определение того, может ли популяция акклиматизироваться, а затем распространиться и вызвать негативные последствия, являются важнейшими факторами при проведении оценки фитосанитарного риска. Изменение климата имеет очевидные последствия в отношении потенциального ареала вредных организмов, а также потенциала их распространения и масштаба наносимого вреда. Несмотря на важность проблемы климатических изменений, в настоящее время не существует четкого руководства, описывающего, следует ли и каким образом включать вопросы изменение климата в оценку фитосанитарного риска. В данной статье приведён обзор того, как проблема изменения климата рассматривалась до настоящего времени в области оценки фитосанитарного риска и в смежных областях, а также рассмотрено, как учёт климатических изменений может повлиять на общую оценку фитосанитарного риска. Кроме того, на основе проведенного анализа предлагаются возможные решения для включения вопросов изменения климата в оценку фитосанитарного риска, с учетом того, что они влекут за собой серьезные политические, экономические, социальные и экологические последствия.

1 | INTRODUCTION

Pest risk assessment for quarantine pests is the evaluation of the probability of the introduction and spread of a pest and the magnitude of the associated potential economic consequences (FAO, 2023). Various biotic and abiotic factors can influence the ability of a pest to enter, establish, spread and cause damage in a new area. Environmental variables such as temperature, precipitation, humidity and ultimately carbon dioxide concentration in the atmosphere have an impact on the life cycle of species. Changes in these variables can undoubtedly affect the risk that a pest poses to a specified region. As such, there is a need to develop new methods which consider the inclusion of climate change into the assessment of the risks posed by plant pests. According to the International Standards for Phytosanitary Measures (ISPM) 5 (FAO, 2023), a pest is defined as "Any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products". Throughout this text "pest" will be used according to this definition.

Typically, pest risk assessments consider historical climate information only, and the impact of potential future changes in climate is not included (see Supplementary Data S1). Pests are generally adaptable organisms but they respond differently to climate change (Yamamura & Kiritani, 1998): faster physiological development due to an increase in average temperatures can result in an increased number of generations per year; milder temperatures may allow a species to expand its geographic range, increase overwintering survival at higher latitudes and altitudes, and increase the chances of establishment in new regions (Szyniszewska et al., 2024). On the other hand, certain pests might face challenges, such as altered precipitation patterns or temperature extremes, which could inhibit their reproduction, survival or ability to thrive in certain regions. Climate change can also cause disruption to the synchrony between the phenology of a pest and its host, as well as its natural enemies (Renner & Zohner, 2018; Singer & Parmesan, 2010). Overall, the effect of climate change on pests is undoubtedly complex, impacting distribution, abundance, development and phenology, favouring some organisms while inhibiting others (Skendžić et al., 2021). Furthermore, it is becoming more evident that climate change, combined with increasing global trade and movement of people, provides pests with a greater number of pathways and opportunities to invade and establish in new areas (Choudhary et al., 2019; Gullino et al., 2022; Hulme, 2009; Juroszek & von Tiedemann, 2015; Seebens et al., 2017, 2021; Taylor et al., 2018), thus posing serious threats to agriculture, forestry and natural ecosystems.

Pest risk modelling is widely used to understand short-term (e.g. from the present day into the next decade) risks and impacts. However, as pest risk profiles change under new climates, modelling frameworks are being expanded to include anthropogenic pest risk drivers, such as integrated/coupled models of pest, trade, and climate. These integrated modelling tools exist and are detailed in Kriticos et al. (2024). The rapid pace of climate change advocates for it to be considered within pest risk assessments, where appropriate. This would allow for predicted changes in pest distribution and expected changes to trade pathways to be assessed to better understand, anticipate and respond to pest risks in future. Pest risk analysis (PRA) activities need to be intensified at national, regional and international levels and it has been argued that climate-change aspects need to be included in the assessment of pest risk (FAO, 2021).

In this paper, we (i) describe how climate and climate change are currently incorporated into different risk assessment frameworks, (ii) debate the benefits of incorporating climate change considerations and (iii) discuss perspectives for its future integration into the assessment of pest risk. For the purposes of this work, the term "climate change" refers only to future climate expectations and does not include the effects of climate change that have already occurred. Figure 1 shows how climate change can affect a pest and its cascading impacts on each step of the pest risk assessment.

2 | HOW IS CLIMATE CURRENTLY INCORPORATED INTO PEST RISK ASSESSMENTS?

The evaluation of the suitability of the climate for a pest of interest in a particular region is an important part of pest risk assessment (Szyniszewska et al., 2024). There are numerous methods available to evaluate and model the climate suitability for pest establishment and spread, and more detail on these can be found in Kriticos et al. (2024). Venette (2015) and Eyre et al. (2012) have also provided recommendations and guidance on the selection of the most appropriate method, from the large number available, for climate suitability analysis. Ultimately, the selection of the method should be based on the available information on the pest's physiological responses to climate and the current range of its distribution, taking into account the level of detail and quality of the available information (Eyre et al., 2012). There are various scenarios requiring different methods for consideration of current climatic suitability in pest risk assessments, including the following:

- *No climate suitability consideration*. No consideration of climatic suitability can be a defensible option when the risk of outdoor establishment is considered unlikely with high confidence for other reasons. An example in this category is the pest risk assessment for the tomato mottle mosaic virus in the United Kingdom (DEFRA, 2022), where climatic suitability evaluation was not deemed necessary because the host is not grown year-round and is not grown commercially outdoors.
- *Examination of cardinal threshold temperatures*. The developmental, survival and reproductive responses of pests to temperature pose practical challenges owing to variability between individuals and high mortality near lower and upper threshold temperatures (Régnière et al., 2012), especially with increasing periods of exposure (Bale & Hayward, 2010). Field and laboratory studies can help identify pests' thermal tolerances and if the region of interest experiences temperatures outside the determined ranges, the likelihood of establishment can be regarded as low. An example of a pest risk assessment in this category is that of *Tuta absoluta*, the tomato leaf miner moth (Potting, 2009), where the probability of establishment outdoors in the Netherlands and the United Kingdom was regarded as very unlikely because it was assumed that the pest would only be able to survive temperatures slightly below zero for short periods. Another example is the use of world hardiness zones (Magarey et al., 2008) for invasive alien plants.
- *Comparison of climate data between regions*. Comparing climate data from areas with no establishment to climate data from areas with established populations may be appropriate when it is not known which cardinal threshold temperatures prevent establishment. Instead of raw climate data, pest risk assessments can also use Köppen–Geiger climate classifications to determine similarities between the

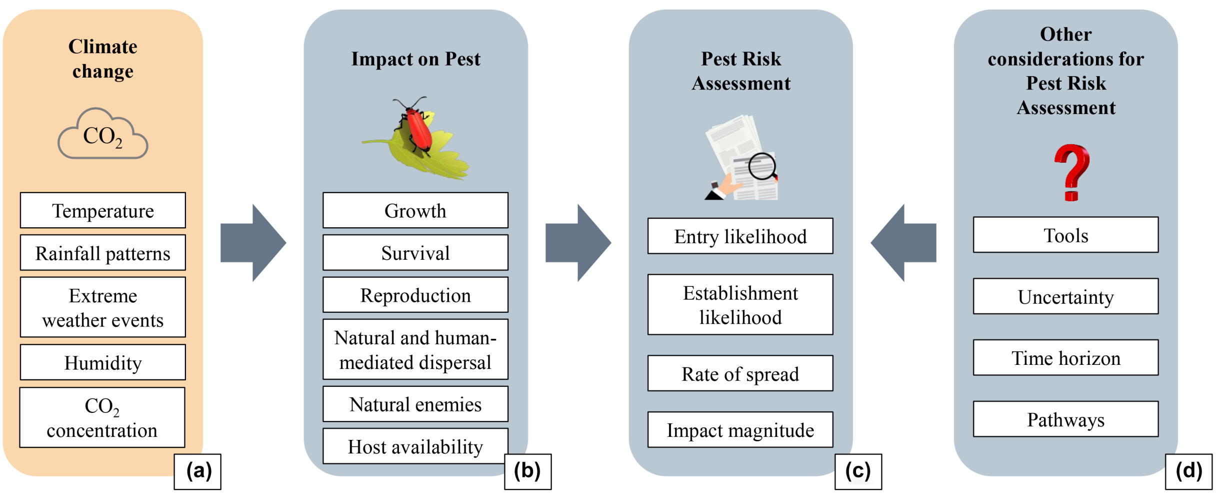

FIGURE 1 Illustration of climate change (a) impacts on the survival and life cycle of pests (b). When including climate change in the pest risk assessment, its effects on the pest need to be considered, as they might directly affect conclusions on the entry, establishment, spread and magnitude of impact on the food production (c). In (d), other inputs necessary for framing the pest risk assessment are reported, e.g. tools are available to estimate the effects of climate change on the pest risk assessment; it is important to recognize the deep uncertainty posed by climate change; the time horizon chosen might affect the impact that climate change will have on the overall risk assessed.

areas at risk and areas with pest establishment. An example of pest risk assessment using Köppen–Geiger climate classifications is the one for *Citripestis sagittiferella* (Lepidoptera: Pyralidae), the citrus pulp borer (EFSA PLH Panel, 2023a), which indicated that Southern Europe could be at risk as it contains the same climate zones as locations where the pest is already established.

