

Review

Climate Change and Pathways Used by Pests as Challenges to Plant Health in Agriculture and Forestry

Maria Lodovica Gullino ¹, Ramon Albajes ², Ibrahim Al-Jboory ³, Francislene Angelotti ⁴ , Subrata Chakraborty ^{5,6} , Karen A. Garrett ⁷, Brett Phillip Hurley ⁸ , Peter Juroszek ⁹ , Ralf Lopian ¹⁰, Khaled Makkouk ¹¹, Xubin Pan ¹² , Massimo Pugliese ^{1,*}  and Tannecia Stephenson ¹³

- ¹ AgriInnova, University of Torino, 10095 Grugliasco, Italy
² Agrotecnio Center, Universitat de Lleida, 25002 Lleida, Spain
³ Department of Plant Protection, University of Baghdad, Baghdad 10070, Iraq
⁴ Brazilian Agricultural Research Corporation (EMBRAPA), Embrapa Semi-Arid, Petrolina 56302-970, Brazil
⁵ Faculty of Science, Agriculture, Business and Law, School of Science and Technology, University of New England, Armidale, NSW 2351, Australia
⁶ Center for Advanced Modelling and Geospatial Information Systems, Faculty of Engineering and IT, University of Technology Sydney, Sydney, NSW 2007, Australia
⁷ Plant Pathology Department and Global Food Systems Institute, University of Florida, Gainesville, FL 32605, USA
⁸ Department of Zoology and Entomology, Forestry and Agricultural Biotechnology Institute (FABI), University of Pretoria, Pretoria 0002, South Africa
⁹ Central Institute for Decision Support Systems in Crop Protection (ZEPP), 55545 Bad Kreuznach, Germany
¹⁰ Ministry of Agriculture and Forestry of Finland, 00023 Helsinki, Finland
¹¹ Ex-National Council for Scientific Research (CNRS), Beirut LB 2260, Lebanon
¹² Institute of Plant Quarantine, Chinese Academy of Inspection and Quarantine, Beijing 100176, China
¹³ Department of Physics, Faculty of Science and Technology, The University of the West Indies (UWI), Mona, Kingston 7, Jamaica
* Correspondence: massimo.pugliese@unito.it



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Abstract: Climate change already challenges people's livelihood globally and it also affects plant health. Rising temperatures facilitate the introduction and establishment of unwanted organisms, including arthropods, pathogens, and weeds (hereafter collectively called pests). For example, a single, unusually warm winter under temperate climatic conditions may be sufficient to assist the establishment of invasive plant pests, which otherwise would not be able to establish. In addition, the increased market globalization and related transport of recent years, coupled with increased temperatures, has led to favorable conditions for pest movement, invasion, and establishment worldwide. Most published studies indicate that, in general, pest risk will increase in agricultural ecosystems under climate-change scenarios, especially in today's cooler arctic, boreal, temperate, and subtropical regions. This is also mostly true for forestry. Some pests have already expanded their host range or distribution, at least in part due to changes in climate. Examples of these pests, selected according to their relevance in different geographical areas, are summarized here. The main pathways used by them, directly and/or indirectly, are also discussed. Understanding these pathways can support decisions about mitigation and adaptation measures. The review concludes that preventive mitigation and adaptation measures, including biosecurity, are key to reducing the projected increases in pest risk in agriculture, horticulture, and forestry. Therefore, the sustainable management of pests is urgently needed. It requires holistic solutions, including effective phytosanitary regulations, globally coordinated diagnostic and surveillance systems, pest risk modeling and analysis, and preparedness for pro-active management.

Keywords: global warming; plant pathogens; insect pests; invasive species; pest risk

1. Introduction

Climate change affects biological systems at multiple scales, from genes to ecosystems [1–3]. It can have important effects on plant pests, where “pest” here is any species, strain, or biotype of plant, animal, or pathogenic agent injurious to plants or plant products. On average, between 10 and 28 percent of crop production is lost to pests at a global scale [4]. Post-harvest losses also occur, and mycotoxins in food and feed can severely threaten the health of humans and livestock [5,6].

Climate change may threaten food security through impacts on food crops and plant-based animal feed, in terms of both quality and quantity. For wheat, rice, soybean, and maize, the worst impacts are expected in the tropics and subtropics, with climate change projected to negatively impact production, where the local temperature increases by 2 °C or more above late-twentieth-century levels. While some higher altitude or latitude locations may benefit from this change, these will likely be the exception [7]. Plant protection and plant biosecurity may also be adversely impacted [8–11], and thus, improved biosecurity measures and climate-smart plant protection methods will be needed [12,13].

We review the effect of climate change on plant pests and methods for studying these effects and future pest risks. Case studies on insect pests and plant pathogens affected by climate change are provided. We also discuss the main pathways of pest invasion and how these are influenced by global trade. We emphasize that preventive, mitigation, and adaptation measures are needed to reduce the projected increase in pest risk, and investments in these measures will have benefits beyond adaptation to climate change.

2. Effects of Climate Change on Plant Pests

Climate-change effects on pest species are complex. They include indirect and direct effects and their potential interactions [14]. Examples of likely impacts of climate change on plant pests in different climate zones are reported in Table 1, where from this point we do not include weeds in the term “pest”.

Table 1. Examples of some likely effects of climate change on plant pests in different climate zones (modified after [13]).

