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ORIGINAL ARTICLE

Beyond the present: How climate change is relevant to pest risk analysis

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Abstract
Climate change is widely recognized as a critical global challenge with far-reaching consequences. It affects pest species by altering their population dynamics, actual and potential distribution areas, as well as interactions with their hosts and natural enemies. Climate change thus has potentially important implications for multiple areas of the pest risk analysis (PRA) process. The importance of including climate change in PRA may vary depending on the climatic context of the PRA area in relation to the speed of climate change. If climatic changes within the time horizon of interest are minimal, their potential impact on pest risk is reduced accordingly. For PRAs in a changing climate, we need to be concerned with how future climates could alter our assessment of the risks currently posed by each pest species. While climate can influence the distribution and abundance of pests and hosts alike, its significance will vary depending on the situation. The inclusion of climate change within a PRA also presents challenges. The dynamic nature of climate change, with its complex interactions and uncertainties, can make it difficult to predict and assess the future risks posed by pests accurately. Uncertainties related to future predictions may be much greater than the potential effects associated with climate change and species' responses to it. This paper outlines examples of the effects of climate change on hosts and different groups of pests, including invertebrates, pathogens, weeds and vector species. The aim is to review the opportunities and challenges of incorporating climate change into PRA, offering insights for a variety of stakeholders including policymakers on this topic.

Au-delà du présent: Dans quelle mesure le changement climatique est-il pertinent pour l'analyse du risque phytosanitaire?
Le changement climatique est largement reconnu comme un défi critique d'envergure mondiale engendrant des conséquences importantes. Il affecte les espèces d'organismes nuisibles en modifiant leur dynamique de population, leur répartition géographique actuelle et potentielle, ainsi que les interactions avec leurs plantes-hôtes et leurs ennemis naturels. Le changement climatique a donc des implications potentiellement importantes dans de multiples domaines du processus d'analyse du risque phytosanitaire (ARP). L'importance d'inclure le changement climatique dans l'ARP peut varier en fonction du contexte climatique de la zone analysée et de la vitesse à laquelle le climat y évolue. Si les changements climatiques dans l'horizon temporel d'intérêt sont minimes,

leur potentiel impact sur le risque phytosanitaire est réduit en conséquence. Pour les ARP effectuées sur une zone à climat changeant, nous devons nous intéresser à la façon dont les futurs climats pourraient modifier notre analyse des risques posés actuellement par chaque espèce d'organisme nuisible. Bien que le climat puisse influencer à la fois la répartition géographique et la quantité d'organismes nuisibles et de plantes-hôtes, son importance variera en fonction de la situation. L'inclusion du changement climatique dans l'ARP présente également des défis. La nature dynamique du changement climatique, avec ses interactions complexes et ses incertitudes, peut rendre difficile la prévision et l'analyse précise du risque futur causé par les organismes nuisibles. Les incertitudes liées aux prévisions futures peuvent être beaucoup plus grandes que les effets potentiels associés au changement climatique et aux réponses des espèces. Cet article présente des exemples d'effets du changement climatique sur les plantes-hôtes et sur différents groupes d'organismes nuisibles, y compris les invertébrés, les agents pathogènes, les mauvaises herbes et les espèces vecteurs. L'objectif est d'examiner les opportunités et les défis de l'intégration du changement climatique dans l'analyse du risque phytosanitaire, en fournissant des informations à diverses parties prenantes, y compris les décisionnaires.

За рамками настоящего: насколько изменение климата важно для анализа фитосанитарного риска

Изменение климата считается серьёзной глобальной проблемой с масштабными долгосрочными последствиями. Оно оказывает влияние на виды вредных организмов, изменяя динамику их популяции, нынешний и потенциальный ареалы, а также воздействует на их хозяев и естественных врагов. Таким образом, изменение климата потенциально может иметь важные последствия для многих этапов процесса анализа фитосанитарного риска (АФР). Важность включения фактора изменения климата в АФР зависит от климатических условий в анализируемом регионе и от скорости изменения климата. Если в заданный период времени климатические изменения минимальны, то их потенциальное воздействие на фитосанитарные риски соответственно снижается. При подготовке АФР для условий изменяющегося климата, необходимо непременно учитывать то, как будущее изменение климата может изменить оценку рисков, которые в настоящее время представляют каждый из рассматриваемых видов вредных организмов. Хоть климат и оказывает влияние на распространение и численность популяций как вредных организмов, так и их хозяев, его значимость в данном вопросе варьирует в зависимости от ситуации. Учёт изменения климата в АФР также имеет определенные сложности. Динамичный характер климатических изменений со сложными взаимодействиями и неопределённостями может затруднить точное прогнозирование и оценку будущих рисков, создаваемых вредными организмами. Неопределённости, связанные с будущими прогнозами, могут быть гораздо больше, чем потенциальные последствия, связанные с изменением климата и реакцией видов на него. Данная статья рассматривает примеры воздействия изменения климата на хозяев и различные группы вредных организмов, включая беспозвоночных животных, патогены, сорные растения и виды-векторы. Цель работы – проанализировать возможности и проблемы, связанные с включением изменения климата в АФР, а также поделиться экспертным мнением с различными заинтересованными сторонами, в том числе с профессионалами, ответственными за разработку политики в этой области.

1 | INTRODUCTION

The Earth's climate is not static. Owing to variations in our orbit around the sun, the Earth's climate slowly changes over tens of thousands of years (Zhang et al., 2021). Over much shorter periods of time (from months to a few years), natural events, such as volcanic eruptions and solar activity, can also change our climate (Solomon et al., 2019; Swingedouw et al., 2017). These natural phenomena alter the amount of the Sun's energy reaching the Earth's surface and the amount of energy being released back into space, leading to fluctuations in global temperatures.

Human activities such as burning fossil fuels release greenhouse gases, which trap the Sun's energy in our atmosphere, causing progressive warming of our planet. The climate of the Earth is now approximately 1°C warmer than the 1850–1900 global annual average temperature owing to greenhouse gas emissions, and regionally, the increases can be much larger (IPCC, 2021). Twenty-first-century global warming projections far exceed the natural climate variability of the past 1000 years (Crowley, 2000). In addition to elevating average temperatures, climate change is altering regional weather patterns, meaning that some areas are experiencing drier conditions while others are becoming wetter. Moreover, there have been notable increases in the frequency and magnitude of extreme weather events such as floods, droughts and heatwaves (IPCC, 2021).