- *Degree-days accumulation calculations*. Degree-days are measurements of heat accumulation over time, calculated by adding the difference between mean daily temperatures and minimum developmental temperature for the pest over time. Degree-days can be used to predict phenological events and overall life cycles of pests. These calculations are useful to investigate the time of emergence of an insect, or a pathogen's latent period (Zearfoss et al., 2011), and the number of possible generations per year when the minimum temperature required for the development of the pest is well known and development stages are closely linked to temperature. Examples using this method are the work of Ni et al. (2012) and Kistner-Thomas (2019) on *Bactrocera zonata* and *Popillia japonica* (the Japanese beetle), respectively, where the degree-days required for a generation were calculated for use in the CLIMEX modelling approach. Another example is the pest risk assessment on *Resseliella citrifrugis* (EFSA PLH Panel, 2023b), where a comparison of the sum of degree days between the regions with reports of the pest in China and the EU citrus growing area was performed.
- *Species distribution modelling (SDM)*. Using climatic niche models to predict species distribution may be useful to predict the potential for establishment and estimate the risks associated with future spread. An example of a pest risk assessment using SDM is Acute Oak Decline in the United Kingdom (Forest Research, 2014), where it was used because the decline-disease was established in some parts of the United Kingdom, but the potential distribution of the vector was unknown. Other examples include the pest risk analysis for *Prosopis juliflora* (EPPO, 2018a), where SDM identified suitable areas for establishment in the Mediterranean and Macaronesia biogeographical region, and the risk assessment of *Tuta absoluta* from Ponti et al. (2021), where a mechanistic physiologically based demographic model that captures the weather-driven biology of the moth was developed to explain and predict prospectively the invasiveness of the pest in uninvaded areas; the model also included climate change scenarios.

Datasets documenting historical climate data often used in pest risk assessments include either point data derived from meteorological stations or model-derived climate data available from numerous sources. Some datasets are readily available with models/software; some need to be downloaded and summarized and/or aggregated for the purpose of being used in the SDMs. Some commonly used datasets are listed in Table 1.

3 | HOW IS CLIMATE CHANGE CURRENTLY INCORPORATED INTO RISK ASSESSMENT?

3.1 | Climate change in various domains of risk assessment

Invasive plants and animals represent a significant threat for agriculture, forestry and other managed or unmanaged terrestrial and aquatic ecosystems. In risk assessments of invasive alien species (IAS), the influence of climate change appears to be frequently considered. In the EU, for example, following the EU regulation 1143/2014 (EU, 2014), climate change is included in the criteria for IAS of Union concern, and, in the risk assessment, climate change should be regarded in relation to the risk of introduction and spread. Globally, various risk assessment schemes have been employed for IAS, but there are variations in how climate change is addressed, if at all. Some risk assessment schemes have included the influence of climate change as part of the scenario being considered, while others include a separate part where the potential effect of climate change on the risk is described (Table 2). The EPPO Decision-Support Scheme for an Express Pest Risk Analysis (Standard PM 5/5(1), EPPO, 2012) was specifically amended to incorporate the minimum requirements for risk assessment when considering invasive alien plant species under the EU Regulation 1143/2014 (e.g. EPPO, 2018b). Amendments are specific to the LIFE project "Mitigating the threat of invasive alien plants to the EU through pest risk analysis to support Regulation 1143/2014" (EU-funded LIFE project). According to the scheme reported in that project, the assessment of entry, establishment, spread and impact should be given separately for the current climate and under foreseeable climate change conditions. The applied emission scenario and future timeframe as well as the components of climate change that are expected to be most relevant for the organism should be stated. The assessments are supported by modelling the potential range of the organism under the considered emission scenario and timeframe using various algorithms for climate suitability or SDM (e.g. EPPO, 2018b).

As detailed in Kriticos et al. (2024), the most common approach in the risk assessment of invasive organisms involves combining climate change scenarios with habitat suitability models or SDMs. While this approach is valuable, it has limitations, particularly when applied to climatic conditions different from those used to train the model (Elith & Leathwick, 2009). In some cases, this approach is combined with the selection of a group of

TABLE 1 Some readily available datasets documenting historical climate data.

Dataset	Spatial resolution as indicated in the dataset	Reference period	Description	Available at
Global Historical Climatology Network daily (GBCNd)	–	Nineteenth century to present	Daily climate observations (temperature, precipitation and others) from over 100 000 weather stations worldwide	https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily
WorldClim 2.1	30 s (~1 km^2) to 10 min (~340 km^2)	1970–2000	Monthly temperature, precipitation, and bioclimatic variables describing temperature and precipitation patterns across the year	https://www.worldclim.org/
Climate Research Unit (CRU) Time Series (TS) 4.0	0.5° latitude by 0.5° longitude grid	1901–2022	Monthly climate data (temperature, precipitation and others) from over 6000 weather stations worldwide	https://www.uea.ac.uk/web/groups-and-centres/climatic-research-unit/data
CHELSA	30 arcsec, ~1 km	1979 to present	Global downscaled climate dataset which also includes several different future climate models and scenarios	https://chelsa-climate.org/
ERA5-Land	0.1° (native resolution 9 km)	1950 to present	ERA5-Land is a climatic data resulting from a combination of model data and observation data from across the world	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview
AgERA5	0.1°	1979 to present	AgERA5 is based on bias-adjusted ERA5 data. It includes daily aggregates of agrometeorological data (covering temperature, precipitation, humidity, radiation)	https://www.copernicus.eu/en/access-data/copernicus-services-catalogue/app-agriculture-agera5-explorer-data-extractor
AgMERRA	0.25°	1980–2010	AgMERRA provides consistent, daily time series with global coverage of climate variables required for agricultural models	https://data.giss.nasa.gov/impacts/agmipcf/agmerra/

organisms through a prioritization process (e.g. Chai et al., 2016; Firn et al., 2015) or the identification of the most relevant organism with a non-formalized process (e.g. Shrestha et al., 2018). Species distribution models are correlative methods that establish a relationship between the occurrence of the species with the environmental conditions of the sites, as opposed to more mechanistic, process-based models that rather rely on the physiology and thermal tolerance of the species. Despite their drawbacks, correlative SDMs are nonetheless frequently preferred because they are easier to develop and have more manageable data requirements relative to other mechanistic techniques (Briscoe et al., 2019).

Other schemes do not take climate change into account, but the risk assessments can be re-evaluated if needed to allow any changes owing to climate change to be captured and to make sure the conclusions previously reached are still valid (e.g. Ontario Ministry of Natural Resources and Forestry, 2016). Establishment is generally considered to be the key step, for organisms in both aquatic (D'Amen & Azzurro, 2020; Gallardo & Aldridge, 2013) and terrestrial ecosystems (Heshmati et al., 2019). However, examples are available where the effects of climate change are evaluated also for other steps, such as entry, as for instance variation in propagule pressure may be a consequence of climate change (Chown et al., 2012).