Climate Zones	Likely Effects of Climate Change on Future Pest Risk (Mainly 2050–2100)	References
Arctic	Increasing pest risk in the tundra.	[15]
Boreal	Increasing insect pest and plant disease risk in boreal forests.	[16]
Temperate	Increasing insect pest risk in agriculture and forestry.	[17]
	Increasing insect pest and plant disease risk in forests.	[16]
	Increasing disease risk in agriculture and horticulture (mostly based on western European studies).	[18,19]
	Often poleward shift of insect pest and pathogen risk in different managed and unmanaged ecosystems.	[20]
	Often range expansion of important insect pests in agriculture and horticulture.	[21]
Subtropical	Increasing risk of weeds in different managed and unmanaged ecosystems.	[22]
	Increasing saturation of insect pest risk in agriculture and forestry in southern Europe.	[17]
	Increasing disease risk in agriculture and horticulture.	[23]
Tropical	Often range expansion of important insect pests in agriculture and horticulture.	[21]
	Insects will often face supra-optimal temperature conditions in the future, presumably resulting in decreasing insect pest risk.	[24]
	Conflicting information and expert opinions on disease risk in agriculture and forestry with respect to Brazil.	[19,25,26]

Possible indirect and direct effects on pests include: changes in their geographical distribution, such as range expansion or retreat, or increased risk of pest introduction; changes in seasonal phenology, such as the timing of spring activity or the synchronization of pest life-cycle events with their host plants and natural enemies; and changes in aspects of population dynamics, such as overwintering and survival, population growth rates, or the number of generations of polycyclic species [27–29].

In general, all important life-cycle stages of pests (growth, maturation, and reproduction for insect pests, survival, reproduction, and dispersal for plant pathogens) are more or less directly influenced by humidity, temperature, light quantity or quality, wind, or combinations of these factors [30]. The physiological processes of most pest species are particularly sensitive to temperature [31,32]. For example, plant pathogens may be particularly favored by high temperatures until their upper-temperature threshold is reached [33,34]. Indirect effects are mediated through the host plant or through climate-change-driven adaptations to crop management [30]. Warmer mean air temperatures, especially in early spring under temperate climatic conditions, may result in earlier occurrence of life-cycle stages in the host plant [35]. This can affect pathogens that infect the host during a particular life-cycle stage [36], for instance, wheat pathogens such as *Fusarium* species that infect wheat during flowering [13,18,37,38].

2.1. Methodology to Investigate the Effects of Climate Change on Plant Pests

Over the past 30 to 40 years, the effects of several factors—increased temperature, CO₂, ozone or ultraviolet-B irradiation, and changing water or humidity patterns—on the incidence and severity of pests have been evaluated, mostly on field crops, such as wheat, barley, rice, soybean, and potato [39–43], horticultural crops [23,44], including tropical and plantation crops [25], and forest trees [45–48].

Many complementary research approaches have been used, including experiments to evaluate the effects of changes in one or more weather parameters (Table 2). Other observational studies have investigated species along latitudinal or elevational gradients as a proxy for changes in climate over time. In addition to these empirical approaches, “theoretical” approaches have also been adopted, such as the meta-analysis of published results [49,50] or the analysis of long-term datasets [51,52]. Finally, some studies have drawn upon expert opinion or have generated simulation models to predict how projected changes in climate or atmospheric composition will alter the distribution, prevalence, severity, and management of pests and other organisms [13].

Table 2. Some examples of experimental and theoretical approaches in climate-change biology research (modified after [27]).

Type of Research Approach	Description and Comments	Selected References
Experiments under controlled conditions	Controlled conditions are not realistic, but it is easier to study one or a few environmental parameters because of lower variability and fewer interactions.	[23]
Experiments on-station, on-farm, and under natural conditions	Field conditions are realistic, but the environmental parameters are difficult to control because of variability and complex interactions.	[53,54]
Studies along an elevation gradient from low to high elevation sites	Effects of changes in temperature and precipitation can be studied over a short distance, with day length the same (e.g., characteristics of a single species can be compared).	[55]
Studies along a latitudinal gradient	Research can be implemented along a climate gradient from temperate to tropical, with long-distance changes in temperature and precipitation, although day length may also vary (e.g., characteristics of a single species, or the biodiversity of species in general, can be compared in different climates).	[56]
Meta-analysis of published data	Involves searches for general patterns in responses of specific taxa to variations in climate factors. A sufficient number of published results should be available to draw meaningful conclusions.	[16]
Data monitoring, long-term datasets of different parameters	Involves long-term field observations to study effects already apparent due to climate warming in recent decades. Long-term weather records are necessary and, if available, other long-term datasets to search for other possible reasons for observed changes (particularly in managed systems).	[57,58]

Table 2. Cont.

Type of Research Approach	Description and Comments	Selected References
Expert opinion	Long-term experiences and knowledge of experts can be used. The complete life cycle of a pest species can be considered in theory; however, this approach is somewhat subjective.	[59]
“Climate matching” approach	A present-day climate analogue to the future climate for an area of interest is found, and the pest dynamics in that location are studied in order to gain an appreciation of the comparative dynamics (e.g., dynamic climate matching model CLIMEX). Other tools can also be used, such as MaxEnt, to compare the habitat suitability of different locations for the species of interest.	[60,61]
A modeling approach using one or several climate-change scenarios or models, or comprehensive ensembles of climate-change scenarios or models, to simulate future pest risk	It is possible to categorize scenarios or models used from “conservative” to “worst case”, and this is also possible within a single climate-change model if different representative concentration pathway (RCP) scenarios are applied.	[26,62]

Experimental approaches can yield valuable insights into the effects of climate change on plant pests, but few studies have realistically mimicked a changing climate [42,63–66]. Climate-change studies carried out in free-air CO₂ enrichment facility (FACE) systems and in open-topped chambers have led to a better understanding of the effects of different parameters on the development of plant diseases in several crops [67]. Such systems have also been used to investigate effects on weeds [68] and insects [69]. In general, most of the insect and disease problems studied in FACE systems under high CO₂ conditions have shown increased impact, as recently summarized by Ainsworth and Long [70].