Climate change is one of several factors presenting an increasingly important threat to 'plant health' (Gullino et al., 2022; Hosseinzadeh-Bandbafha et al., 2023; IPPC Secretariat, 2021; Pautasso et al., 2010). Plant health is a term used to summarize the activities of national plant protection organizations and their legislative and administrative procedures designed to prevent plant pests from entering and spreading within their territories (MacLeod et al., 2010). Pest risk analysis (PRA) is a process conducted by national plant protection organizations and other organizations such as the European Plant Protection Organization and the European Food Safety Authority, which is essential for stakeholders working on assessing and proposing management measures for the risks posed by pests to agriculture, horticulture, forestry, and the environment. The implications of climate change may potentially have important impacts on all elements of PRA, from assessing the likelihood of pest entry and establishment to the management options selected to mitigate the pest risk.

Given the growing evidence of the ongoing impacts of climate change on ecosystems, agriculture, horticulture and forestry, the inclusion of future climate change in PRA may be necessary, but also poses challenges. The objective of this paper is to initiate a discourse on the relevance of incorporating climate change into the PRA process.

2 | PEST ESTABLISHMENT WITHIN PRA

A crucial element of PRA is the assessment of the likelihood of pest establishment in the area under assessment. Considering that the development and survival of many plant pests are strongly influenced by temperature and humidity, a critical factor to consider when assessing the suitability of the PRA area for pest establishment, and more widely mapping the pests' potential distribution, is to determine if the climate in the PRA area can allow the pest to complete its life cycle, reproduce, initiate a founder population and perpetuate in the area for the foreseeable future. The availability of host plants in the PRA area is equally important. Other factors to consider are described in the international standard defining how to conduct pest risk analysis for quarantine pests, ISPM 11 (FAO, 2019a).

Since the era of Cook (1924, 1929, 1931), who pioneered the comparison of climatic conditions in infested and pest-free areas to identify the relationship between climate data and pest distribution, abundance and damage, the methods used to identify endangered areas have increased in sophistication, but the concept has remained the same. Cook identified a pattern of pest infestation that can be related back to climate and that divides an area of potential pest presence into three zones: (1) where the pest is continuously present and causes damage, or the 'zone of normal abundance'; (2) where the pest is occasionally present and causes damage sometimes, the 'zone of occasional abundance'; and (3) where the pest cannot maintain a permanent population, but where infestations may occur under special circumstances, for example during an outbreak or epidemic, the 'zone of possible abundance'. In the context of climate change, the extent of all three zones is not static: zone 1 is likely to be shifting further polewards, whereas changes to zones 2 and 3 may be more variable, change frequency and be linked to climate fluctuations, extremes and other climate-induced events such as severe storms or prolonged droughts. Since Cook, climatic mapping for agricultural pests has been reviewed on several occasions, including by Messenger (1959), Meats (1989), Sutherst et al. (1995) and Venette (2017), and for pathogens by Coakley et al. (1999) and Lantschner et al. (2019).

Together with information on host distribution, climatic mapping is the principal method for identifying regions that could provide suitable conditions for the establishment of a plant pest, taking key abiotic factors into account (Baker, 2002). Eyre et al. (2012) described a decision-support scheme to assist pest risk analysts when assessing climatic suitability and the likelihood of pest establishment within a PRA area. Baker et al. (2012) went further to develop a decision-support scheme for mapping the areas where the presence of a particular pest could cause unacceptable harm to the endangered area, and provide examples to illustrate the scheme. However, neither scheme considered climate change.

3 | CLIMATE CHANGE WITHIN PRA

Luck et al. (2014) reviewed the potential direct and indirect effects that climate change could have on plant biosecurity, through a range of changes, including phenology changes and inter-species interactions. The authors highlighted that conventional PRAs tend to rely solely on historical data, including historical pest range information, interceptions and occurrence data, and past information on pest impacts. The authors note that analyses guided solely by past evidence and which do not consider future scenarios may be unreliable guides to what may happen in the future given ongoing climate change.

Pest risk analysts frequently use historic 30 year climate averages to inform judgements about pest establishment. However, conclusions regarding establishment suitability based on climate data from 1970 to 2000 could be quite different from conclusions reached using more recent climate data (e.g. 1990–2020) or conclusions reached using projections of potential future climates. Early examples of PRAs which take climate change into account include an assessment of the root-knot nematode *Meloidogyne chitwoodi* for Finland (Tiilikkala et al., 1995) and the Colorado beetle *Leptinotarsa decemlineata* for the United Kingdom (Baker et al., 1998).

Nonetheless, given the uncertainty around future greenhouse gas emissions and subsequent climatic responses (Bradshaw et al., 2024), phytosanitary measures that are introduced to prevent the introduction of a pest based on, for example the likelihood of its establishment under a future climate scenario, could be open to great scrutiny and challenged by trading partners. Article 5 of the World Trade Organization (WTO) Sanitary and Phytosanitary (SPS) Agreement (WTO, 1995) notes that relevant ecological and environmental conditions shall be taken into account when assessing risk. Whether uncertain future climate scenarios should be judged as relevant and can justify present day phytosanitary measures remains to be officially decided.

The regional plant protection organization for North America, NAPPO, developed a discussion paper (NAPPO, 2011) and a subsequent position paper (NAPPO, 2012) regarding climate change and PRA. In providing interpretations of rulings from the Appellate body of the WTO regarding quarantine measures that had been imposed but deemed to violate the SPS Agreement based solely on inadequate risk analyses that failed to show that the measures were necessary and not overly restrictive, NAPPO (2011) noted that climate change can be taken into consideration when developing a risk assessment, but with the caveat that there must be an "actual potential for adverse effects", and the risk assessment must evaluate what is likely or probable rather than possible. NAPPO (2011) also noted that climate change projections within a PRA must be sufficiently robust to meet the requirement that the PRA is considered to provide "sufficient evidence" that a chosen measure is not arbitrary, unjustified, or a disguised barrier to trade, although the definition of "sufficient" is relative.

A 2011 report from the World Bank and Standards and Trade Development Facility stated that "there is no agreement in the scientific community, or among trade policy practitioners, on how to deal with climate change in risk assessment. The central question is whether risk assessments should reflect the current situation or include future climate change scenarios. The problem is that while climate change is occurring and accelerating and will impact the SPS situation, the nature and size of the impact is highly uncertain and will vary in different scenarios" (World Bank/STDF, 2011). The situation currently remains unresolved.

Recognizing the importance of climate change to plant health, the International Plant Protection Convention (IPPC) initiated a work programme to assess the impacts of climate change on plant health within its 10 year strategic framework (FAO, 2019b). The framework includes plans to develop recommendations with regard to climate change and plant health and, if necessary, associated guidelines for pest risk analysis and surveillance (Eyre et al., 2024).