In the field of conservation, the assessment of a species' degree of threat or extinction risk is essential to inform action plans, as well as to support the development of regulations and laws. Following the recognition of the threat posed by climate change to biodiversity, the conservation community has readily responded to the challenge by developing sensitive and robust methods for assessing species' vulnerability to climate change (Foden & Young, 2016). Three main broad categories of approaches have been developed to assess species' vulnerability to climate change (Foden & Young, 2016; Pacifici et al., 2015), which are further detailed in Kriticos et al. (2024):

1. Correlative approaches (e.g. Araujo et al., 2006; Huntley et al., 2008; Thuiller et al., 2005) relate the geographic distribution to historical climate to estimate the climatic requirements (climatic niche) of the species. Vulnerability is usually inferred from the

TABLE 2 Examples of how climate change is included in different risk assessment templates.

Risk assessment scheme	How is climate change included?	Sources and examples
Conservation planning for threatened species		
International Union for Conservation of Nature (IUCN) Species Survival Commission (SSC) Guidelines for Assessing Species' Vulnerability to Climate Change	Depending on the approach chosen for the climate change vulnerability assessment (CCVA), climate change is incorporated slightly differently: • correlative (niche-based) methods – projections of future climate (scenarios) are used to predict the potential distribution of species in the future; • trait-based methods – species' sensitivity and adaptive capacity to climate change is estimated by experts based on species' biological and ecological characteristics; • mechanistic (process-based) methods – projections of future climate (scenarios) are used to predict habitat suitability and species' growth in the new environment. The choice of a timeframe (time horizon) depends on the: • goal of the CCVA – provide input for a specific conservation plan; detect areas with a high concentration of species threatened by climate change, etc. • target species – it is important to consider generation length. For short-lived species, shorter projection intervals are more appropriate (e.g. according to IUCN Red List guidelines, three generations, with a minimum of 10 years), while for longer-lived species, longer intervals are necessary to adequately estimate vulnerability (e.g. three generations, to a maximum of 100 years).	Foden and Young (2016)
NatureServe Climate Change vulnerability index	The index divides vulnerability into three components as follows: • exposure to climate change is assessed by examining (via an online tool) the magnitude of predicted temperature and moisture change across the range of the species, and by considering the influence of indirect factors such as sea level rise, presence of natural/anthropogenic barriers, land use change; • species' sensitivity considers ecological and life-history traits that are associated with climate change sensitivity (temperature and precipitation sensitivity, habitat specificity, dietary versatility, etc.); • adaptive capacity (dispersal ability, genetic variation, etc.).	NatureServe, online Examples: • Climate change vulnerability of Alberta's terrestrial biodiversity (Shank & Nixon, 2014); • Climate change vulnerability assessment of species in the Ontario Great Lakes Basin (Brinker et al., 2018); • Mapping the drivers of climate change vulnerability for Australia's threatened species (Lee et al., 2015)
Invasive alien species domain		
GB Non-native Organism Risk Assessment Scheme	Climate change is addressed by the inclusion of three questions: (1) What aspects of climate change, if any, are most likely to affect the risk assessment for this organism? (2) What is the likely timeframe for such changes? (5, 10, 20, 50, 100 years?) (3) What aspects of the risk assessment are most likely to change as a result of climate change? The assessor is asked to provide a confidence rating (low, medium, high, very high) with regard to the response provided	NNSS (2023) Example: western green lizard (*Lacerta bilineata*) (Gleed-Owen, 2012)
GB Non-native Species Rapid Risk Assessment (NRRA)	Climate change is addressed with one question: (1) What is the likelihood that the risk posed by this species will increase as a result of climate change? Text is provided to support the rating (very low, low, moderate, high, very high) and the assessor is asked to provide a confidence rating (low, medium, high, very high) with regard to the response provided	NNSS (2023) Example: *Cephalothrix simula* (a nemertean worm) (Gibson, 2020)
Generic Ecological Impact Assessment of Alien Species (GEIAA) used e.g. in Norway and Sweden	Climate change is included into the risk assessment as such by: (1) Including a description of the potential distribution of the species based on the most likely situation 50 years into the future. (2) Setting a time frame of 50 years[a] into the future for the assessment of the ecological effect, but only if it can be documented or substantiated. In addition, the effect of climate change on the scores for invasion potential and/or ecological effects are also to be described.	Sandvik et al. (2019); Sandvik et al. (2017) Example: *Bursaphelenchus xylophilus* (Magnusson et al., 2018)

(Continues)

TABLE 2 (Continued)

Risk assessment scheme	How is climate change included?	Sources and examples
Guidance for Invasive Species Assessments Under the Invasive Species Act, 2015 used in Ontario, Canada	Climate change does not appear to be included in the scheme used, but it is clearly stated that over time it is necessary to re-evaluate the risk assessments, e.g. owing to the potential effects of climate change on the risk, and that re-evaluation will be done periodically.	Ontario Ministry of Natural Resources and Forestry (2016)
Marine Invasive Species Risk Assessment used in Alaska, USA	A habitat suitability analysis is performed considering the potential effects of climate change by comparing current and future suitability models.	Reimer et al. (2017)
Mitigating the Threat of Invasive Alien Plants to the EU Through Pest Risk Analysis to Support the Regulation 1143/2014	Template based on the EPPO Standard PM 5/5 Decision-Support Scheme for an Express Pest Risk Analysis where assessments should be given separately for current climate and under foreseeable climate change conditions. Effects on pathways, establishment, spread and impacts should be assessed separately. The applied timeframe and scenario should be stated and which of the following components of climate change was thought to be most relevant for the organism: temperature, precipitation, CO_2 levels, sea-level rise, salinity, nitrogen deposition, acidification, land use change, or another component specified by the risk assessor. Importantly, owing to uncertainty of the effects and influence of climate change it did not feature in the overall consideration of the scoring.	For example, EPPO (2018b) (http://www.iap-risk.eu/)
Study on Invasive Alien Species – Development of Risk Assessments to Tackle Priority Species and Enhance Prevention	Template where assessments should be given separately for current climate and under foreseeable climate change conditions. Entry, establishment, spread and impact should be assessed separately. The applied timeframe and scenario should be stated and, interestingly, if other choices than RCP 2.6 and RCP 4.5 are used, the choice of the assessed scenario has to be explained (see Section 4.2 for further details). Furthermore, the aspects of climate change which are most likely to affect the risk assessment should be stated, e.g. increase in average winter temperature or increase in drought periods.	For example, Galanidi et al. (2022)
Plant health domain		
Guidance on Quantitative Pest Risk Assessment (EFSA)	The quantitative pest risk assessment is performed based on defined scenarios. Climate change would thus be included if this is specified in the formulated scenarios. However, no guidance on how this should be done is provided. For example, one of the scenarios defined in the pest risk assessment for the plant parasitic nematode *Radopholus similis* specifies that the risk assessment should consider a climate change of +2°C.	Gilioli et al. (2017), EFSA PLH Panel (2018) Example: *Radopholus similis* (EFSA PLH Panel, 2017)

Abbreviation: RCP, Representative concentration pathway.

[a]Fifty years or five generations (the longest is used, but max 300 years).

difference in range size and occasionally from the degree of fragmentation (Foden & Young, 2016).

2. Trait-based approaches (e.g. Foden et al., 2013; Zhang et al., 2019) use species' characteristics (traits) to estimate their sensitivity and potential adaptive capacity to climate change. Scores of sensitivity, adaptive capacity and sometimes exposure are then combined to assign the species to a particular category of vulnerability.
3. Mechanistic or process-based approaches (e.g. Kearney & Porter, 2009; Radchuk et al., 2013) use estimates of species' physiological tolerance and demographic rates (obtained from laboratory experiments or field observations) to estimate the fundamental niche of the species. Some of the challenges of implementing these types of models are discussed in Briscoe et al. (2019).

The practice of combining these approaches is gaining consensus since they complement each other. All of these approaches produce different measures or metrics of climate change vulnerability spanning from simple vulnerability indices to measures of range and population changes, to estimates of extinction risk. Outputs can be used to prioritize species (e.g. Harper et al., 2022; Maggini et al., 2014) or areas for conservation and restoration (e.g. Gaisberger et al., 2022; Maggini et al., 2013; Summers et al., 2012).