Phytotrons, environmental chambers built to test the effect of combinations of environmental parameters [71,72], have been used to study the effects of short-term increases in CO₂ and temperature on host–pathogen relationships [23]. They are used to understand how specific diseases may evolve in the future and to develop practical solutions to cope with future scenarios. For example, these studies can provide support to the plant-breeding industry. Phytotrons have also been used to investigate more indirect effects of climate change on plants, such as effects on mycotoxin production or on disease-management practices [73,74].

Field approaches in natural environments include research along an elevation gradient from low- to high-elevation sites [55,75], with associated changes in temperature and air humidity. Another approach is research in habitats along a latitudinal gradient, including, for example, subtropical, temperate, and semi-arid climatic conditions [56,76]. The first approach has the advantage of the photoperiod being the same along the elevational gradient. In the second approach, the photoperiod is likely to vary across the latitudinal gradient. For example, in the tropics, days are shorter, and nights are longer during summer and the other way round in winter, compared to temperate climatic conditions. These differences in photoperiod need to be considered when interpreting results. Nevertheless, both approaches can help identify broad patterns across wide environmental gradients and a range of climatic regions under real-world conditions. Such studies can help to determine whether a certain species is limited to a specific climate or is widely occurring, indicating whether it is likely to invade locations that are getting warmer [13,27].

Meta-analyses of published datasets have been performed to search for general patterns in the responses of specific pests to differences in climate variables [77–79]. In addition, long-term datasets from field observations have been used to study climate change effects that are already apparent owing to warming in recent decades [57,80–85], and they can help researchers distinguish impacts due to climate change from those due to other factors [1,86]. Attempts have been made to improve estimates of climate-warming effects on insects by

combining data from long-term datasets, large-scale experiments, and computer modeling [17,87,88]. For example, a meta-analysis of data from laboratory studies concluded that higher trophic levels (e.g., predators) are more susceptible to climate change than lower-order organisms (plants or herbivorous insects) [89]. This is relevant when studying the changing role of natural enemies on insect pest dynamics and biological control under climate change—a subject addressed by very few field data [13,90].

Simulation models can be used to project future climate change impacts on pests [2,91], and to help determine tactics and strategies to control pests [92–95]. One modeling approach, for example, uses “climate matching”, whereby a geographical area that has a present-day climate analogous to the future climate in the area of interest is studied (for pest dynamics in this case), and then the findings extrapolated to a future scenario in the area of interest [60]. Other modeling approaches may rely on long-term datasets for weather parameters, crop development, and pest distribution and prevalence to develop and validate “pest-crop-climate” models [26,37]. Other recent examples of modeling studies, listed in Table 2, consider parameters such as the number of generations per year for insect pests, the timing of plant flowering and related disease severity [13].

2.2. Future Pest Risk

Simulation studies to determine future pest risks under climate change scenarios have mostly employed species-distribution models, population-dynamics models, or hybrids of both (Table 3). Climatic factors considered include temperature, precipitation and humidity, but elevated CO₂ has generally not been considered [13,19,67]. The effects of climate change are probably easier to predict for those pest species that are primarily affected by temperature. Prediction is more difficult for pests whose reproduction and dispersal are strongly related to water availability, wind, and crop management [13]. This is also true for pests that are strongly affected by interactions with other organisms, such as vectors of pathogens [31], unless their interactions are well studied [27,96,97], and thus, predictable (see the case study for *Xylella fastidiosa*).

Table 3. Examples of pest risk simulation studies where pest models were linked to climate change scenarios and time spans indicated future projections (modified after [13]).

Country or Region	Time Span or Spans	Crops Affected, Pest Species and Projection of Change	Selected Reference
Insects			
Global	2050, 2100	Multiple crops: Area suitable for fall armyworm (<i>Spodoptera frugiperda</i>) is projected to increase.	[98]
Global	2050	Tomato: It is projected that several nations face a potential increase in two-spotted spider mite (<i>Tetranychus urticae</i>) outbreaks, while biological control by its key predator <i>Phytoseiulus persimilis</i> will not improve.	[99]
Global	2041–2060 2061–2080	Potato: Expansion of Colorado potato beetle (<i>Leptinotarsa decemlineata</i>) into northern regions is projected.	[100]
Africa	2041–2060	Multiple crops: Habitat suitability for oriental fruit fly (<i>Bactrocera dorsalis</i>), mango fruit fly (<i>Ceratitidis cosyra</i>), and tomato leafminer (<i>Tuta absoluta</i>) is projected to partially increase across the continent.	[61]
Luxembourg	2021–2050, 2069–2098	Oilseed rape: Pollen beetle (<i>Meligethes aeneus</i>) is projected to invade crops earlier in the year.	[101]

Table 3. Cont.