4 | CLIMATE CHANGE IMPACT ON PEST DISTRIBUTION

Climate change is exacerbating the recognized problem of plant pest invasions around the world, and new pest introductions are increasing in frequency and cost presenting an ongoing threat to plant health (Chapman et al., 2017; Seebens et al., 2017). The changing climate enables some plant pests to expand, or shift, the range in which they can become established (Bebber, 2015; Yan et al., 2017). Rising temperatures can accelerate pest development in a season, enable completion of more generations within a single year and increase pest density by limiting exposure to cold stress, or have adverse impact on populations owing to increased exposure to prolonged heat (Schneider et al., 2022; Skendžić et al., 2021). All in all, the effects of climate change on pest populations, combined with the rapid and increasingly frequent movement of goods and people globally, can facilitate the spread of pests across wider geographical areas (Karthik et al., 2021; Singh et al., 2023).

4.1 | Invertebrate pests

Insect, mite, mollusc and nematode plant pests are poikilothermic, with temperature tolerances for their development characterized by lower and upper optima. Prolonged exposure on either side of the optima impairs their development. A warming climate can directly influence the growth of both individuals and populations, by accelerating the rate of development and reproduction and changing timing of seasonal events while reducing the rate of cold-induced mortality. Warmer temperatures may also allow completion of a full generation, or allow more generations, in a season. Conversely, warming beyond the upper optima can increase exposure to heat stress and associated heat stress-induced mortality (Kikuchi et al., 2016; Musolin et al., 2010a; Robinet & Roques, 2010; Stange & Ayres, 2010). Since temperature strongly affects invertebrate population dynamics, global climate change will probably result in shifts in the geographic ranges for most of them, with some regions currently too cool for establishment becoming suitable (Battisti & Larsson, 2015; Bradshaw et al., 2019; Lawton et al., 2022). Such responses have already been observed (Table 1).

Owing to warmer winters, some invertebrate pests have moved into higher latitudes and altitudes, become more severe and affected larger areas, e.g. forest pests in northern North America and northern Eurasia (Müller et al., 2022). A study by Yan et al. (2017) investigated the shift in global distribution of invasive crop pest species using species distribution models and while they estimated that the overall probability of crop pest presence will probably increase, species richness was predicted to increase more often in regions with lower temperature or lower precipitation. Selected instances of shifts in plant pest distribution, as highlighted in Table 1, are described in a greater detail as case studies. Box 1 represents a case study on *Dendroctonus ponderosae* (the mountain pine beetle), describing how climate change has facilitated the expansion of its distribution, the availability of new hosts and a greater impact. Another case study, presented in Box 2, describes the response to climate change by *Nezara viridula* (southern green stink bug). A third case study (Box 3) notes that *Phoracantha semipunctata* outbreaks globally are linked to drought stress in host eucalypts, which is projected to become an increasing concern.

4.2 | Pathogens

Elevated atmospheric carbon dioxide, increased temperatures, changes in water availability, and more frequent extreme weather events will have direct and indirect effects not only on invertebrate pests but also on plant pathogens: bacteria (including phytoplasmas), fungi, nematodes and oomycetes, as well as viroids, viruses and their vectors (Jones, 2016; Velásquez et al., 2018). Altered environmental conditions may influence the development, survival, reproduction and virulence of the pathogens directly as well as indirectly via effects on other organisms with which the pathogens interact, e.g. host susceptibility changes as a response to climate-induced host stress, altered resource quality, phenological mismatches and by affecting vectors and natural enemies (e.g. Jones, 2016; Simler-Williamson et al., 2019; Velásquez et al., 2018). Consequently, these alterations in climate patterns can potentially lead to modifications in the abundance, impact and distribution range of pathogens.

For instance, the fungus *Sclerotinia sclerotiorum* becomes more virulent as air humidity rises, with disease development in lettuce plants reaching its peak when air relative humidity exceeds 80% (Clarkson et al., 2014). Sturrock et al. (2011) predicted increasing or decreasing impacts for different forest pathogens depending on whether the climate would be warmer and drier or warmer and wetter. In warmer and drier conditions, increased impact is expected, primarily owing to increased host susceptibility. Although directly affected by temperature and moisture for infection, host stress may be a prerequisite for the pathogens to further invade host tissue (Sturrock et al., 2011). *Diplodia pinea* causing tip blight of pines and other conifers may remain latent after infecting the trees, and increased symptoms and disease outbreaks are often induced by host stress, for example, owing to drought (Blumenstein et al., 2022; Desprez-Loustau et al., 2006). Evans et al. (2008) investigated the effects of climate change on *Leptosphaeria maculans* (a pathogen of brassica crops) and illustrated that owing to climate change the epidemics of the pathogen will become more severe. A recent review summarizing the crop disease risk simulation studies suggests that climate change will in most cases alter the disease risk either by increasing (most common) or decreasing the risk (Juroszek et al., 2022).

Shifts in distribution have been projected for a range of different plant pathogens applying climate change scenarios in species distribution models (e.g. Burgess et al., 2017; Ikegami & Jenkins, 2018; Ramirez-Cabral et al., 2017; Watt et al., 2011). Changes in distribution ranges are frequently observed, but there are few studies directly connecting observed range shifts to a changing climate (Bebber, 2015). Nevertheless, Dudney et al. (2021) studied white pine blister rust caused by *Cronartium ribicola* in an elevation gradient and found that warmer conditions owing to climate change resulted in an expansion of the fungus into higher elevations and a contraction at lower elevations. Overall, the prevalence declined over time, probably owing to host–pathogen interaction (lack of the alternate host at higher elevations) and varying water availability (water deficiency increased host mortality and inhibited new infections) (Dudney et al., 2021).

A latitudinal shift of pests and pathogens poleward in the northern hemisphere since 1960 was demonstrated by Bebber et al. (2013). The pattern, however, depended on the taxonomic groups, where fungi as a group had a

TABLE 1 Examples of changes in plant pest distribution facilitated by climate change.

