Working Paper

Scientific Linkages Between Climate Change and (Transboundary) Crop Pest and Disease Outbreaks

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3 Other experts point to a more conservative estimate with global average losses falling in the range between 15-20 percent. Of course, in localised settings, untreated pest damage could vary widely, reaching as high as 100% in the case of locust swarms, for instance. Of further note, pesticide use might increase losses because it can lead to pest resurgence and resistance.
4 FAO. Climate Related Transboundary Pests and Diseases. Available online: http://www.fao.org/3/a-ai785e.pdf.
5 Sánchez-Bayo, Wyckhuys., Worldwide decline of the entomofauna: A review of its drivers, Biological Conservation, Volume 232, 2019

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1 Introduction

"Devastating crop diseases suddenly emerge from obscurity—often becoming epidemic far from their place of origin. In the 1840s, for example, a hitherto obscure fungus from Mexico devastated the Irish potato crop for several years, bringing about a famine that killed a million people. It would not be at all surprising if a changing climate led to conditions that caused similar epidemics." [1]

The latest estimates by the Food and Agriculture Organisation (FAO) of the United Nations (UN) point to between 20 and 40 percent of all annual food crops grown worldwide lost to plant pests and diseases.[2,3] Transboundary and transoceanic expansion of pest and disease ranges have been exacerbated by international trade and travel. Climate change, habitat destruction and biodiversity losses have facilitated the establishment of major agricultural pests and diseases in previously inhospitable environments. As with all pest outbreaks, prevention is far more cost-effective (both fiscally and environmentally) than dealing with full-blown crises, and what is more, plant pests and diseases are often impossible to eradicate once they have established themselves.

That climate change has increased the frequency and intensity of pest outbreaks is often regarded as a natural corollary in the media, to the extent that the link has evolved into a truism. However, the empirical evidence supported by scientific enquiry and evidence for this linkage is scant in published research, and is rarely cited by media proponents of the "climate change – pest outbreak" thesis. While much of the published scientific literature points to significant uncertainties in how crop pests and diseases are likely to evolve and migrate in a changing climate, there is, however, an overarching message from this literature that farmers should at the minimum brace themselves for new and more intense pest and disease pressures in the coming years owing to climate change. Already, the FAO has proclaimed that the "the spread of crop pests and diseases across physical and political boundaries threatens food security and is a global problem common to all countries and all regions". [4]

Motivated by the recent desert locust upsurge (2019-2022) in the Horn of Africa, the aim of this working paper is to review how climate change and other anthropogenic drivers affect populations of pests and crop diseases as well as their geographical expansion. The paper focusses primarily on the adaptation of pest insects to climate change, noting the precipitous fall in beneficial and other insect numbers around the world.[5] A key message of the paper is that plant pests and diseases do not confine themselves to national border and water bodies, including oceans will not prevent their spread, either. For this reason, plant pest and disease surveillance, improved detection systems, and global predictive pest and disease modelling are necessary to mitigate future outbreaks to protect global food supplies and ecosystems.

The working paper is divided into five sections. The next section provides an exhaustive list of the dimensions of

1. https://www.economist.com/science-and-technology/2019/04/17/understanding-how-crop-diseases-and-climate-change-interact-is-vital
2 https://www.fao.org/news/story/en/item/1187738/icode/#:~:text=FAO%20estimates%20that%20annually%20between,insects%20around%20US%2470%20billion
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4 FAO. Climate Related Transboundary Pests and Diseases. Available online: http://www.fao.org/3/a-ai785e.pdf.
5 Sánchez-Bayo, Wyckhuys., Worldwide decline of the entomofauna: A review of its drivers, Biological Conservation, Volume 232, 2019

climate change that may give rise to increased crop pest and disease pressure and pestilence in existing and new geographical zones, focusing on insect pests. If pests and diseases spread and do indeed establish themselves in new geographical areas, there is a need for their early identification. Consequently, section three provides a literature survey of existing detection measures for the purpose of mitigation, which are in the realm of machine learning (ML)-driven algorithms in the field of image recognition – typically object detection for pests and image classification predominantly for crop diseases – and their success rates. Section four proposes a plan to integrate these technologies into a holistic early warning and early control system (centred in the Horn of Africa, a region that is perennially prone to climate vulnerabilities) and in partnership with the Intergovernmental Authority on Development (IGAD), whose remit is to strengthen resilience in farming systems, while safeguarding national and regional food security. Finally, section five provides some concluding remarks, paving the way forward, especially in terms of governance.