Country or Region	Time Span or Spans	Crops Affected, Pest Species and Projection of Change	Selected Reference
Scandinavia and central parts of Europe	2011–2040, 2071–2100	Forest trees, spruce: Increased frequency and length of late-summer swarming events of the European spruce bark beetle (<i>Ips typographus</i>) are projected. A second generation in southern Scandinavia is possible and a third generation in the lowlands of central Europe.	[102]
Switzerland	2070–2099	Multiple crops: Brown marmorated stinkbug (<i>Halyomorpha halys</i>), which has a wide range of potential hosts, is projected to expand into higher altitudes, produce more generations per year, and be active earlier in spring.	[103]
United States of America, Midwest	2001–2050, 2051–2100	Corn and soybean: The pressure of nine different insect pests is projected to increase in general. Insect pests will move northward, because “optimal climatic conditions” will be further north.	[104]
Pathogens (diseases)			
Global	2050, 2100	Bean: The area favorable for soybean rust (caused by <i>Phakopsora pachyrhizi</i>) is projected to decrease.	[105]
Brazil	2011–2040, 2041–2070, 2071–2100	Grapevine: The area favorable for downy mildew (caused by <i>Plasmopara viticola</i>) is projected to decrease across Brazil, although there are differences across regions or states.	[26]
Canada, Quebec	2041–2070	Soybean: The number of generations of soybean cyst nematode (<i>Heterodera glycines</i>) is projected to increase.	[106]
China, central	2030s, 2050s, 2070s, 2080s	Kiwi: The area favorable for bacterial canker (caused by <i>Pseudomonas syringae</i>) is projected to increase.	[107]
Europe	2070	Pine trees: Pine wilt disease risk (caused by the pine wilt nematode, <i>Bursaphelenchus xylophilus</i>) is projected to increase.	[108]
France	2020–2049, 2070–2099	Wheat: Risk of leaf rust (caused by <i>Puccinia triticina</i>) is projected to increase in spring time.	[62]
France	2020–2049, 2070–2099	Apricot: Risk of blossom blight and twig blight (caused by <i>Monilinia laxa</i>) is projected to decrease or increase, depending on the cultivar grown (early vs late flowering).	[36]
Germany, south-west	2050, 2100	Sugar beet: Risk of Cercospora leaf spot (caused by <i>Cercospora beticola</i>) is projected to increase.	[109]
India	2010–2039, 2040–2069	Rice: Infection ability of leaf blight (caused by <i>Magnaporthe oryzae</i>) is projected to increase during the winter season (December to March), whereas during the monsoon season (July to October), it is projected to remain unchanged or to decrease slightly.	[110]
Italy	2030, 2050, 2080	Grapevine: Increased importance of downy mildew (<i>Plasmopara viticola</i>), due to more spring days with favorable conditions, with earlier attacks and more treatments needed.	[111]
Philippines	2050	Banana: The area favorable for Fusarium wilt (caused by <i>Fusarium oxysporum</i>) is projected to increase.	[112]

The outcome of simulations depends on the data and methods used, including the global climate model used, the emission scenarios, the regional climate model, the specific pest model, and the precise parameters used in the simulation [18]. All of these contribute

to the outcome of pest risk projections [62,113,114] and should be borne in mind when reading and interpreting the results from simulation studies such as those listed in Table 3; consequently, generalizations should be treated with extreme caution and researchers need to be careful when extrapolating their results [30]. In addition, the effect of climate change on pest risk can vary across a country (e.g., lowlands vs mountains, north vs south, summer vs winter, hot and wet vs cool and dry season) [18] and according to geographical location [13,115].

According to Juroszek and von Tiedemann (2015) [19], in general, the projected change (increase or decrease) in pest risk will be more pronounced by the end of the twenty-first century than earlier in the century if increasing temperature is the primary driver of results. This reflects the fact that global warming is projected to be greater by the end compared to the middle and the beginning of the twenty-first century (e.g., 3 °C vs. 2 °C vs. 1 °C global temperature increase, respectively).

Recently, Seidl et al. (2017) [16] published a comprehensive, global analysis of available results (more than 1600 single observations) and concluded that around two-thirds of all observations show that the risk of abiotic (e.g., fire, drought) and biotic (e.g., insect pests, pathogens) stress factors will increase in forestry worldwide. Warmer and drier conditions favor disturbances by insects, whereas warmer and wetter conditions favor disturbances by pathogens. The same trend is expected for many crop diseases (e.g., [19]) and insect pests (e.g., [21]), with increasing pest risk in most cases, at least in locations with currently relatively cool temperature conditions until supra-optimal temperature and/or sub-optimal humidity conditions are reached for plant pest species [13].

2.3. Case Studies

Some pests have already expanded their host range or distribution, at least in part due to changes in climate. Examples of these pests, selected according to their relevance in different geographical areas indicated between brackets, are summarized below.

2.3.1. Insects

Emerald ash borer (*Agrilus planipennis*) (Asia, Europe, North America) is a phloem-feeding beetle that infests ash trees (*Fraxinus* spp.) [116]. Native to north-east China, the Korean peninsula and the east of the Russian Federation, this pest has spread to other parts of Asia, North America (Canada and the United States of America) [117], and Europe (e.g., the western and southern parts of the Russian Federation, and Ukraine) [118]. It was probably introduced to North America in 2002, via wood packaging material, about a decade before its detection. The subsequent spread of the beetle was perhaps facilitated by the movement of infested nursery stock, logs, and firewood [119]. It is the most destructive and costly invasive forest insect in the United States of America [120], with economic losses exceeding USD 12.5 billion as well as negative effects on biodiversity and human health [121]. Modeling by Liang and Fei (2014) [122] has projected that climate change would result in a more northern distribution of the beetle in North America, and a subsequent long-lasting risk to ash in those areas. However, it is expected that the southward invasion of the emerald ash borer in North America would be limited within a warming climate change scenario, as the beetle requires strong seasonality with a long winter season. Extreme climate events associated with climate change could reduce the efficacy of biological control of the beetle with larval parasitoid species [123].