Pest name (scientific/common name)	Effect of climate change on pest distribution	Reference
Individual species		
Coraebus florentinus (Coleoptera: Buprestidae), oak burncow	Expanded its northern range margin northward within the last 30 years	Buse et al. (2013)
Dendroctonus frontalis (Coleoptera: Curculionidae), southern pine beetle	The northward expansion has been linked to improved conditions for overwintering beetles	Williams and Liebhold (2002)
Dendroctonus ponderosae (Coleoptera: Curculionidae), mountain pine beetle	Increased temperatures have made it possible for the beetle to survive winters in geographical areas previously unsuitable, e.g. in Canada	Carroll et al. (2006)
Drosophila nepalensis (and *D. ananassae*) (Diptera: Drosophilidae), fruit flies	A significant change in average temperatures of the Western Himalayas has affected the altitudinal distribution and boundaries of drosophilids	Parkash et al. (2013)
Epirrita autumnata (Lepidoptera: Geometridae), autumnal moth	Warmer climate led to an expansion of *E. autumnata* to the coldest, most continental areas	Jepsen et al. (2008)
Leptinotarsa decemlineata (Coleoptera, Chrysomelidae), Colorado potato beetle	In Russia, the main range expansion was observed (through cartographic modelling of two sets of 20 years) in the eastward direction, and the greatest changes took place in the zones with the possible development of one or two generations per year	Popova (2014)
Nezara viridula (Heteroptera: Pentatomidae), southern green stink bug	The northern limit of distribution shifted northwards by approximately 85 km during 45 years (i.e. at a mean rate of 19 km per decade). A general linear model showed that the mean temperature and number of cold days are the most important factors controlling the northern limit of the *N. viridula* distribution	Tougou et al. (2009)
Operophtera brumata (Lepidoptera: Geometridae), winter moth	Climate warming led to a pronounced north-eastern expansion of *O. brumata* into areas previously dominated by *Epirrita autumnata* outbreaks (as observed using a 15–20 year window)	Jepsen et al. (2008)
Stenotus rubrovittatus (Hemiptera: Heteroptera: Miridae), sorghum plant bug	Distribution expanded with a relative increase in voltinism and synchrony of egg hatching dates in the range expansion area	Osawa et al. (2018)
Thaumetopoea pityocampa (Lepidoptera: Notodontidae), pine processionary moth	Warmer winters have led to a gradual but substantial expansion of its range both latitudinally and altitudinally	Battisti et al. (2006)
Groups of species		
329 species (16 large taxa) of invertebrates and vertebrates distributed in Great Britain	The northern range boundaries of 83.6% of species have shifted to the north during the 25 year period (from 1960 to 2000 for different groups); the boundaries of 0.6% of species have remained the same, and those of 15.8% of species have shifted to the south. The average shift of the northern range boundary was 31–60 km (the mean values for different subgroups)	Hickling et al. (2006)
48 butterfly species in Finland (Lepidoptera)	These species shifted their range margins northwards on average by 59.9 km between the study periods (1992–1996 and 2000–2004), with maximum shifts of over 300 km for three species	Pöyry et al. (2009)
Dragonflies (Odonata) in Great Britain	British Odonata as a group were shown to be tracking shifts in isotherms between 1960 and 2005	Hassall and Thompson (2010)
Insect and marine species	Distribution records indicated poleward range expansions of 18–140 km per decade	Ogawa-Onishi and Berry (2013)
1573 southerly distributed species from 21 animal groups in Great Britain	Most taxa shifted their northern range margins poleward (the mean northward range margin change was 18 and 23 km per decade in two time periods when the British climate warmed by 0.28 and 0.21°C per decade, respectively)	Mason et al. (2015)
Phoracantha spp., eucalyptus longhorned borer beetles	Low water potential and drought stress in eucalypts increase the severity of *Phoracantha semipunctata* outbreaks. The range and outbreak severity of *P. semipunctata* are modelled to increase under climate change conditions, in part owing to the higher frequency of drought conditions	Hanks et al. (1999), Zhao et al. (2023)

positive shift towards the poles, while no shift was found for bacteria and oomycetes, and a negative shift was found for viruses and nematodes. Chaloner et al. (2021) coupled global gridded crop models with fungal and oomycete plant pathogen data, illustrating that for most crops both yields and the temperature dependent infection risk are likely to increase in high latitudes, while in the tropics crop productivity will remain stable or even decrease and the infection risk is likely to decline.

4.3 | Vectors

Climate change can affect vectors, generally insects, in particular sap-feeding Hemiptera (aphids, leafhopper and whiteflies), by expanding geographical ranges, shifting phenology, increasing the number of generations and density, altering feeding and reproductive activity, desynchronizing relationships with plants they feed on, or increasing overwintering survival (Canto et al., 2009; Skendžić et al., 2021). An increase in insect vectors' geographic distributions, populations and performance can in turn favour the occurrence and spread of insect-transmitted plant diseases and have a major impact on their epidemiology (Skendžić et al., 2021).

Vectors of plant diseases are suspected to be particularly responsive to temperatures (Juroszek & von Tiedemann, 2013). Kriticos et al. (2020) has reported the first case where observed historical climate changes have been attributed to the increase in abundance of an insect vector (*B. tabaci*), contributing to a crop disease pandemic (cassava diseases caused by viruses vectored by *B. tabaci*) in Uganda (Box 4). Reynaud et al. (2009) showed that vector abundance (*Cicadulina mbila* and *Peregrinus maidis*) and the incidence of viral disease (maize streak virus) were closely related to temperature, increasing rapidly above 24°C, but decreasing above 30°C, a temperature that is detrimental to both the vector and the virus transmission success. This suggests that global warming might promote many insect vectors and the pathogens they transmit, at least within a certain temperature range (Gullino et al., 2022). Aphids are expected to have higher reproductive rates in warmer spring/summer and a higher survival rate in milder winters, which could influence the amount of viral inoculum and the incidence of viral disease transmission and spread (Skendžić et al., 2021), as highlighted in the epidemic of aphid-transmitted viruses in melon crops in Spain (Alonso-Prados et al., 2003). In addition, aphids can travel long distances when they encounter favourable atmospheric conditions (thermal ascending and horizontal currents) that propel them; climate change could favour such conditions (Skendžić et al., 2021). One of the most important and detrimental grapevine phytoplasma diseases in Europe is flavescence dorée (Jeger et al., 2016). Its main vector is the Nearctic leafhopper *Scaphoideus titanus*, which, in Europe, completes its life cycle on grapevine (Chuche & Thiéry, 2014). Short summers are considered a barrier to the northern spread of *S. titanus* owing to the insect's inability to complete its full life cycle within a vegetation season (Rigamonti et al., 2018). However, with climate change and the consequent increase in average temperatures, *S. titanus* is expected to expand its range in northern vineyards (e.g. in Germany) and increase the risk of introduction of flavescence dorée into these regions (Boudon-Padieu, 2007; Mirutenko et al., 2018).

Xylella fastidiosa is a vector-transmitted bacterial plant pathogen associated with serious diseases such as Pierce's disease of grapevine, olive quick decline syndrome and *Citrus* variegated chlorosis that can have important economic consequences. Native to the Americas, *X. fastidiosa* has been detected in several European countries of the Mediterranean Basin since its first appearance in the Apulia region of Italy in 2013. According to simulation studies, the currently reported distribution is small compared with the extent of climatically suitable area and the subspecies *multiplex* and *fastidios*a could become a threat to most of Europe (Godefroid et al., 2019). However, these simulations neglect an important factor in the outbreaks of *Xylella*, which is the insect vectors responsible for its spread. Fortunately, the main vector *Philaenus spumarius* and possibly other putative vectors of *X. fastidiosa* are likely to suffer from a decrease in climatic suitability as a result of climate change and this will probably limit the spread of *X. fastidiosa* in the rest of Europe (Godefroid et al., 2022).