2 How a changing climate affects the dynamics of pest and disease expansion and migration

Before delving into the scientific state of the art about climate change impact on crop pests and diseases and to set the stage for this working paper, Box 1 (next page) provides a simplified overview of why certain pests and diseases show outbreak dynamics, and why their transboundary migration cannot be ignored during the climate crisis.

First of all, it is also important to mention that pests and diseases are able to undergo rapid evolutionary changes through natural selection within the timescale of climate warming.[6] Invasive species, by definition, have succeeded in areas outside of their native range and therefore have higher adaptive capacity relative to native species.[7,8] Evolution and adaptation are the inherent mechanisms that explain why pests and diseases pose a consequential threat (both localised and transboundary) under a changing climate. Natural selection also explains why an increasing number of insect pests have become resistant to pesticides.[9]

2.1 Sea temperature rise and ocean anomalies

Outbreaks of one of the most destructive pests, the desert locust,

6 Tougeron, K., Brodeur, J., Le Lann, C. and van Baaren, J. (2020), How climate change affects the seasonal ecology of insect parasitoids. Ecol Entomol, 45: 167-181. https://doi.org/10.1111/een.12792
7 Logan, M.L., Minnaar, I.A., Keegan, K.M. and Clusella-Trullas, S. (2020), The evolutionary potential of an insect invader under climate change*. Evolution, 74: 132-144. https://doi.org/10.1111/evo.13862
8 Snell-Rood, E.C.; Kobiela, M.E.; Sikkink, K.L.; Shephard, A.M. Mechanisms of plastic rescue in novel environments. Annu. Rev. Ecol. Evol. Syst. 2018, 49, 331–354.
9 "Repeated use of the same class of pesticides to control a pest can cause undesirable changes in the gene pool of a pest leading to another form of artificial selection, pesticide resistance. When a pesticide is first used, a small proportion of the pest population may survive exposure to the material due to their distinct genetic makeup. These individuals pass along the genes for resistance to the next generation. Subsequent uses of the pesticide increase the proportion of less-susceptible individuals in the population. Through this process of selection, the population gradually develops resistance to the pesticide."(https://www.canr.msu.edu/grapes/integrated_pest_management/how-pesticide-resistance-develops).
11 https://earthobservatory.nasa.gov/images/4905/locusts-plague-northern-and-western-africa

which continue to wreak havoc in many parts of Africa, usually occur under a confluence of ideal meteorological conditions. These are periods of sustained heavy rainfall that succeed periods of sustained dryness/ drought. For instance, the last serious transboundary locust outbreak in West Africa over 2003-05, had its origins[10] in Northern and Western Africa, in which unseasonal heavy rain fell for two days over the region, where some areas received more than 100 mm of rain whereas they normally receive about 1 mm of rain in a year. Consequently, with growth of new vegetation, ecological