Tephritids are a diverse family of flies containing several invasive species causing substantial economic damage when their larvae develop in fruits of high market value. *Bactrocera oleae* on olive trees, *B. dorsalis* on several dozen fruit plant species, and *Ceratitis capitata* on a moderate number of tree crops are among the most relevant invasive species in the family. Tephritids have been able to expand geographically following the expansion of cultivation of their hosts, international trade, and because climate change has allowed their winter survival and reproduction in habitats otherwise unsuitable for the species. This has been the case of *B. oleae* and the new areas of olive trees in California and Mexico and

potentially in areas where olives could be grown in the future [124]; although *B. dorsalis* is primarily tropical and subtropical, the risk of direct economic losses from an incursion into temperate areas is low, but climate modification by global warming could allow a rapid increase in fly populations in mild seasons [125]. *C. capitata*, which occurs in rather temperate areas, could expand to colder areas due to its capacity to overwinter as larvae in fruits stored in warm places and then spread through the international trade of oranges, mandarins, and lemons [126].

Red palm weevil (*Rhynchophorus ferrugineus*) (Near East, Africa, Europe) is one of the most economically damaging insect pests of various palm species, including coconut and date palm [127,128]. Native to south-east Asia and Melanesia, the annual losses due to death and removal of palms severely infested by red palm weevil in the Gulf region of the Near East have been estimated to range from USD 5.2 million to 25.9 million, despite all means of integrated control [129,130]. First detected on date palms in the Near East in the mid-1980s, it subsequently spread to other countries in the Near East, and to Africa and Europe. Its global distribution has probably been assisted by the movement of palm offshoots as planting material. It has been reported in 45 countries, and ecological-niche modeling predicts that it could expand its range even further [131], resulting in its expansion towards the north of China [132].

Fall armyworm (*Spodoptera frugiperda*) (native to tropical and-subtropical areas of the Americas) is a noctuid moth with a host range of hundreds of plant species, causing damages in forage grasses and cereals, causing particularly high losses on maize. In the last ten years, it has spread to sub-Saharan Africa and Egypt, all over southern and eastern Asia [133], several eastern Mediterranean areas [134], and the Australian continent. Such expansion in warmer climates is due to its adaptability to different environments, high dispersal capacity, the wide range of potential hosts, and the intense international trade of commodities attacked by the larvae or pupae of the moth [135]. A reduction or even partial disappearance of the species in the southern American hemisphere, due to the warmer and drier conditions expected there, is predicted [135]. In the European Union, some southern warm Mediterranean areas could provide suitable climatic conditions for the establishment of the species [136].

Desert locust (*Schistocerca gregaria*) (Africa, western and southern Asia [137], and occasionally south-west Europe) swarms and voraciously feeds on key crops such as maize and sorghum, pastures, and any green vegetation, thereby significantly affecting smallholder farmers and pastoralists [138]. It shows periodic changes in its body form and can change over generations, in response to environmental conditions, from a non-migratory form to a gregarious, migratory phase in which it may travel long distances, finally invading new areas. In general, the desert locust breeds extensively in semi-arid zones, threatening the livelihoods of people in over 65 countries. However, there is also a much less well-known subspecies, *S. gregaria* subsp. *flaviventris*, that occupies a limited area in southern Africa; the potential of these subspecies to pose a threat in the future should be investigated [139]. Outbreaks of desert locusts have been recorded over many centuries. The increases in temperature and rainfall over desert areas, and the strong winds associated with tropical cyclones, provide a new favorable environment for breeding, development, and migration. Consequently, climate change may have an impact on future migration routes of the desert locust.

The old world date bug (dubas bug), *Ommatissus lybicus*, has caused heavy yield losses over the last ten years in the Arabian Peninsula [140]. Evidence for the effect of current climate change on date palm pests is still limited. The northern part of Oman is currently at significant risk of dubas bug infestation. The infestation level is predicted to remain high in 2050 and 2070, and integrated pest management will be of great importance in the future to control this insect pest [141]. Climatic suitability studies have been used to develop distribution maps that also indicate areas projected to become unsuitable for the dubas bug and, therefore, potentially suitable for expansion of date palm production [141].

Changes in the pest's biology and ecology due to global warming have also been observed over the last decade in Iraq.

Parlatoria date scale insect (*Parlatoria blanchardii*) (Near East) is widely distributed throughout most of the date-growing regions of the world, namely Algeria, Egypt, Libya, Iraq, the Islamic Republic of Iran, Israel, Morocco, Saudi Arabia, Oman, and the United Arab Emirates. It is easily spread to new locations through offshoots of the host plants [142], and it infests all parts of the date palm and cause the fruits to shrink, rendering them unmarketable [143]. The Parlatoria date scale is one example of an insect pest that may be less of a problem in the future. In the climate change scenarios, considering three time series (2011–2040, 2041–2070, and 2071–2100) for a district near Luxor in Egypt, all expected values for the number of nymphs, adult females, and the total population across all-time series and RCP scenarios were smaller compared with the current population [144]. The total population was, therefore, projected to be smaller in 2071–2100.

Among forest pests, some bark beetle species are examples of insects in which the impact of climate change has been projected to predict intra- and inter-continental movement. In the pine beetle of western North America, *Dendroctonus ponderosae*, and the bark beetle in European *Picea*, *Ips typographus*, a physiological model was used and concluded that the strategy to maintain univoltine populations will promote both populations to shift northward in native areas with warming throughout the century. However, the tendency of expansion of *Pinus* and *Picea* habitats supporting a second generation in both continents can cause inter-continental establishment of both species [145].