These examples emphasize the importance of accounting for vectors' ecological characteristics when assessing risk of vector-borne diseases, especially under climate change.

4.4 | Weeds and invasive plants

Weeds compete with crops for resources, e.g. light, nutrients and water. Climate change can facilitate the expansion of their distribution to higher latitudes or altitudes, owing to warmer temperatures and changing precipitation patterns. Conversely, other species may struggle to survive in areas with hotter temperatures or prolonged dry conditions. Climate change may affect the timing of weed emergence and flowering, with an earlier onset of spring and an extended vegetative season facilitating weed growth and reproduction. Some weeds may increase their invasiveness, and their impact on yields may be more pronounced.

There is a general consensus on the fact that climate change will increase plant invasion, and this mainly through three mechanisms: (1) poleward and altitudinal upward spread owing to climate warming; (2) range expansion owing to changing precipitation regimes; and (3) increased dispersal and establishment owing to extreme climate events (Clements & Jones, 2021). *Sorghum halepense* is an example of a very aggressive weed and a quarantine pest in several countries including USA and China, whose northward expansion was driven mainly by climate change. This perennial C4 grass, native of the Mediterranean Basin, was introduced in all continents as a forage crop and quickly became an invasive weed. The successful colonization of Northern American maize areas and the continuous progression of its northern edge are due to climate warming and to the phenotypic plasticity of the species, that also developed new ecotypes with rhizomes adapted to cold temperatures (Warwick et al., 1986).

5 | CLIMATE CHANGE IMPACT ON CROP DISTRIBUTION AND PRODUCTIVITY

Climate is one of the main factors controlling the distribution of plants and regulating their productivity. Studies that separate out climate change from other factors affecting crop yields have shown that yields of some crops will be negatively affected by climate change in the lower-latitude regions, while in many higher-latitude regions, yields of some crops will probably increase (IPCC, 2019). The results published by the Agricultural Model Intercomparison and Improvement Project used an ensemble of global gridded crop models to simulate expected crop yields using a range of emission scenarios. Their results indicate that the future yield responses for maize, soybean and rice have overall losses in productivity while wheat showed yield gains owing to higher CO_2 concentrations, especially at high latitudes (Jägermeyr et al., 2021). Using observational data and output from 23 global climate models, Battisti and Naylor (2009) reported that by the end of the twenty-first century temperatures during the growing season in the tropics and subtropics will exceed the most extreme seasonal temperatures recorded between 1900 and 2006, dramatically impacting agricultural productivity, farm incomes and food security. Changes in precipitation patterns may potentially be more significant for crop production than an increase in temperature (Skendžić et al., 2021). Changed climatic conditions have already altered the area suitable for production of some crops (Gardner et al., 2021) and made possible the cultivation of subtropical crops in new areas, such as Southern Europe. The relatively recent introduction and cultivation of avocado (*Persea americana*), mango (*Mangifera indica*) and papaya (*Carica papaya*) outdoors in Spain, Greece, Italy, Cyprus and Portugal and the rapid growth of the areas cultivated with these crops (Figure 1) are partly a consequence of the warmer climate in the Mediterranean basin. Data on

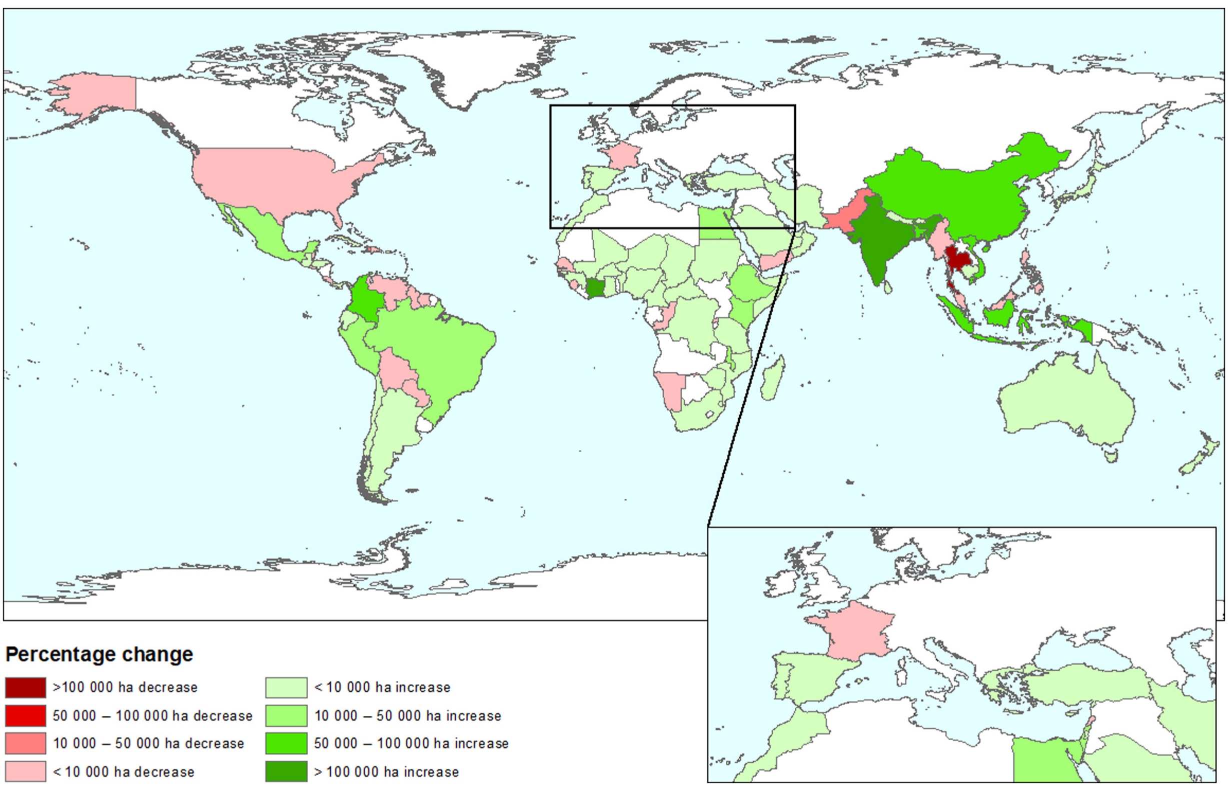

FIGURE 1 Change in harvested area of avocado, mango and papaya between 2017 and 2021 (data from FAO, 2023).

avocado shows that during the last 5 years the cultivated area increased steadily in all Mediterranean European countries, with Spain leading with more than 18 000 ha (FAO, 2023).