Box 1. Transboundary agricultural pests and diseases under climate change

- Migratory insects and diseases, referred to as transboundary plant pests, can spread to a number of countries and can reach epidemic proportions in which control and management require cooperation between those countries. Each year, plant diseases alone cost the global economy over $220 billion, and invasive insects at least $70 billion.[1]
- The International Institute for Sustainable Development (IISD) reports[2] that climate change is expected to affect, where crops are cultivated, the distribution of plant pests, the introduction of new pests, the frequency of major pest outbreaks and the risk of pesticide residues in food. The consequences of climate change and its effect on plant pests could cause severe reductions in crop production, such as an increasing number of crops to fail, and a greater potential reliance on synthetic pesticides, which are highly toxic to both the environment and human health.
- While global trade and international passenger travel are well-known mechanisms to incur the spread of pests and diseases potentially contributing to their epidemic and pandemic proportions, the primary drivers that influence a change in plant pest dynamics[3] are climatic conditions such as increases in temperature, variability in rainfall intensity and distribution, change in seasonality, drought, carbon dioxide concentration in the atmosphere and extreme high rainfall events (e.g., hurricanes, storms, floods). Other factors such as pest characteristics (e.g., lifecycle, optimal growth conditions, and host interaction) and intrinsic ecosystem characteristics (e.g., monoculture, biodiversity) will affect these dynamics.
- As a result, there is a strong likelihood of a greater number of emerging plant pests, which come into contact with new hosts that do not necessarily have an appropriate level of resistance, or are introduced in the absence of naturally occurring biological control agents. New and more virulent and aggressive strains of plant pathogens are likely to develop as experienced recently for wheat, coffee and cassava.[4]
- So far, climate change has significantly affected the spread and adaptation of insect vectors such as flies, thrips, and aphids, resulting in higher frequency and wider spread of diseases transmitted by these vectors and causing substantial damage to infested crops.[5]
- Although the specific implications of climate change on plant pests and diseases are difficult to predict, it seems possible to project in what conditions such pests and diseases would thrive.
- For example, the desert locust, which is one of the most dangerous and damaging of all migratory pests, has survived multiple climate changes and adapted to semi-arid or desert environments where rainfall is scarce and irregular.
- Potential changes in temperature, rainfall and wind patterns associated with climate change are expected to have dramatic effects on the desert locust, such as causing faster development and allowing seasonal breeding to commence earlier and last longer[6]. Similarly, increased El Niño events due to climate change are likely to have an impact on other locust species (e.g., Italian, Moroccan, and Migratory).
- In 2021, International Plant Protection Convention (IPPC) Secretariat published a *Scientific review of the impact of climate change on plant pests – A global challenge to prevent and mitigate plant pest risks in agriculture, forestry and ecosystems.*[7] The scientific review informs that global heating increases the risk of pests spreading in agricultural and forestry ecosystems, especially in cooler Arctic, boreal, temperate and subtropical regions. The review warns that a single, unusually warm winter may be sufficient to assist the establishment of invasive pests. The IPPC analysed 15 pests that have already expanded their host range or distribution at least in part due to climate change. These pests are divided into four groups: 1) insects; 2) pathogens and 3) nematodes and 4) weeds, as shown in the table on the next page.

Table 1. Fifteen pests that have already expanded their host range or distribution at least in part due to climate change

Insects	**Plant Pathogens**	**Nematodes**	**Weeds**
Emerald ash borer (Agrilus planipennis) (Asia, Europe, North America)	Coffee leaf rust (Hemileia vastatrix) (Africa, Asia, Latin America)	Citrus lesion nematode (Pratylenchus coffeae) (global)	Butterfly bush (Buddleja davidii) (global)
Tephritid fruit flies (global)	Banana Fusarium wilt (Fusarium oxysporum f. sp. cubense) TR4 (Australia, Mozambique, Colombia, Asia, Near East)	Soybean cyst nematode (Heterodera glycines) (global)	Serrated tussock grass (Nassella trichotoma) (global)
Red palm weevil (Rhynchophorus ferrugineus) (Near East, Africa, Europe)	Xylella fastidiosa (Americas, southern Europe, Near East)	Pine wilt nematode (Bursaphelenchus xylophilus) (North America and eastern Asia)	
Fall armyworm (Spodoptera frugiperda) (Americas, Africa, Asia)	Oomycetes, including Phytophthora infestans and Plasmopara viticola (global)		
Desert locust (Schistocerca gregaria) (Africa, western and southern Asia)	Fungi producing mycotoxins, e.g., Magnaporthe oryzae and Botrytis (global)		

Source: IPPC Secretariat. 2021. Scientific review of the impact of climate change on plant pests – A global challenge to prevent and mitigate plant pest risks in agriculture, forestry and ecosystems. Rome. FAO on behalf of the IPPC Secretariat. https://doi.org/10.4060/cb4769en