2.3.2. Plant Pathogens

Faba bean necrotic yellows virus (FBNYV) (Near East) is insect-transmitted and causes yellowing, stunting, and poor pod setting in chickpea, faba bean, and lentil crops. During the past three decades, a high incidence of insect-transmitted viruses has led to a substantial reduction in crop yield in Egypt, the Islamic Republic of Iran, Jordan, the Syrian Arab Republic, and Tunisia [146]. With changes in the weather and the crop varieties used, viruses that previously occurred rarely may suddenly dominate, as happened in central Egypt during the 1991/1992 growing season. This has had substantial long-term impacts, with the production of faba bean subsequently having been forced to move from central to northern Egypt (the Nile Delta), where the weather and possibly other conditions do not permit the frequent occurrence of high populations of aphid vectors that carry the virus. The average temperature in the delta region is lower than in central Egypt, which is presumably one reason why aphid populations are often lower in the delta region. However, with climate change and higher temperatures expected in the years to come, epidemics of FBNYV (or possibly other viruses) on faba bean may perhaps emerge in the delta region of Egypt in the near future, unless appropriate agricultural practices and crop protection methods are developed and implemented.

Coffee leaf rust (*Hemileia vastatrix*) (Africa, Asia, Latin America and the Caribbean) is one of the main factors limiting arabica coffee yield worldwide. It has caused serious losses (up to 50–60 percent yield losses) in some Central American countries, such as Colombia and Mexico, in the past few years. One of the factors that promoted the occurrence of the rust epidemics in Central America was a reduction in the diurnal thermal amplitude, decreasing the latency period of the disease [147], which promotes the rapid increase of the pathogen population. Similarly, the pathogen's incubation period may be reduced with global warming with more pathogen cycles within a growing season [25]. Consequently, the risk of coffee leaf rust epidemics might increase in the future unless other factors, such as a reduced ability of the pathogen to infect coffee plants, change. Less cold winters can increase the amount of inoculum in anticipation of pathogen infection [147], but cold temperatures may not present a problem for the pathogen [148] and the pathogen can adapt to different climates [147].

Banana Fusarium wilt (*Fusarium oxysporum* f. sp. *cubense* tropical race 4) (Australia, Jordan, Mozambique, Colombia, Asia, Near East) was found in 1990 in eastern Asia,

parts of south-east Asia, and northern Australia, attacking ‘Cavendish’ clones in the tropics [149,150]. The planting of ‘Cavendish’, a resistant cultivar, was the solution found for the devastation caused by race 1 of the pathogen [149,151]. Since 2010, tropical race 4 (TR4) has spread to south and south-east Asian countries (India, the Lao People’s Democratic Republic, Myanmar, Pakistan, and Vietnam), the Near East (Israel, Jordan, Lebanon, and Oman), Africa (Mozambique) [152], and South America (Colombia) [153]. High temperatures (24–34 °C) and extreme environmental events, including cyclones and tropical storms, may increase the risk of the disease, particularly when ‘Cavendish’ banana plants suffer from waterlogged soil [154,155].

Xylella fastidiosa (Americas, southern Europe, Near East) is a xylem-limited, Gram-negative bacterium that causes diseases on economically important crops, such as grapevine, citrus, olive, almond, peach, and coffee, and in ornamental and forestry plants [156,157]. It was reported in North and South America and Asia in the 1980s [158] and Italy in 2013 [159]. *X. fastidiosa* is transmitted by numerous species of sap-sucking hopper insects, including spittlebug and sharpshooter leafhoppers, mainly of the Aphrophoridae and Cicadellidae families [158,160]. Models of species bioclimatic distribution have shown that the bacterium has the potential to expand beyond its current distribution and may reach other areas in Italy and elsewhere in Europe [161,162]. The subspecies *fastidiosa* represents a threat to most of Europe [163] and the Mediterranean basin, particularly Lebanon, runs the highest risk for the establishment and spread of *X. fastidiosa* [164], followed by Turkey, Greece, Morocco, and Tunisia. Based on disease symptoms and laboratory analysis, *X. fastidiosa* has been found also associated with almond leaf scorch and Pierce’s disease in grapevine in several provinces of the Islamic Republic of Iran [165], indicating that it will start to spread to neighboring countries in the Near East. However, the complete “host plant-vector-bacterium” relationship should also be considered when predicting future risk [161]. Fortunately, vector performance is likely to suffer due to supra-optimal temperature and suboptimal humidity conditions, as recently simulated by Godefroid et al. (2020) [166].

Oomycetes, including *Phytophthora infestans* and *Plasmopara viticola* (global), will potentially be displaced poleward because of climate change and will present a challenge for plant protection, mainly in the northern hemisphere [20]. *P. infestans*, the oomycete that causes late blight in potatoes and tomato, has a great capacity to adapt to changing conditions. It first occurred in Europe in the 1840s and caused the Great Irish Potato Famine and still today continues to be the main threat to potato production. It is favored by cold summers and wet weather conditions, particularly in northern European countries, with risk of severe epidemics in the future and several studies suggested an increased risk in several countries [167–170]. Studies in Egypt on the impact of climate change on tomato and potato late blight have shown how warmer winter weather affects their incidence and management [171,172]. Up to three additional fungicide sprays would, therefore, be needed each growing season in Egypt during the coming decades (2025–2100). Favorable conditions in the winter allow a build-up of pathogen inoculum on early cultivars early in the growing season, leading to a tendency for the blight to appear in later-planted potato crops. It can, therefore, be expected that climate change will promote late blight epidemics in the future [172].

Downy mildew of grapevine, caused by the oomycete *P. viticola*, is another serious disease resulting in 5–40% production losses, in most grape-growing regions. As many of these regions have a temperate climate with suboptimal temperatures for the pathogen, an increase in air temperature will favor the occurrence of the disease. Studies considering future climate change scenarios have, therefore, projected earlier disease outbreaks that require more treatments to control [26,94,111]. Short-term studies carried out in phytotrons have also confirmed an increased severity of grape downy mildew under simulated climate change conditions [173].