3.2 | Climate change in pest risk assessments

To obtain an overview of how climate change has been incorporated in pest risk assessments, risk assessments available in the EPPO Platform on PRAs (EPPO, 2023) were downloaded and a text search was conducted for the term “climate change”. Out of the over 1000 reports contained in the Platform, 55 relevant reports were found to include consideration of climate change (see Supplementary Data S1 for details). In the majority of these cases, no separate assessment of the risk in the current and future climate was performed. Instead, climate change was generally considered as one aspect of the reasoning that may affect the overall assessment and its associated uncertainty.

Although most assessment schemes contain no specific guidance on how climate change should be incorporated in the reasoning process, some do provide guidance. For example, according to the pest risk assessment scheme tested and developed in the project “Pest risk assessment for the European Community: plant health: a comparative approach with case studies” (short name Prima phacie), the assessor should define and justify a time period considered in the assessment. In addition, the assessor has an option to select whether climate change is taken into account, and if so, the climate change scenarios considered should be noted (MacLeod et al., 2012).

Guidance is provided, such as a 5 year time horizon being considered as medium term, whereas 30 years would be long term. It is at this point that assessors need to consider whether climate change is to be taken into account.

In the assessments that have taken climate change into account, the effect of climate change was typically estimated based on a literature review (Supplementary Data S1). In other cases, the assessment is supported by purpose-specific modelling. The modelling methods most used in pest risk assessments reviewed were correlative SDMs, but other modelling tools such as CLIMEX (e.g. Ibáñez-Justicia et al., 2010) and Köppen–Geiger climate classification (e.g. Boberg & Björklund, 2021) have also been used.

Typically, the suitability of the future climate for a pest has been modelled for certain time horizons, for which openly available climate change data exist, such as 2050 and 2070, using one or more emission scenarios (Supplementary Data S1). However, in some cases, the effect of climate change has been modelled by considering a certain temperature increase to the current climate without considering any time step or emission scenario. Climate change has most frequently been considered in the assessment of establishment (50 out of 55 risk assessments), but occasionally, also in assessments of entry, spread and impact.

3.2.1 | Some examples of integration of climate change into pest risk assessment

Examples of integration of climate change into pest risk assessment come from pest risk assessments themselves and from scientific studies conducted to support them. For example, the New Zealand pest risk assessment for *Lymantria dispar* (the spongy moth) includes maps of establishment probability under climate change using the median of regional warming forecasts for 2030 and 2080 (Pitt et al., 2007). It is important to mention that the terms “forecast”, “prediction” and “projection” are used in this paper to try to adhere to the definition reported in the IPCC Glossary (IPCC, online). The potential range of the blueberry maggot (*Rhagoletis mendax*) in Canada was modelled for a policy decision to rationalize regulations preventing entry to regions of the country that were considered climatically unsuitable, but that were suspected to be becoming suitable owing to climate change (Damus, personal communication). The analysis was relatively basic owing to time constraints and was limited to correlative SDM modelling (Maxent) of future climate conditions (Phillips & Dudík, 2008) and estimation (Bioclim) of limiting climatic factors (Busby, 1991). Similar research by Régnière et al. (2009), which modelled the climatic suitability of Canada for *L. dispar*, tracked the close link between climatic suitability and past spread in Canada and predicted future spread based on expected climate up to 75 years in the future. Another example is the work by Ni et al. (2012) who projected the potential distribution of *B. zonata* under climate change scenarios, indicating that relevant expansion of the pest will occur in areas currently too cold for its establishment. The authors of the paper also suggest that biosecurity authorities should consider the effects of climate change when undertaking pest risk assessments. In that work, the CLIMEX model was used for the assessment of the response of *B. zonata* to current climate and for the predicted climate for the 2070s. More recently, two climate change scenarios were included in the pest risk assessment of *Trirachys sartus* (syn. *Aeolesthes sarta*) in Pakistan using the CLIMEX model (Hayat et al., 2023). Future climatic data were made available based on two global circulation models. The changing and generally higher temperatures in central and southern Pakistan would probably cause the distribution of *T. sartus* to shift under future climatic conditions. Additionally, Camac et al. (2021) recently implemented a model integrating trade, climate suitability and pest border contamination rates for the Australian Department of Agriculture, Fisheries and Forestry and the New Zealand Ministry of Primary Industries. This model estimates the expected number of pest-specific contamination events arriving at a country's border (i.e. propagule pressure) and the expected number of these events likely to occur in climatically suitable locations within a country (i.e. establishment exposure) by combining border interceptions records data on international trade flows, known pest occurrence and the geographic distributions of both human population and climate suitable to the pest(s) of concern. This original model was applied to *Halyomorpha halys*, the brown marmorated stink bug (Rice et al., 2014; Valentin et al., 2017). While the original model was capable of making short-term predictions of country propagule pressure and establishment exposure of hitchhiking pests, it was not used to forecast pest exposure over longer time horizons and under different potential climate scenarios. The Centre of Excellence for Biosecurity Risk Analysis (University of Melbourne) has now extended this model to forecast both propagule pressure and ultimately the establishment exposure of hitchhiking pests arriving at a country's border (associated with trade) under different climate and trade scenarios. To achieve this, the team integrated the model with temporal forecasts in pest climate suitability (derived from 23 General Circulation Models), human population and trade flows for 68 countries and 40 commodity sectors. Trade flows were estimated using a large-dimensional Computational General Equilibrium Model called the Global Trade Analysis Project. This trade flow model utilizes temperature, precipitation and CO_2-response functions calibrated with national average impacts of climate change on agricultural productivity, labour productivity, limited sea-level rise (i.e. loss of arable land) and tourism. This allowed climate change impacts to be reflected in predicted export and import trade flows under different representative concentration pathways (RCPs). This integration of temporal predictions in trade, pest climate suitability and human population has allowed the model to forecast how *H. halys* propagule pressure and establishment exposure could vary over time under different shared socio-economic pathways (SSP) and RCP scenarios. Moreover, it allows users to identify the trading partners contributing the most to the estimated propagule pressure for different countries, as well as the commodity types exhibiting the highest contamination rates. This updated model has recently been applied to five hitchhiking pests identified by the Australian Department of Agriculture, Fisheries and Forestry: *H. halys*, *Lissachatina fulica* (giant African snail), *Apis cerana* (Asian honey bee), *Trogoderma granarium* (the khapra beetle), and *L. dispar*.

In the European Union (EU), the European Food Safety Authority (EFSA) Plant Health Panel has recently been requested to include the analysis of the effect of climate change on some pests in their quantitative pest risk assessments. The first quantitative pest risk assessment which included a climate change scenario informing establishment likelihood was published for the pathogen of grapevine *Xanthomonas citri* pv. *viticola* (EFSA PLH Panel, 2022). Factors such as the appearance of heavier storms owing to the tropicalization of climate around the Mediterranean and effects on host plants distribution and phenology were considered when evaluating climate change scenarios. WorldClim bioclimatic variables projected to the period 2041–2060 with a suite of climate models were overlaid onto EU locations, where the values of these variables matched the current distribution of *X. citri* pv. *viticola* to produce an establishment potential map. Three climate change emissions scenarios (low, intermediate and high greenhouse gas emissions) were considered and the variability among the climate model outputs was measured using the coefficient of variation. As for many grapevine-producing areas in the EU, the average difference across bioclimatic variables slightly changed when comparing the current climate with climate projection; the values elicited via expert knowledge elicitation estimating the pest probability of establishment were also higher when considering climate change. According to the model results, the likelihood of establishment of *X. citri* pv. *viticola* in the EU was estimated to be slightly higher under climate change.

A second example is the EFSA quantitative pest risk assessment for *Elasmopalpus lignosellus* (lesser cornstalk borer) (EFSA PLH Panel, 2023c). The analysis was based on the output of four regional climate models under the representative emission scenario RCP8.5 (Kriticos et al., 2012). CLIMEX simulations were run for each climate change model and then averaged. The effect of irrigation was also considered: top-up irrigation (rainfall plus up to 2.5 mm day^{-1}) was applied to the irrigated areas indicated by Meier et al. (2018), upscaled to the same resolution of the climate data used by CLIMEX. The climate change model ensemble allowed the authors to identify, at a regional level, the increase in areas of potential establishment for the period 2040–2059, as well as to make an estimate of the potential number of generations in the European territory under these future climate conditions.