- In 2019, at the Meeting of G20 Agricultural Chief Scientists (MACS-G20) on "Recent Challenges of Transboundary Plant Pests and the FAO strategy" listed five important transboundary plant pests[8]
  - Locusts
  - Fall armyworm (moth) - recent emerging pest; feeds on more than 80 crop species (esp. maize)
  - Wheat rust (fungal disease) – distributed worldwide; a recurrent problem amplified with increased rains
  - Banana fusarium wilt (fungal disease) – a new strain of the fungus (TR4) is posing the most serious threat to banana production in Asia, Africa, Near East, Latin America and the Caribbean
  - Bacterium Xylella fastidiosa - a vector-borne pest with 500+ host plants, e.g., olive, grapevine, citrus and coffee.
- In addition, fruit flies and cassava diseases were added to the FAO list of the most destructive transboundary plant pests in the world.

1 http://www.fao.org/news/story/en/item/1402920/icode/
2 http://sdg.iisd.org/commentary/guest-articles/potential-effects-of-climate-change-on-transboundary-plant-pests-and-diseases-faos-response-and-contributions/
3 Skendži´c, S.; Zovko, M.; Živkovi´c, I.P.; Leši´c, V.; Lemi´c, D. The Impact of Climate Change on Agricultural Insect Pests. Insects 2021, 12, 440.
4 http://sdg.iisd.org/commentary/guest-articles/potential-effects-of-climate-change-on-transboundary-plant-pests-and-diseases-faos-response-and-contributions/
5 ibid.
6. https://reliefweb.int/report/kenya/technical-paper-desert-locust-and-climate-weather-and-bio-climatic-case-study-desert
7 IPPC Secretariat. 2021. Scientific review of the impact of climate change on plant pests – A global challenge to prevent and mitigate plant pest risks in agriculture, forestry and ecosystems. Rome. FAO on behalf of the IPPC Secretariat. https://doi.org/10.4060/cb4769en
8 https://www.macs-g20.org/fileadmin/macs/Annual_Meetings/2019_Japan/Recent_Challenges_of_Transboundary_Plant_Pests_and_the_FAO_Stragety_IPPC.pdf

conditions remained favourable for at least six months and allowed several successive generations of rapid desert locust breeding.[11]

Similarly, the origins of the recent desert locust crisis (2019-2022) can be attributed to irregular climatic events (see Box 2).

The proliferation of desert locusts in Eastern Africa and in Western and Southern Asia is intrinsically linked with weather dynamics of the Indian Ocean[12], the warmest of the five oceans

Box 2: A closer look at the origins of the current desert locust upsurge

- The IOD governs sea surface temperatures in the Indian Ocean, and in 'positive phase' the western Indian Ocean becomes warmer relative to the eastern part of the ocean, which can trigger cyclones and extreme rainfall. The IOD was in positive phase in the June-December period of both 2018 and 2019. In October 2019, the dipole reached its most extreme positive level in 40 years (see figure 1).

Figure 1: Indian Ocean Dipole surface temperature anomaly[1] and desert locust outbreaks[2]

Source: NOAA Climate.gov

Source: Showler et al. (2021)

- The Arabian Peninsula – the land mass between East Africa and Asia comprising Saudi Arabia, Yemen, Oman, Kuwait, Qatar, Bahrain and the United Arab Emirates – was struck by unusual and severe cyclones between 2018 and 2019. When the first storm – Cyclone Mekunu – hit the Peninsula in May 2018, it filled a vast desert in Saudi Arabia - Rub al Khali (the "Empty Quarter"), with freshwater lakes.
- The moisture caused vegetation to grow in the habitually barren environment, attracting desert locusts to search for food in the area, and provided them with an optimal breeding ground. Upon reaching a threshold density – sufficiently high numbers in a given area – desert locusts changed into their gregarious form, in which they began to swarm, escalating into a transboundary threat.
- By the time a second cyclone hit the same region in October 2018, a critical point was reached in which locusts started to multiply rapidly, increasing their numbers exponentially in just a few months.
- Following a particularly mild winter, locusts survived in large numbers, and in the summer of 2019, the insects began to migrate from the Arab peninsula into the Horn of Africa. As the locusts moved through the Horn, the region was also hit by unusually wet conditions (with precipitation 300 percent higher than normal) as well as more cyclones – allowing the swarms to grow even larger. Overall, the Horn of Africa was hit by eight cyclones in 2019, the largest number in any year since 1976.
- As well as providing the conditions needed for vegetation growth, the cyclones provided winds that enabled the locusts to travel rapidly over long distances, at small energetic cost, yielding more energy for them to reproduce. By the end of 2019, there were swarms recorded in Ethiopia, Eritrea, Somalia, Kenya, Saudi Arabia, Yemen, Egypt, Oman, Iran, India and Pakistan (see Figure 1).