The presence of mycotoxin-producing fungi in crops are in general expected to increase as a result of climate change. However, the complexity of the fungal flora associated with each crop and its interaction with the environment makes it difficult to draw conclusions

without conducting specific studies. For instance, the work carried out by Battilani et al. (2016) [174] indicates that global warming could extend the northern limit of aflatoxin risk in maize in Europe, and [6] have made quantitative estimations of the impact of climate change on mycotoxin occurrence. Medina et al. (2017) [175] reviewed the impact of climate change on mycotoxigenic fungi by key spoilage fungi in cereals and nuts, including *Alternaria*, *Aspergillus*, *Fusarium*, and *Penicillium* species. The growth of *Aspergillus flavus*, responsible for producing aflatoxin B1, appears to be unaffected by simulated climate change scenarios. However, a significant stimulation of aflatoxin B1 production has been found both in vitro and in vivo in maize. In contrast, the behavior of other *Aspergillus* species, responsible for ochratoxin A contamination, and *Fusarium verticillioides*, producing fumonisins, suggests that some species are more resilient to climate change than others, especially in terms of mycotoxin production. In addition, climate change could also influence the mycotoxin production of emerging pathogens, such as the increases shown experimentally by Siciliano et al. (2017) [176,177] in *Alternaria* and *Myrothecium* species. Furthermore, acclimatization of mycotoxigenic fungal pathogens to climate change factors may result in increased disease and perhaps mycotoxin contamination of staple cereals as well as other crops. Thus, managing mycotoxin risks will remain a great challenge in the future [114], as climate change could worsen the situation [178].

2.4. Main Pathways Used by Pests, Also in Relation to Global Trade

Pest dispersal occurs through both natural and anthropogenic processes, accelerated during the past decades by the globalization of markets for plants and plant products, including food, planting material, and wood. Global travel and the trade of agricultural products have moved crops, weeds, pathogens, and insect pests away from their native environments to new ones. Horticultural trade is known to improve the spread of emerging plant pathogens outside of their distributional range [179]. In total, 5 to 61 new arrivals of plant pathogens by 2020 were forecasted in the US using historical data on merchandise import volumes and non-native species arrival rates [180]. Indeed, US border inspection points intercepted more than 50,000 non-indigenous plant pests in 2000, compared to around 20,000 in 1984 [181]. Trade network connectivity is a strong predictor of plant pest invasion in Europe and the Mediterranean region. Patterns of invasion are mainly governed by global trade networks connecting source areas for non-native species and the dispersal of those species through multiple trade networks [182].

In fact, the increased market globalization in recent years, coupled with increased temperatures, has led to a situation that is highly favorable to pest movement and establishment, with concomitant increases in the risk of severe yield losses [4,31]. Newly introduced crops may expand pest distribution, and the introduction of new pests into a completely new ecosystem may cause extremely serious damage because pests and hosts may not have coevolved together. The coevolution of plants and their pests [183] can create a stable balance between hosts and pests in their endemic ecosystems. Anderson et al. (2004) [184] reported that half of all emerging diseases of plants were spread by global travel and trade, while natural spread, assisted by weather events, is the second most important factor. Since the early 2000s, global trade has expanded exponentially, with effects on pest movement. Considerable national and international efforts have been made to reduce the risk of the international movement of pests [185], including the publication and implementation of International Standards for Phytosanitary Measures (ISPMs), with guidance on how to conduct pest risk analysis (PRA) to determine the risk of introduction (entry and establishment) and spread of pests and to select which measures to apply to prevent introduction. Such phytosanitary measures are generally applied with reference to pathway risks and are periodically reviewed.

Wood packaging, such as pallets and dunnage, has played a major role in spreading plant pests, such as the wood beetle *Anoplophora glabripennis* (Coleoptera: Cerambycidae) [133,186], a polyphagous species. Native to China and the Republic of Korea, it has been introduced to the United States of America and Canada through infested wood

packaging and it has also been detected in several European countries. Careful inspection and treatment of wood packaging material is an international requirement to prevent new introductions. Modeling efforts to predict the geographical distribution of the beetle have shown that climate change may alter its distribution and impact [187]. Wood packaging has also been indicated as the likely pathway of many bark beetle species. Movement of the pine wilt nematode, *Bursaphelenicus xylophilus*, or its insect vector through untreated wood packaging material, has also been reported [188].

Seeds, planting material, soil, and growing media, due to the globalization of their production and marketing, are among the main causes of the recent and rapid spread of pests to new regions. Some newly introduced pathogens and insect pests typical of warm areas have spread readily in temperate regions because of temperature increases. Mature plants can be an important source of live insects, including mites, aphids, caterpillars, leaf miners, and thrips. Particularly in the vegetable sector, the recent spread of old and new seed-borne pathogens, such as *Alternaria* spp., *Fusarium equiseti*, and *Myrothecium* spp., in several countries is linked to the fact that their diffusion is favored by market globalization and amplified by global warming [189]. Tomato brown rugose fruit virus is another example of a pathogen that emerged in the last few years and spread quickly with seed movement. Even low levels of seed infection can lead to the rapid emergence of new diseases in distant geographical areas [190–192].

The ornamental industry, due to its international nature, is greatly affected by the introduction of pests through infected material [193]. A vast pool of alien pests and diseases of ornamental species may already be present in gardens, but not able to establish or spread until there are novel climatic conditions [194]. Only ornamental plants micropropagated through tissue culture (generally foliage plants) have a considerably reduced risk of infection by pathogens, provided that they are kept clean, consequently avoiding reinfection [195]. Ornamental plants, whether started from seed, from cuttings, or from cane sections, can easily harbor pests [196]. Several of the most damaging insect and mite pests of greenhouse crops have originated by importing infected plant material and have established quickly because of the favorable environmental conditions in greenhouses [197,198]. Ornamental coffee plants imported from Costa Rica and infected by *Xylella fastidiosa* subsp. *pauca* are considered the possible source of this destructive pathogen in Europe [199].