4 | PERSPECTIVES FOR FUTURE INCLUSION OF CLIMATE CHANGE IN PEST RISK ASSESSMENT

The inclusion of climate change in a risk assessment will probably depend on at least one of the following factors: (i) whether climate change is expected to either increase the potential impact of a pest to an unacceptable level or decrease it to an acceptable level; (ii) the amount of uncertainty behind a pest's potential to establish or the range it might occupy; (iii) whether the pest is an immediate threat (e.g. one already found during inspections or surveys) or a hypothetical threat (e.g. one that has not already been found in the pest risk assessment area but which has recently spread to regions with a similar climate); and (iv) available resources (e.g. monetary, time, available data and expertise and skills). The time horizon is a crucial aspect of pest risk assessments and the definition of it should result from an agreement between risk assessors and risk managers. Furthermore, every national plant protection organization will have its overarching policy considerations to deal with when it comes to integrating climate change into pest risk assessments.

Here we aim to provide indications when considering the integration of climate change in a pest risk

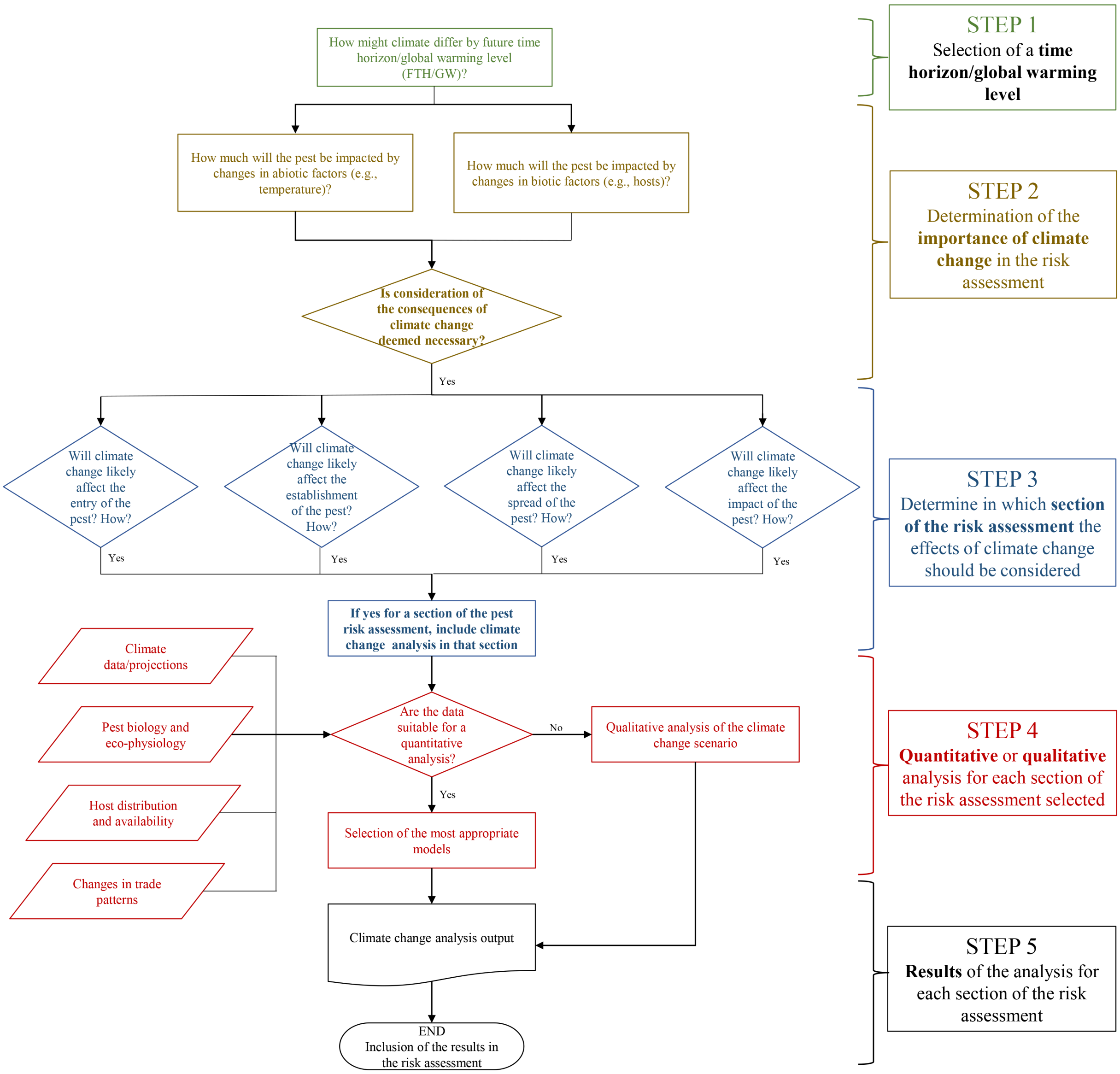

FIGURE 2 Flowchart showing a possible path for the inclusion of climate change in risk assessment, if climate change considerations are deemed necessary.

assessment. There is no intent to fit all possible situations, but to provide useful generalizations that will need to take the policy framework of each specific risk assessment into account. This guidance is inspired by previous documents written to help national plant protection organizations decide whether to model and map the suitability of climate during pest risk analysis (e.g. Eyre et al., 2012; NAPPO, 2011). The flowchart in Figure 2 shows a proposed flexible structure to follow. In some cases, the decision to include climate change in the assessment might be driven by its effect on pest physiology, potential introduction, spread and impact. In other cases, the decision might depend on the time horizon selected for the assessment; therefore, the importance of climate change scenario(s) is evaluated according to the selected time horizon. To select and prioritize the elements indicated in Step 3 of the flow chart, the MoSCoW method (must have, should have, could have, won't have: Clegg & Barker, 1994) can be used. It is a prioritization technique used in other fields of decision-making to understand the importance that stakeholders give to the inclusion of each element. Overall, for every risk assessment including climate change, the following two elements are considered "must haves": (i) Selection of at least one climate scenario, or set a climate change of e.g. +2°C, for a given time horizon; and (ii) analysis of the climate suitability for the pest in reference to the pest risk assessment area. Nevertheless, elements considered as must have, should have, could have, won't have may vary depending on resource availability, as shown in Table 3 and detailed in the next paragraphs. The content of Table 3 refers

TABLE 3 The MoSCoW method (must have, should have, could have, won't have; Clegg & Barker, 1994) prioritization approach and relevant considerations to be included in each risk assessment step (i.e. entry, establishment, spread and impact).

	Low resources[a] for pest risk assessment				Medium resources[a] for pest risk assessment				High resources[a] for pest risk assessment			
Risk assessment steps	**Must have**	**Should have**	**Could have**	**Won't have**	**Must have**	**Should have**	**Could have**	**Won't have**	**Must have**	**Should have**	**Could have**	**Won't have**
Selection of at least one climate scenario for a given time horizon, or set a climate change of e.g. +2°C, for a given time horizon	✓				✓				✓			
Effects of climate change on entry			✓			✓			✓			
Multiple emission scenarios				✓			✓			✓		
Changes in host/s trade				✓			✓			✓		
Variation in entry pathways				✓			✓			✓		
Pathway models			✓			✓				✓		
Effects of climate change on establishment	✓				✓				✓			
Multiple emission scenarios				✓			✓			✓		
Future climate Köppen–Geiger classification		✓			✓				✓			
Climate (e.g. temperature–precipitation pattern variations) effects on pest/s biology	✓				✓				✓			
New host/s available in areas previously unsuitable			✓				✓			✓		
Variation in host/s distribution and availability			✓				✓			✓		
Models (See Kriticos et al., 2024)				✓		✓			✓			
Effects of climate change on spread			✓			✓			✓			
Multiple emission scenarios				✓			✓			✓		
Variation in the spread rate of the pest				✓			✓			✓		
Effects of climate change on impact			✓			✓			✓			
Multiple emission scenarios				✓			✓			✓		
Variation in harm potential of the pest			✓			✓			✓			
Suitability of the host/s for infection or attack				✓			✓			✓		
Environmental impact				✓			✓			✓		

Note: The content of the table refers to cases where climate change scenarios are relevant to be included and do not apply to all pest risk assessments. If the data are not suitable for a quantitative analysis, a qualitative analysis of the climate change scenarios might be performed.