1 https://www.climate.gov/news-features/blogs/enso/meet-enso%E2%80%99s-neighbor-indian-ocean-dipole
2 Showler, A.T.; Ould Babah Ebbe, M.A.; Lecoq, M.; Maeno, K.O. Early Intervention against Desert Locusts: Current Proactive Approach and the Prospect of Sustainable Outbreak Prevention. Agronomy 2021, 11, 312. https://doi.org/10.3390/agronomy11020312

in the world. Weather systems emerging from the Indian Ocean largely depend on the unpredictable natural phenomenon called the Indian Ocean Dipole (IOD), which also has some forbearance on El Niño anomalies.[13]

Warmer water temperatures in the Indian Ocean leads to warmer air to rise that carries with it large amounts of moisture, much of which condenses as clouds and returns as rain.

In recent years, the Indian Ocean has been warmer than usual, leading to a large number of storms. The stronger the dipole, typically the heavier and more diffuse is rainfall, and the more cyclones formed in the western half of the Indian Ocean. Historically, this dipole has stayed within relatively safe limits. However, the difference crossed 2 degrees Celsius in 2018. It is expected to get worse, and more anomalies (positive IOD events) will be frequent due to climate change.[14]

Wenju et al. (2014)[15] have shown that under extreme warming, climate change could cause positive dipole events to increase by a factor of three by 2099, when compared to the period 1900-1999. This suggests an increasing frequency of cyclones and their intensity as well as heavy rains that have the potential to green habitually arid areas, leading to increased desert locust population, and the sufficiently strong winds to facilitate transboundary crises.

Furthermore, there is a temptation to conclude that "historical" breeding grounds that instigated previous locust outbreaks will continue into the future, and all that is needed is to focus resources on surveillance operations on these historical breeding sites (e.g., Mauritania and Morocco: West Africa incursion 2003-05; and Saudi Arabia: recent incursion 2019-2022). However, this is clearly not the case when climate change is added to the picture. Kimathi et al. (2020)[16] analysed 9,134 desert locust occurrence records and applied a ML algorithm to predict potential desert locust breeding sites in East Africa using key climatic factors (temperature and rainfall) and edaphic variables (sand and moisture content). Their research, while confined to East Africa, demonstrated that vast areas of Kenya and Sudan, north eastern regions of Uganda, and south eastern and northern regions of South Sudan are at high risk of providing a conducive breeding environment for desert locusts in the future, as a result of climate change.

The research did not assess non-traditional breeding grounds in other parts of the subcontinent, but it is probable that in these parts similar ideal breeding sites are likely to unfold that could be an important fixture in the future.

In this regard, it is also important to note that with climate change, there is a strong likelihood that desert locusts might not remain in present outbreak range but could expand northwards to