A study conducted for Greece assessed the suitability for the cultivation of 20 new crops, previously cultivated only in sub-tropical regions, in the four climatic areas of the country (Georgakopoulos et al., 2016). It was found that 13 of the crops could adapt to a climate zone where average maximum and minimum temperature ranges are 14–30.5 and 8.3–23.3°C, respectively, while the annual precipitation ranges from 502 to 592 mm. Six crops i.e. quinoa (*Chenopodium quinoa)*, maca (*Lepidium meyenii*), psyllium (*Plantago indica*), chia (*Salvia hispanica*), cassava (*Manihot esculenta*) and pecan (*Carya illinoinensis*), could adapt to all climatic zones of Greece, subject to certain conditions (Georgakopoulos et al., 2016).

Climate change-related crop management includes the use of irrigation, the discontinuation of deep soil tillage, the changing of sowing dates and the production of multiple crops per year (Juroszek et al., 2020). In South-Eastern Africa, irrigation has made it possible to grow maize all year round, but has also increased insect-vector populations, which has resulted in greater maize streak virus pressure in irrigated crops and later also in rainfed crops (Juroszek et al., 2020; Shaw & Osborne, 2011).

6 | OTHER DRIVERS OF INTERNATIONAL PEST INVASION

Apart from its impact on altering the geographical range where pests can establish and thrive, climate change presents another major threat to plant health in the context of the global dissemination of pests facilitated by human activities (Chapman et al., 2017; Hulme, 2009; MacLeod et al., 2010; Seebens et al., 2017). As climate change reshapes the ecosystems, the pathways through which plant pests travel evolve, necessitating flexible strategies for surveillance and prevention of new pest introductions. The increased number of pest introductions historically has been frequently attributed to growing international trade (Garnas et al., 2016; Liebhold et al., 2012; Roy et al., 2014) facilitated through trade liberalization by the WTO (Maye et al., 2012) and faster and more efficient transport systems (Rodrigue et al., 2016). Global trade connectivity has been linked with numerous economic, developmental and peace benefits. While the WTO aims to encourage international trade to alleviate poverty and provide wider economic benefits, it also recognizes that expanding trade opens pathways for plant pests. To mitigate the phytosanitary risks from trade, countries can establish import requirements in the form of phytosanitary measures designed to inhibit the introduction and spread of plant pests (Allen et al., 2017; MacLeod & Eyre, 2023). Phytosanitary measures should have limited interference with international trade and must be technically justified (FAO, 2002; Schrader & Unger, 2003; WTO, 1995). The WTO and IPPC recognize that appropriate PRA provides the technical justification for phytosanitary measures. Pest risk analysis incorporates both pest risk assessment and pest risk management and provides the rationale for phytosanitary decision-making, supporting decision-makers to protect plant resources (FAO, 2019a). The risk associated with a pathway defined in a PRA may be affected by climate change, as some countries will be able to grow new crops creating new pathways, or the productivity of traditionally cultivated crop may change owing to new weather patterns providing a bigger host reservoir for pest development (e.g. Machovina & Feeley, 2013). In addition, the season in which the pest population is active may be extended, or the seasonal pest population density may increase, which will affect propagule pressure (Szyniszewska et al., 2016).

7 | THE COMPLEXITY OF ATTRIBUTION BETWEEN DRIVERS

We discussed in this paper a number of drivers contributing to the international spread and emergence of plant pests. Attributing the extent to which a single driver contributes to the spread of plant pests thus becomes challenging. For example, climate change may be a contributor to land use changes and land use changes can also alter the climate. At the global scale though, there is high confidence that observed changes in physical and biological systems in recent decades have been beyond that which can be attributed to natural variability (e.g. Rosenzweig et al., 2008). A definitive detection and attribution of impacts from climate change relies first and foremost on the availability of a long time series (several decades) of observational data (Stone et al., 2013), and from the PRA perspective, this data needs to cover not just the area of interest but also surrounding areas and regions where pathways to the PRA area exist. The adaptive capacity of pests to respond to changes in their environment (e.g. a more poleward distribution) provides an important evidence base for the detection of impacts to climate change (Stone et al., 2013). The approaches used in attribution studies may not be applicable everywhere, and may for example be inconclusive where climate models do not replicate processes adequately or where those processes are not fully understood, such as in the case of the East Asian monsoon system affecting China (Qian et al., 2022; Zhai et al., 2018).

Climate change interacts with other agents of global change, including proliferation of irrigation and the availability of water for irrigation (El-Nashar & Elyamany, 2023). New irrigated areas provide new habitats and thus new areas that may be prone to pest infestations (Bradshaw et al., 2022).

8 | DISCUSSION

The evidence for anthropogenic climate change is now unequivocal and unprecedented (IPCC, 2021). Climate change is not only a problem for the future, but an ongoing process we have already experienced, and its effects in recent decades are well documented (IPCC, 2019). While there is evidence that the actual and potential ranges for species distribution are changing continuously, it is important to recognize that climate change is not a linear process, and species responses to new climate trends are often also not linear. Nevertheless, recognizing that the distributions of many plants and plant pests are strongly influenced by climate, one might expect PRAs to take climate change into account, not least to identify whether the climate of the PRA area would be suitable for pest establishment in the time horizon of interest. However, there are very few examples of PRAs in which climate change has been explicitly taken into account (see Rosace et al., 2024).

To determine whether or not climate change is important for a particular PRA, the assessors should determine whether the pest climatic envelope covers the PRA area or if it is likely to be covered within the time frame considered by the PRA. The incremental climate change in certain areas may not have a great effect on the overall PRA outcome. In areas where the potential for species survival may be much more probably affected by changing climate though, for example in higher latitudes, the importance of taking climate change into account will increase.

One important aspect of incorporating climate change into PRA would be the time frame, or the relevant time horizon. While it is important not only from the policy-making perspective, the longer the time frame is, the greater the significance of future climates, but also the greater uncertainty of the results (see Bradshaw et al., 2024). However, most PRAs do not explicitly provide a time frame or mention a time horizon despite the fact that when assessing the potential consequences of pest introduction the magnitude and extent of impacts will often depend upon how quickly the pest spreads spatially and temporally within the PRA area. Therefore, to assess impacts assessors should specify the time frame within which the pest's spread and impact are being considered (Devorshak & Neeley, 2012).