[a]"Resources" refers to economic, data and/or human resources.

Low, medium and high resources are indicated by varying shades of green (light green, olive green and dark green respectively).

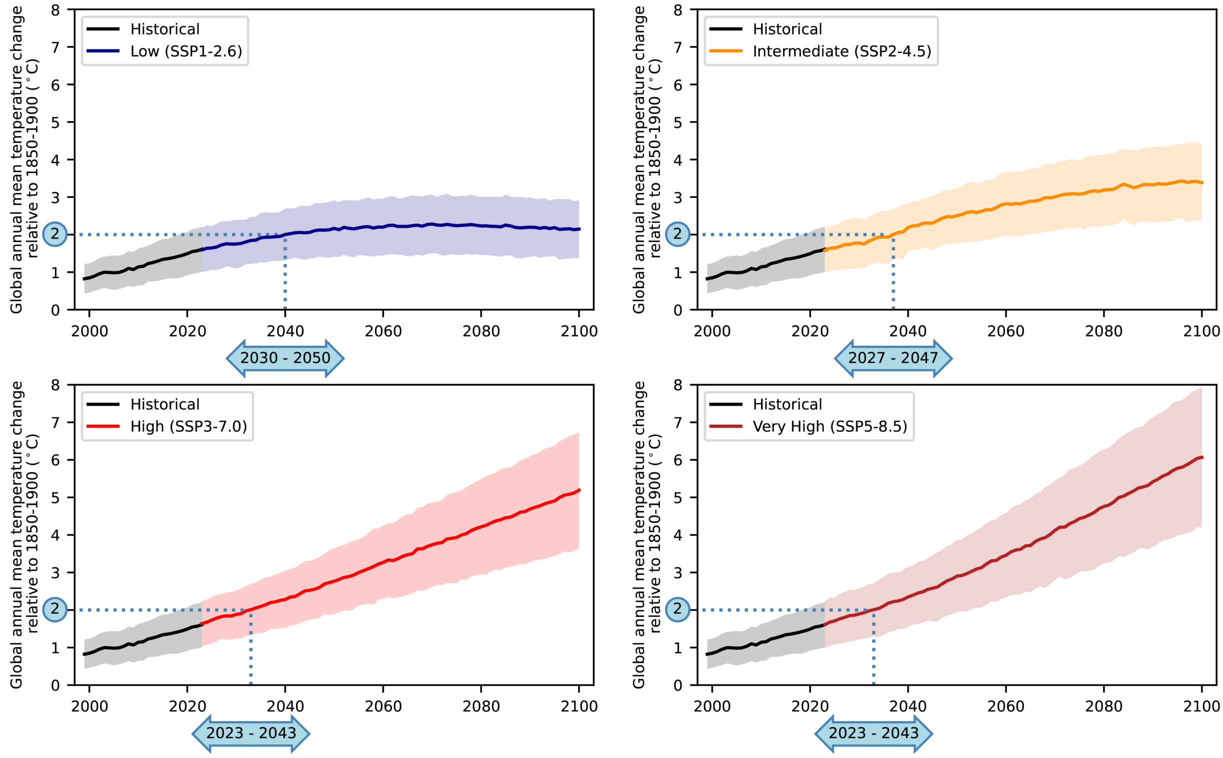

FIGURE 3 Projected global annual mean temperature changes above preindustrial levels for the socio-economic pathway (SSP)–representative concentration pathway (RCP) scenarios. Coloured lines show the model ensemble mean values; shading indicates the 10th to 90th percentile ranges. Data taken from Nicholls et al. (2020). In the case of selecting a fixed time horizon in the future, the convention would be to use model data for 10–15 years either side of that time. Note that in this case, the time horizon is fixed across all models being analysed but the amount of warming simulated will vary between them. The alternative is to allow the time horizon to vary between models being analysed but to choose a fixed global warming level. The blue highlighting shows how the time horizon would be selected for a 2°C warmer scenario using the ensemble mean as an example model, e.g. for the SSP3-7.0 climate change scenario in the bottom left panel, the ensemble mean experiences a 2°C warmer world in 2033, therefore the time horizon selected for assessing the pest risk would be 2023–2043 (10 years either side of the crossing point). Note that each individual model used in a pest risk assessment would have its own time horizon using this method.

to cases when climate change scenarios are relevant to be included, and it does not apply to all pest risk assessments. Countries with very low resources available, that currently do not conduct pest risk assessments, should first prioritize a system for conducting and implementing risk assessment. Simple resources to promote the importance of PRA are available online (e.g. FAO, 2017). Furthermore, even if resources are available in terms of data or human resources, and climate change scenarios will be included in the assessment, justification for the inclusion of the aspects listed in Table 3 is needed. For instance, the assessor will need to state what is the added value of having more scenarios, why a specific time horizon was chosen, whether models are available to account for changes in the host range, pathways or spread rate of the species and how to deal with the related uncertainties. Finally, if the data are not suitable for a quantitative analysis, a qualitative assessment of the climate change scenarios might be performed, as also indicated in Figure 2.

4.1 | Step 1. Choose a time horizon for the pest risk assessment

Choosing an appropriate time horizon (which will result in different warming thresholds according to the different climate change scenarios selected, e.g. a 1.4–4.4°C average temperature increase) when performing a pest risk assessment is not a straightforward process, as no standardized protocols currently exist. Surprisingly, quantitative justifications for the choice of a specific time horizon are lacking in the literature (Abernethy & Jackson, 2022). Typically, climate change scenarios extend their projections up to the end of the century, with the year 2100 being a common benchmark. Choosing between a short-, mid- or long-term time horizon can have both advantages and disadvantages that need to be considered. Overall, there are three options for selecting the time horizon: (i) a single time horizon/global warming level; (ii) multiple time horizons/global warming levels; and (iii) a time horizon/global warming level based on the worst-case scenario (Gilioli et al., 2014). As shown in Figure 3, the projected global annual mean temperature changes above preindustrial levels for the SSP–RCP scenarios. In the case of selecting a fixed time horizon in the future, the convention would be to use model data for 10–15 years either side of that time. The alternative is to allow the time horizon to vary between models being analysed but to choose a fixed global warming level.

Short-term time horizons (e.g. from the present day out into the next decade) allow for an assessment of the likelihood of pest introduction and spread in a relatively immediate and still foreseeable future, where potential impacts can be estimated with less uncertainty. Short-term time horizons also suffer less from scenario-based uncertainty: the differences in projected radiative forcing between the various emission scenarios are relatively small for the near future but increase dramatically in later futures (see Figure 3). This makes short-term climate projections not only more accurate, but also less uncertain; however, the magnitude of the consequences of near-time climate projections could be relatively low and their effect on some of the variables of the assessment less likely to be detected (Stocker et al., 2013; Bradshaw et al., 2024). The impact of climate change on pests can be immediate and severe, thus making a thorough evaluation of the short-term effect of climate on the organism and its surroundings necessary (e.g. Chidawanyika et al., 2012). If choosing a short-term climate projection, it should be considered that only detailed phenological studies might be able to provide the data needed to evaluate how the pest responds to these small changes in abiotic factors. In these cases, uncertainty may be high for small temperature rises, allowing pests to establish in a new area (i.e. short-term time horizon), but less for larger temperature increases (i.e. longer-future time horizon). The text of the assessment should explain the reasoning and assumptions behind the choice made.

Mid-term climate change projections extend to approximately 20 years and could make possible useful comparisons with the current climate with regard to a pest's potential to establish and cause harm. However, pest risk assessment usually focuses on a shorter time frame (NAPPO, 2011), leading to potential conflict in data choices vs. policy needs. Because a shift to longer-term time horizons may be appropriate for pest risk assessment given climate change considerations, we recommend, following NAPPO (2011), that the time frame be explicitly defined along with the pest risk assessment area in the scope of the document.