11 Ibid.
12 Salih, A.A.M., Baraibar, M., Mwangi, K.K. et al. Climate change and locust outbreak in East Africa. Nat. Clim. Chang. 10, 584–585 (2020). https://doi.org/10.1038/s41558-020-0835-8
13 Zhang, L., Han, W. Indian Ocean Dipole leads to Atlantic Niño. Nat Commun 12, 5952 (2021). https://doi.org/10.1038/s41467-021-26223
14 An average of four positive-negative IOD events occur during each 30-year period with each event lasting around six months. However, there have been 12 positive IODs since 1980 and no negative events from 1992 until a strong negative event in late 2010. The occurrence of consecutive positive IOD events is extremely rare, and it widely attributable to climate change.
15 Cai, Wenju & Santoso, Agus & Wang, Guojian & Weller, Evan & Wu, Lixin & Ashok, Karumuri & Masumoto, Yukio & Yamagata, Toshio. (2014). Increased frequency of extreme Indian Ocean Dipole events due to greenhouse warming. Nature. 510. 254-8. 10.1038/nature13327.
16 Kimathi, E., Tonnang, H.E.Z., Subramanian, S. et al. Prediction of breeding regions for the desert locust Schistocerca gregaria in East Africa. Sci Rep 10, 11937 (2020). https://doi.org/10.1038/s41598-020-68895-2

Box 3: Desert Locust Case Study: Climate as Compounding Effect on Food Security

At the end of 2019, desert locust swarms infested Eastern Africa and caused widespread damage to crops and pastures, threatening food security and livelihoods (Kimathi et al., 2020; Salih et al., 2020). The FAO estimates that over 200,000 ha of crop and pastureland were damaged, rendering 2 million people in the region acutely food insecure (IGAD, 2020). The desert locust infestation was facilitated by two tropical cyclones that created desert lakes in a usually dry region of Saudi Arabia. Moist soils, warm temperatures and ample vegetation provided a suitable environment for desert locust breeding and migration to Yemen and Somalia, where the pest remained uncontrolled due to conflict and spread to neighbouring countries. A series of political and socioeconomic weaknesses such as armed conflict, limited financial resources, and lack of early actions compounded the impact of the current invasion and made it the most damaging in 70 years (Meynard et al., 2020; Salih et al., 2020). Although desert locusts have been here for centuries, this recent outbreak can be linked to a unique feature of the positive Indian Ocean Dipole event (IOD), in part caused by long-term trends in sea surface temperatures (Wang et al., 2020a). The warming of the western Indian Ocean has increased frequency and intensity of severe weather, including tropical cyclones (Roxy et al., 2014; Murakami H, 2017; Roxy et al., 2017). Under a 1.5° C warmer climate, extreme positive IODs are anticipated to occur twice as often, which could also increase the occurrence of pest outbreaks (Cai et al., 2018). Climate change increases the need for robust adaptation measures, such as transnational early warning systems, biological control mechanisms, crop diversification, and further technological innovations in areas of sound and light stimulants, remote sensing, and modelling for tracking and forecasting of movement (Maeno and Ould Babah Ebbe, 2018; Peng et al., 2020). The desert locust outbreak and the role of the Indian Ocean warming show that the impacts of climate change can increase unpredictable events. Extreme weather events act as a compounding effect, exacerbated further by weak governance systems, political instability, limited financial resources, and poor early warning systems (Meynard et al., 2020).

Source: Bezner Kerr, R., T. Hasegawa, R. Lasco, I. Bhatt, D. Deryng, A. Farrell, H. Gurney-Smith, H. Ju, S. Lluch-Cota, F. Meza, G. Nelson, H. Neufeldt, and P. Thornton, 2022: Food, Fibre, and Other Ecosystem Products. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.

Southern Europe and eastwards into other parts of Asia.[17,18]

The takeaway message here is that increased carbon dioxide (CO2) levels in the atmosphere (anthropogenically-induced) are leading to rising sea temperatures, which in turn can give rise to storm systems and cyclones reaching landfall in regions that rarely witness them, and that climate change can lead to newfound breeding grounds, elsewhere in Africa, Asia and even in Southern Europe.

Furthermore, the latest climate report on "Impacts, Adaptation and Vulnerability", released on 28 February 2022 by the Intergovernmental Panel on Climate Change (IPCC)[19], emphasises the impact of climate change on increased and unpredictable transboundary pest outbreaks and the consequent need for improved governance and early warning system to enhance resilience. The report, representing the work of hundreds of scientists, calls for immediate action on global emissions and uses the 2019 Desert Locust (presented verbatim in Box 3) upsurge as a case study to illustrate climate change as a compounding effect on food insecurity.