There are many variables and sources of uncertainty within the current approach to PRA. For example, information on pest distribution and host association is often incomplete and can change rapidly, independent of climate change. This is especially true for newer, less studied, emerging pests. Movement of commodity production around the world also creates opportunities for new pest–host interactions. Control practices and treatments are also subject to change, which can affect risk management in the PRA area.

With changing climatic conditions at the origins of potential pathways and within the PRA area itself, new pathways facilitating the arrival of harmful pests may emerge and some may diminish. The propagule pressure driving the spread of pests may be enhanced by increased pest population growth and density, and consequently, this may affect the chance of successful transport and establishment. However, there may also be instances of asynchrony between pests and their hosts owing to altered seasonal patterns. The higher concentration of carbon dioxide in the atmosphere may stimulate compensatory growth in hosts, potentially influencing host–pest dynamics. In addition to that, the efficacy of various risk management measures may be affected by climate change, as the effectiveness of certain methods could change under different climatic conditions.

The influence of the uncertainties regarding how these elements of risk change in the future are usually greater than the influence of climate change, which may be one of the reasons why climate change is so seldom included within PRAs. Nevertheless, there is frequently a substantial uncertainty within a PRA largely owing to a lack of data necessary to reach secure conclusions (Griffen, 2012) and for data that are available, there is often a disconnect between the relatively small scale at which data is often collected and the scale at which risk assessors use it to inform judgements about future consequences (MacLeod & Lloyd, 2020).

The level of detail in a PRA is limited by the amount and quality of information available, the tools, and time available before a decision is required. Given the limited resources available to those responsible for conducting PRAs, a PRA should be cost-effective, and only as complex as is required by the circumstances to support a phytosanitary decision. Nevertheless, a PRA should provide the necessary technical justification to support phytosanitary decisions which the PRA informs. There is substantial uncertainty regarding aspects of climate change (Bradshaw et al., 2024) but the influence of climate change may have a large impact on the risk that a pest constitutes in the future. The importance of climate change and whether or not to address climate change and its associated uncertainties within PRA are still a matter of debate more than 10 years after NAPPO (2012) reported that there was ongoing considerable discussion as to whether there is benefit to be gained or justification for including climate change in PRA.

9 | CASE STUDIES OF PESTS' RESPONSES TO THE ONGOING CHANGES IN CLIMATE

BOX 1 The mountain pine beetle, *Dendroctonus ponderosae* (Coleoptera: Curculionidae: Scolytinae): climate change, range expansion, new hosts and impact.

The mountain pine beetle is a bark beetle native to North America that has a long history of causing large-scale pine tree mortality during outbreaks. It is an example of a pest for which there is relatively strong evidence that climate change has contributed to its range expansion (Carroll et al., 2003; Sambaraju & Goodsman, 2021). This can be attributed to factors such as the availability of long-term monitoring data (since the early twentieth century in British Columbia, Canada) and extensive knowledge of the key factors that regulate population levels. These factors include sufficient degree-day accumulation for the beetle to synchronize its univoltine life cycle, absence of lethal winter temperatures, appropriate temperatures during its dispersal period and adequate spring precipitation (Carroll et al., 2003). The timing, frequency and duration of cold snaps, in particular, have been demonstrated to strongly influence the likelihood of outbreaks (Sambaraju et al., 2012).

Owing to the range expansion, the mountain pine beetle now has outbreaks in areas where the trees have not previously been exposed to outbreak levels of the beetle (Cudmore et al., 2010). The reproductive success in these trees is much higher than in areas that have a history of frequent outbreaks, presumably owing to there having been no selection pressure upon the defensive mechanisms of the trees by the beetle in those areas. This has been suggested to be one of the key factors for the swift increase in population levels that has led to unparalleled death of host trees across vast regions in western Canada (Cudmore et al., 2010).

The range expansion has also increased the access to several new host tree species, e.g. whitebark pine (*Pinus albicaulis*), which is now considered endangered partly owing to extensive mountain pine beetle outbreaks (Buotte et al., 2017). The ecological impacts of large-scale mountain pine beetle outbreaks are vast and diverse, including both positive impacts, e.g. increased forest diversity, and negative impacts, e.g. transforming the forested region in British Columbia from a carbon sink to a net carbon source (Kurz et al., 2008; Sambaraju & Goodsman, 2021). The economic impact is also very high and will remain high into the future owing to, for example, a reduction in available timber, as the stands will take several decades to regrow. In one study the long-term cost of the outbreak in BC, Canada was estimated to be 57 billion CAN dollars from 2009 to 2054 (Corbett et al., 2016).

BOX 2 The southern green stink bug, *Nezara viridula* (Heteroptera: Pentatomidae): response to the current climate change.

The rapid range expansion of the southern green stink bug, a polyphagous agricultural pest, was studied in detail in central Japan (Figure 2). In the 1960s, it was shown that the northern limit of the species range lay in the Wakayama Prefecture (approximately 34.1°N) and coincided approximately with the +5°C isotherm for the mean air temperature of the coldest winter month (usually January; Kiritani et al., 1963, Kiritani & Hokyo, 1970). A wide-scale field survey conducted 45 years later demonstrated that the northern limit of *N. viridula* had shifted northwards by approximately 85 km (i.e. at a mean rate of 19 km per decade; Tougou et al., 2009). Over the next 5 years it moved further northward by 25 km (Geshi & Fujisaki, 2013). An assessment of overwintering of adult *N. viridula* in different habitats showed that winter temperature was the principal factor that determined adult mortality during the hibernation period. Only 1.5% of males and 3.5% of females managed to survive the severe winter of 1962/1963 when the mean temperature in January fell to +2.9°C. Survival during moderately cold winters was much higher (40–65%; Figure 3; Kiritani et al., 1966; Kiritani, 1971). Overwintering mortality correlated negatively with the mean temperature of the coldest month and a decrease of 1°C results in approximately a 15% increase in mean overwintering mortality. Thus, the mean January temperature was proposed to be the principal factor that determined the northern limit of the distribution of *N. viridula* in Japan (Kiritani et al., 1963). These early field data are supported by a series of outdoor experiments (Figure 2; Musolin & Numata, 2003, 2004; Musolin, 2007, 2012; Tougou et al., 2009). An analysis of historical climatic data further suggested that the shift in distribution of *N. viridula* in Japan most likely was promoted by the milder overwintering conditions in the region during recent decades. The mean temperatures in the region in January and February were 1.03–1.91°C higher during 1998–2007 than during 1960–1969. The number of cold days in January and February (with mean daily temperatures below +5°C) also decreased, and the annual lowest temperature also rose from 1960–1969 to 1998–2007. The analysis showed that the mean January temperature and the number of cold days were the most critical factors that determined the northern distribution limit of *N. viridula* (Tougou et al., 2009).