Soil and potting media, often imported, can harbor soil-borne pathogens (e.g., *Fusarium* spp., nematodes), the larvae of insect pests, and weed seeds. This has been well documented in relation to peat and other media used in the ornamental industry and in nurseries. Contamination of growing substrates by soil-borne pathogens (e.g., *Fusarium oxysporum*, *Pythium* spp., *Rhizoctonia solani*) results in incomplete disinfestation and in early infection of young plants [200].

In addition to the pest risk posed by the movement of seed, planting material, soil and growing media described above, the increasing online market that spreads planting material around the world poses a new type of threat. This planting material is often of low quality and generally not subject to phytosanitary control. This potential new pathway for pest introduction should be given due consideration in the future.

Conveyances, cargo, and movement of animals are other important pathways. Tractors, cars, trucks, trains, ships, airplanes, containers, re-sold used agricultural equipment, and other vehicles are common means for passively moving pests. Historically, the spread of pests is considered to be directly related to the speed of conveyances. The global shipping network is widely recognized as a pathway for vectoring invasive species. One insect species that is known to have spread throughout the world by shipping, including transportation by ships and shipping containers, is the spongy moth, *Lymantria dispar*. This species may be introduced into a new area when the port has a suitable climate for the survival and establishment of the species. Two subspecies, with different geographical origins, are known today, and the global distribution threat from the Asian subspecies has been estimated using a CLIMEX model [201]. The heteropteran brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), is another example of an invasive

insect travelling mainly through international trade as a contaminant of non-regulated goods such as machinery, containers, and vehicles, but also by passengers and to a lesser extent through movement of plant material. It is highly polyphagous, feeding on more than 300 plant-host species, including food crops, forest trees, and ornamentals. This pest has caused severe economic losses in hazelnut crops in the Republic of Georgia and fruit crops in Italy since its introduction—most likely from North America. A detailed report of a pest risk assessment for the introduction and establishment of *H. halys* can be found in Burne (2019) [202].

Business travelers and tourists can readily introduce pests, particularly in the absence of strict controls at points of entry. Leisure travel, in particular, is often associated with people bringing food, seeds, or exotic plants, and these can be infested with pests or can themselves be a pest. To counter this, an increasing number of countries are establishing campaigns at points of entry (airports and harbors), aimed at increasing public awareness of the threat to biosecurity posed by the movement of plants and plant parts. Many countries inspect baggage and mail for food and other biosecurity-risk material and encourage incoming passengers to declare potential biosecurity risks. They screen passengers and their luggage using X-rays, detector dogs, and manual inspections. Passengers with risk materials may be fined or even refused entry. In this respect, countries such as Australia, New Zealand, and the United States of America [181] have a long history of strict control, as well as of collecting and reporting data on interceptions.

Natural dispersal, without direct human assistance, remains important for pest introduction. There are examples where native and non-native pests have significantly expanded their geographical ranges naturally, usually in response to significant changes in host distribution or climate. Increasing temperatures are likely the major climate factor facilitating range expansion in pests, especially at higher latitudes and altitudes. In Europe, for example, higher winter temperatures have increased larval survival and nocturnal adult dispersal of the pine processionary moth, *Thaumetopoea pityocampa*, allowing the northern expansion of its range [203]. In addition, wind and storms can transport spores of pathogens over long distances, even across continents. For example, changing wind or storm patterns are projected to promote the future distribution of wheat stem rust caused by *Puccinia graminis* [204]. Additionally, myrtle rust (*Austropuccinia psidii*), detected for the first time in Australia in 2010 on the central coast of New South Wales, is spreading and can now be found in a range of native forest ecosystems, with disease impacts ranging from minor leaf spots to severe shoot and stem blight and tree dieback [205]. The distribution of several pests, including fruit flies, can be affected by hurricanes in the Caribbean, Central America, and the southeastern United States of America. For example, Flitters (1963) [206] observed that several insect species emerged in unusually large numbers in Texas after Hurricane Carla, suggesting that they had been transported there by the cyclone from distant locations.

3. Concluding Remarks

Most studies indicate that pest risk will generally increase in agricultural ecosystems under climate change scenarios [21,22,30,207,208], especially in today's cooler arctic, boreal, temperate, and subtropical regions. Evidence suggests that all climates will be impacted, but that the nature and extent of the impact will vary with the ability of production systems and natural ecosystems to adapt and evolve. This is also mostly true for pathogens and insect pests in forestry [16]. The impacts of global trade and invasion pathways may interact with climate change in many and often complex ways. Understanding them can guide choices about mitigation and adaptation measures.

To conclude, preventive (including biosecurity), mitigation, and adaptation measures are strongly needed [13,209–213] to reduce the projected increases in pest risk in agriculture, horticulture, and forestry. Therefore, research to support these measures should have priority in the future. Taken together, climate change and globalization support the spread of current plant pests and also the emergence of new pest threats. Sustainable

management of pests is urgently needed. It requires holistic solutions, including effective quarantine and phytosanitary regulations, globally coordinated diagnostic and surveillance systems, pest risk and epidemic modeling integrated in risk analysis, and preparedness for proactive management [214]. More information related to holistic, effective and sustainable strategies to manage various plant pests can be derived in recently published articles (e.g., [3,12,13,214]). These approaches are needed to reduce the detrimental effects of pests on the quality and quantity of plant production, to provide food security for an increasing human population.

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