4.2 | Step 2. Determine whether the future climate will be a sufficiently important factor in the risk assessment

This step is intended to prevent effort from being spent when there is limited added benefit. The decision on whether to include climate change in the pest risk assessment should be based on the relevance of climate to the phytosanitary issue considered and whether sufficient data are available to evaluate the risk posed by climate change (NAPPO, 2011). For example, some pests may not be outdoor pests in the pest risk assessment area, but might pose a risk to protected environments (e.g. greenhouses, storage pests), and climate modelling might indicate a localized summertime outdoor risk from such pests. This information may not be required if the indoor risk is sufficient to warrant action. Other pests might be of extreme harm potential elsewhere in the world and even transient populations are of such concern to trading partners that trade may be disrupted. This might apply to hitchhiker pests such as *H. halys* and *P. japonica*, or storage pests such as *T. granarium*. If the host is expected to be important to the ecology/economy in the pest risk assessment area even under short-term climate change conditions, then it might be safe to assume the pest will survive regardless of climate change. If the decision is that climate change may affect the potential for presence or harm significantly, then taking climate change into account is appropriate. What model complexity is fit for purpose is usually a decision based on skill and experience, data availability, and the expected severity of the threat in the pest risk assessment area. The choice of modelling tool is discussed further in the related paper (Kriticos et al., 2024).

Many countries will have climate adaptation strategies that will lead to new crops being grown and different farming practices being applied, which will affect the potential consequences of the establishment and spread of invasive pests (Hulme, 2016). Considering these factors might be complex but can be useful if the goal of the risk assessment is a realistic viewpoint of a future state. These factors are considered "should haves", where resources allow (see Table 3), and include:

- pathway effects – the opening of new pathways to trade based on climate change altering usual source locations for a particular commodity (to be included in the entry assessment);
- the introduction of new hosts as potential crop plants in the pest risk assessment area (to be included in the establishment assessment);
- the effect of climate change on the distribution or range of the host(s) of the pest (to be included in the establishment assessment);
- the effects of climate change on the spread rate of the pest (to be included in the spread assessment);
- the effects of climate change on the potential harm the pest may do in the pest risk assessment area (to be included in the impact assessment); and
- the effects on the susceptibility of the host to infection or attack by the pest (to be included in the impact assessment).

It should be noted that the state of research on climate change effects on crop ecology, economy and pest consequences may not deliver the answers needed to fully evaluate the remaining elements, and complex modelling or directed research beyond literature studies may be required.

4.3 | Step 3. Determine in which section(s) of the pest risk assessment the effects of climate change should be considered and collect the appropriate data

Assuming consideration of the consequences of climate change is deemed necessary (Step 2), the next step is to discern which sections of the pest risk assessment (i.e. entry, establishment, spread, impact) require climate model information. The potential for establishment is usually the most affected by climate change and is often modelled using Geographic Information System approaches and SDMs (e.g. Jarnevich & Young, 2015; Kriticos et al., 2015; Phillips et al., 2021; Roigé & Phillips, 2021; see also Kriticos et al. (2024)). Species distribution data are readily available from various sources, including the Global Biodiversity Information Facility (https://www.gbif.org/) and iNaturalist (iNaturalist: https://www.inaturalist.org/). It is important to note that these data generally require cleaning before use (e.g. see Zizka et al., 2019, 2020) and that any model trained on such data should use an appropriate baseline climate dataset covering the same period as the presence data. Some readily available historical climate datasets are provided in Table 1. At this stage, it is crucial to have suitable data for a quantitative assessment and proceed with the modelling approaches. Should the data not be suitable for a quantitative analysis owing to limitations or uncertainties, then a qualitative analysis can still provide valuable insights. Given the sheer volume of climate model data now available for climate change scenarios in Coupled Model Intercomparison Project Phase 6 (CMIP6), it is likely to be necessary to select a subset of models for all future climate change pest risk assessments due to computational limitations. It will not be practical or feasible for a pest risk assessment to incorporate all climate models, as might have been done for risk assessments in other sectors in the past. How to select the most appropriate models for an assessment is an important consideration. It is not the case that a climate model produced by a modelling centre located in the region of interest is going to be the most appropriate model to use and it is also important to understand that using a single model or an "ensemble mean" only can under- or overestimate the risks. It is essential for a pest risk assessment to use a variety of climate models and scenarios (e.g. Bucklin et al., 2022; Mika & Newman, 2010). We now offer some guidance on how to choose which climate models to use in a pest risk assessment. Practical considerations may limit the number of models and scenarios chosen, such as the perceived importance of the pest, the importance of climate considerations to the overall risk from the pest, time constraints and available resources (Table 3). Even though they were designed with the best understanding of meteorology and physics and are constantly refined, assumptions and levels of simplification, model grid sizes and how they predict physical phenomena may vary (Bradshaw et al., 2024). All models are slightly different and have different biases concerning the observed climate. For this reason, if a pest risk assessment uses absolute temperature or rainfall thresholds to identify the risks, then selecting a subset of the models that have the least bias is an option or, alternatively, bias correction of model data should be performed because using the raw data will give the wrong level of pest risk. Model sub-selection should additionally identify the skilful models that cover the range of climate space covered by the climate change projections, i.e. the subset should as a minimum consist of a hot model, a cold model, a wet model and a dry model for the region of interest. If the pest being considered in a pest risk assessment has an association with a particular circulation pattern (e.g. El Niño) it might also be desirable to focus on models that can simulate those processes well. Supplementary Data S2 provides details of the most appropriate hot, cold, wet and dry models from the CMIP6 archive to use in a pest risk assessment for each region of interest, for each season of importance. These models have been determined using the tool GCMeval (https://gcmeval.met.no/), which is described in Parding et al. (2020).

4.4 | Step 3a. Climate change and entry

As people and goods move faster around the world, crossing large distances within a matter of hours, days or weeks, various organisms, including pests, can unintentionally be introduced and spread into new regions. Therefore, when considering the effects of climate change in the entry assessment, the following should be taken into account:

- *Pathway effects: the opening of new pathways to trade based on climate change altering usual source locations for a particular commodity*

As the climate changes, trade along new routes could supplant current routes and also carry more volumes than are currently possible (e.g. Bayırhan & Gazioğlu, 2021). As already pointed out, the climate is shifting the ranges of crops and desirable plant products, and if a distant horizon is chosen for the risk assessment, it could very well be that the source country list for hosts of the pest under consideration has to be examined in light of these potential range changes. For example, modelling has shown that the tomato yellow leaf curl virus (TYLCV) is predicted to spread to new areas as these areas become suitable for open-field tomato production (Ramos et al., 2019). A risk assessment for TYLCV should recommend monitoring whether tomato plants are imported from new countries in the time horizon considered. In addition to this is the increasing diversification of crops grown in non-traditional areas. Up to the 1980s, blueberries were mainly exported from North America; now there are countries around the world that are growing and exporting them (Lobos & Hancock, 2015). While not directly linked to climate change, these "crop migrations" are likely to be enhanced by climate change (Kelly & Goulden, 2008; Rodrigo-Comino et al., 2021; Sloat et al., 2020).

4.5 | Step 3b. Climate change and establishment

The assessor should consider if the projected climate change within the selected horizon could result in the establishment of the pest in the risk assessment area. Some risk assessments may stop at this point if the evidence suggests that the establishment of a certain pest is unlikely. Nevertheless, things may change considerably when considering climate change. Many pests have range limits set by extreme conditions and rising temperatures can increase their range and distribution, as well as those of their host plants, vectors or natural enemies.

- *The introduction of new hosts as potential crop plants in the pest risk assessment area*

Related to the previous issue, climate change may, within the time horizon chosen, alter climates to the point that novel hosts could be economically grown in the risk assessment area, potentially exacerbating any negative economic effects from the pest under evaluation (this should be considered in the assessment of the impact also). The prediction of which hosts may be grown is difficult, but there are nearly always examples of potential host plants that are grown in new areas. For example, wine grape varieties available to growers in Quebec (Canada) are expanding owing to climate change (Jones, 2012; Jones, 2018), as are the pests found in vineyards (Vincent & Lasnier, 2020). Other changes are potentially longer term and harder to predict, such as the development of crops through *de novo* cultivation in response to climate change (Fernie & Yan, 2019).