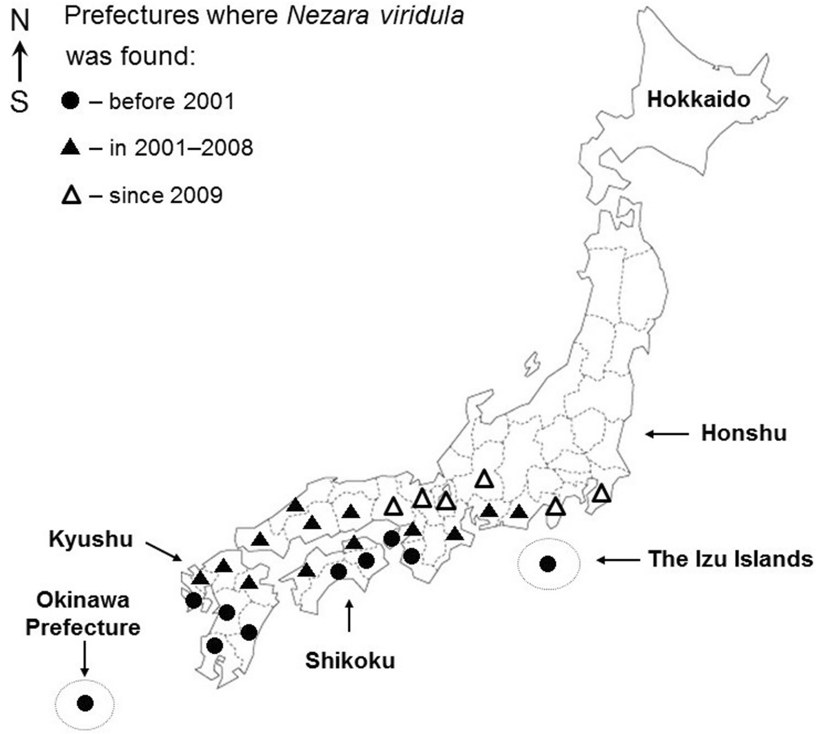

FIGURE 2 Northward expansion of distribution of *Nezara viridula* in Japan. The prefectures where the pest was recorded for the first time before 2001, in 2001–2008 and since 2009 are indicated (data from Esquivel et al., 2018; Kiritani, 2011; Koide et al., 2010; Mizutani, 2013; Musolin, 2012; Suzuki et al., 2011).

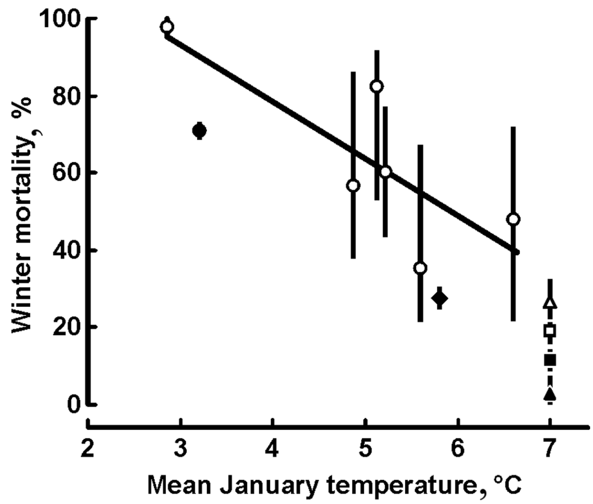

FIGURE 3 The effect of January temperature on winter mortality of *Nezara viridula* adults in Central Japan. Field experiments in Asso in 1961–1967 (open circles): mean (and range of) mortality (data from Kiritani et al., 1966 and Kiritani, 1971); a linear regression trend line refers to the mean mortality ($F_{1,5}$=6.81, p=0.06). Outdoor experiments in Osaka in 1999–2000 and in Kyoto in 2006–2008 (all other symbols): mean mortality and range (mortality in both sexes; data from Musolin & Numata, 2003, 2004; Musolin et al., 2010b; Takeda et al., 2010). In Asso, mortality was measured in the wild and only during the hibernation period, whereas in other experiments the pre-winter mortality was included, and the insects were reared in containers, thus protected from natural enemies (from Musolin, 2012).

BOX 3 The eucalyptus longhorned borer, *Phoracantha semipunctata* (Coleoptera: Cerambycidae): a dieback in Australian snow gums *Eucalyptus pauciflora* and climate change.

The eucalyptus longhorned borer is a highly invasive beetle that infests eucalyptus both within its native Australian range and in timber plantations in South Africa, the Americas and the Mediterranean, where it has been introduced via global trade (Ali & Garcia, 1988; Belal et al., 2017; Day, 1959; Seaton, 2012; Zhao et al., 2023). Heavy larval infestations can rapidly cause tree death (Hanks et al., 1993; Zhao et al., 2023).

Low water potential in susceptible eucalypt species is linked to a higher rate of *P. semipunctata* infestations under laboratory conditions (Hanks et al., 1999). This suggests that *P. semipunctata* invasions outside of its native range may become more pronounced under drought conditions which are projected to increase in frequency and severity owing to climate change (Chiang et al., 2021). Modelling indicates that climate change will enable *P. semipunctata* to expand its range outside of current regions, and that the severity of outbreaks is likely to increase in some regions within its current distribution as they become increasingly suitable (Zhao et al., 2023). Eucalyptus plantations of the Mediterranean and North America are therefore at higher risk of severe infestations under climate change, which will lead to an increased potential distribution of *P. semipunctata* in some regions (Zhao et al., 2023).

BOX 4 The tobacco whitefly, *Bemisia tabaci* (Hemiptera: Sternorrhyncha: Aleyrodidae): a pandemic of cassava brown streak disease in Africa and climate change.

The relationship between climate change and the occurrence of infectious diseases in plants was shown for the tobacco whitefly, a vector of very many plant viruses (De Barro, 1995) including viral diseases affecting cassava, a vital crop in Africa (Kriticos et al., 2020). A climatic niche model (CLIMEX) was used to assess whether outbreaks of cassava brown streak disease (CBSD), which originated in Uganda in the late 2000s and coincided with increasing population densities of *B. tabaci* in the region, could be attributed to climate change and increasing climatic suitability for the insect vector in the region. The model's predictions were validated against field data on *B. tabaci* abundance in Uganda over a 13 year period and the probability of *B. tabaci* occurrence across Africa over 2 years. The results revealed that the climatic conditions for *B. tabaci* significantly improved in the areas affected by the outbreaks during the 39 year period under study, while remaining stable or decreasing elsewhere. This study represented the first documented case where historical climate change was linked to the increased abundance of an insect pest, which contributed to a pandemic of a crop disease.

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