- *Effect of climate change on the distribution or range of the host(s) of the pest*

McKenney et al. (2014) determined that the average northward shift of tree species in North America over 50 years has been 57 km. Shifting the range of the host plant might be a trigger for the establishment of pests in areas where they could not establish before. In another work, a coarse reading from the maps of projected hardiness zone shifts in Europe suggests that they are moving eastward through Central Europe at a pace of 0.5–1 km per year (Gloning et al., 2013). The evidence at this stage does not need to be overwhelming, it only needs to suggest that survival in the pest risk assessment area is considered likely.

Medium to long climate horizons are associated with highly significant range changes for many tree species, in areas as small as the Canadian province of Prince Edward Island (Bourque & Hassan, 2010), and for areas as large as Europe (Buras & Menzel, 2019), or parts of Africa (Heubes et al., 2011; Mtsetfwa et al., 2023). There are many gaps still in the knowledge of the consequences of climate change to the potential ranges of many perennial crops (e.g. Leisner, 2020) and the actual migration of these crops may be influenced by factors more numerous and complex than climate (e.g. Sloat et al., 2020).

Looking at the reverse case, the likelihood of invasion of pests such as *Diabrotica speciosa* was predicted to decrease with climate change for most regions, as precipitation seasonality increases (Marchioro & Krechemer, 2021), even though some areas were still predicted to face an increase in the likelihood of invasion.

4.6 | Step 3c. Climate change and spread

- *Effects of climate change on the spread rate of the pest*

If establishment is possible, it is important to include considerations about the spread in the risk assessment. Some studies indicate that climate change is expected to alter the spread patterns of pests (e.g. Jo et al., 2017). For example, overall climate phenomena will create the conditions for some pests to spread more rapidly than they would have otherwise, by passive spread via extreme climate events through more intense wind and water dispersal. Insects in particular can require threshold temperatures before flight occurs. In a warmer climate individuals may fly more frequently and over longer distances, hence increasing their spread (Robinet & Roques, 2010). Climate change might also affect a pest's ability to overcome dispersal barriers or reduce the biotic resistance of an environment, thus allowing it to reach new areas (Diez et al., 2012). Furthermore, similarly to establishment, shifting the range of some host plants might facilitate movement towards areas where the pest could not spread before.

4.7 | Step 3d. Climate change and impact

- *Effects of climate change on the potential harm the pest may do in the risk assessment area*

In the framework of pest risk assessment, models for impacts often relate the abundance of the pest with the host plant response in terms of yield or quality losses. Pest impacts will be very diverse, complex, dynamic and both species and situation specific, as will the impacts of climate change on pest behaviour (NAPPO, 2011): it will depend on the specific context and the ecosystem at risk.

Extended growing seasons for crops can create new problems with new pests causing major damage. This might be more obvious in cooler climates such as Finland (Hakala et al., 2011), and high-latitude areas in general (Aljaryian et al., 2016; Kistner-Thomas, 2019).

- *Effects on the susceptibility of the host to infection or attack by the pest*

If possible, estimations of future pest risk should be linked to crop models that can inform potential yield losses (IPPC Secretariat, 2021). Climate change has altered and will continue to alter moisture regimes globally (e.g. Lesk et al., 2021) and can alter host–pest relationships (e.g. Pandey & Basandrai, 2021), relationships that have co-evolved and that can be greatly disturbed by rapid changes in the environment (Ennos, 2014). Pests already present but held at low levels owing to marginal climate suitability ("sleeper aliens", e.g. Hulme, 2016) can also be "released" by climate change and alter the resilience of ecosystems, thus aiding and increasing harm that could be caused by new arrivals (e.g. Mansfield et al., 2021). It may be also useful to consider if the presumed hosts are under greater stress because of climate change and therefore more susceptible to attack by the pest. For example, the area of European forests damaged by bark beetle attack has increased by approximately 10% per decade since the 1970s, apparently owing to climate change (Hlásny et al., 2019). Some studies predict that certain historically important crops will diminish in importance in the future (e.g. Pironon et al., 2019), suggesting that their associated pests will diminish in risk potential also. If possible, the risk assessment should evaluate the potential for climate change to alter the susceptibility of the host plant or its ecosystem to attack by the pest, even as this element is also associated with much uncertainty owing to the complex nature of such interactions (e.g. Harvey et al., 2020; Jactel et al., 2019).

4.8 | Step 4. Output of climate change analysis

In the case where the data (or the resources) available are not appropriate to a quantitative analysis, a qualitative analysis may be included in the risk assessment, underlining the main expected effect of climate change in the relevant section(s) of the risk assessment. When data allow, following the ODMAP (Overview, Data, Model, Assessment and Prediction) protocol of Zurell et al. (2020), at least the basic information regarding model choice, design, scale, software and data should be presented in the risk assessment. For the risk managers, understanding the limitations of the output display and the uncertainties and assumptions is going to be critical. While map outputs are attractive and instantly informative, they are not without serious considerations as to reliability, especially when modelled with presence-only data (see Merow et al., 2013).

5 | CONCLUSIONS

National plant protection organizations must be aware of the phytosanitary risks posed by different pests to prevent their introduction and spread, and this understanding will largely come from pest risk assessment. In this context, it is crucial to ensure that the method and process of the pest risk assessment account for effects of climate change to allow assessors to analyse the risks to the best extent possible and propose mitigation measures (FAO, 2021). There is an ongoing debate in the plant health community over whether to take climate change into account when performing a pest risk assessment and, if so, how to best incorporate it (Szyniszewska et al., 2024). Some authors or organizations are in favour of a case-by-case approach, while others consider the pest risk assessment procedure robust enough without climate change scenarios, as: (i) the time horizon to be considered might be an issue when including climate change in the pest risk assessment process; (ii) climate modelling can be complex and time consuming and thus is not always feasible; and (iii) pest risk assessments are sometimes updated, for example, to address new policy questions or importation pathways and changes in distribution/effects of past climate change can be accounted for in these updates. Nevertheless, because of the constantly changing climate, integrating climate change considerations in pests in risk assessments remains important. In this article we have presented how climate and climate change are currently incorporated into pest risk assessments and include some recommendations that can be followed when dealing with this issue. A flowchart (Figure 2) is provided with the intention of helping the assessor's thinking and easing the steps leading to integration of climate change considerations into the pest risk assessment process. We acknowledge that because of time constraints and limited resources (e.g. data, human, monetary), the analysis of climate change considerations might be more or less appropriate, and we propose the MoSCoW approach to assist and simplify decision-making and prioritize what to include (see Table 3).

However, there are a few "must-haves" that should be applied to every risk assessment unless the need for climate change analysis has been *a priori* ruled out for biological or risk-related reasons.

ACKNOWLEDGEMENTS

The authors would like to thank the Secretariat of the European and the Mediterranean Plant Protection Organization (EPPO) for providing information about templates that take climate change into account in pest risk assessment and for granting access to a folder with all the documents in the EPPO Platform on PRAs. Maria Chiara Rosace conducted this work during her PhD studies, supported by the Doctoral School on the Agro-Food System (Agrisystem) of Università Cattolica del Sacro Cuore (Italy). The author Ciro Gardi is employed by the European Food Safety Authority (EFSA). However, the present article is published under the sole responsibility of the authors and may not be considered as an EFSA scientific output. The positions and opinions presented in this article are those of the authors alone and do not necessarily represent the views/any official position or scientific works of EFSA. To learn about the views or scientific outputs of EFSA, please consult its website: www.efsa.europa.eu.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of the html version of this article.

How to cite this article: Rosace, M.C., Björklund, N., Boberg, J., Bradshaw, C.D., Camac, J., Damus, M. et al. (2024) Including climate change in pest risk assessment: Current practices and perspectives for future implementation. *EPPO Bulletin*, 54(Suppl. 1), 52–72. Available from: https://doi.org/10.1111/epp.12989