Of note, the IPCC report focusses on the impact of pest infestations on

17 Meynard, CN, Gay, P-E, Lecoq, M, Foucart, A, Piou, C, Chapuis, M-P. Climate-driven geographic distribution of the desert locust during recession periods: Subspecies' niche differentiation and relative risks under scenarios of climate change. Glob Change Biol. 2017; 23: 4739– 4749. https://doi.org/10.1111/gcb.13739
18 Chen C, Qian J, Chen X, Hu Z, Sun J, Wei S, Xu K. Geographic Distribution of Desert Locusts in Africa, Asia and Europe Using Multiple Sources of Remote-Sensing Data. Remote Sensing. 2020; 12(21):3593. https://doi.org/10.3390/rs12213593
19 AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability — IPCC

Box 4: Key messages on pest insects in the IPCC climate report

Insect pest expansion northward

"Forest insect pests have expanded northward and severity and outbreak extent has increased in northern North America, northern Eurasia, due to warmer winters reducing mortality and longer growing seasons favouring more generations per year (high confidence)."

Changes in temperate and boreal forest areas

"Climate-change driven increases in forest insect pests have contributed to mortality and changes in carbon dynamics in many temperate and boreal forest areas (very high confidence). The direction of changes in carbon balance and wildfires following insect outbreaks depends on the local forest-insect communities (medium confidence)."

"Under continued climate change, increased temperature, aridity, drought, wildfire (Section 2.5.3.2), and insect infestations (Section 2.4.4.3.3) will tend to increase tree mortality across wide parts of the world (McDowell et al., 2020). Boreal and temperate forest loss to fire, wind, and bark beetles could cause more negative than positive effects for most ecosystem services, including carbon storage to regulate climate change (Sections 2.4.4.3, 2.5.2.6, 2.5.2.7, 2.5.3.4), water supply for people (Section 2.5.3.6.1), timber production (Chapter 5), and hazard protection (Thom and Seidl, 2016)."

Changes in temperate and tropical forest

"Climate change has driven or is contributing to increased tree mortality directly through increased aridity or drought and indirectly through increased wildfire and insect pests in many locations (high confidence). Analyses of causal factors have attributed increasing tree mortality at sites in Africa and North America to anthropogenic climate change and field evidence has detected tree mortality from drought, wildfire, and insect pests in temperate and tropical forests around the world (high confidence)."

Changing rainfall patterns and repeated heat waves may interact with insect outbreaks leading to dieback of forests

"On land, changing rainfall patterns and repeated heat waves may interact with biological factors such as altered plant growth and nutrient allocation under elevated CO2, affecting herbivory rates and insect outbreaks leading to widespread dieback of some forests (e.g. in Australian Eucalypt forests) (Gherlenda et al., 2016; Hoffmann et al., 2019a). Risk assessments typically only consider a single climate hazard without changing variability, potentially underestimating actual risk (Milly et al., 2008; Sadegh et al., 2018; Zscheischler et al., 2018; Terzi et al., 2019; Stockwell et al., 2020;)."

41% of major insect pest species will increase their damage further as climate warms: The effect of warming winters: the case of bark beetle

"Unprecedented outbreaks of spruce beetles occurring from Alaska to Utah in the 1990s were attributed to warm weather that, in Alaska, facilitated a halving of the insect's life cycle from two years to one (Logan et 30 al., 2003). Milder winters and warmer growing seasons were likewise implicated in poleward range expansions and increasing outbreaks of several forest pests (Weed et al., 2013), leading to the current prediction that 41% of major insect pest species will increase their damage further as climate warms, and only 4% will reduce their impacts, while the rest will show mixed responses (Lehmann et al., 2020)."

The effect of higher temperatures in Europe

"In addition, insect infestations related to higher temperatures (Okland et al., 2019) have caused extensive mortality of Norway spruce (Picea abies) across nine European countries (Marini et al., 2017; Mezei et al., 2017). Across the Mediterranean Basin, a combination of drought, wildfire, pest infestations, and livestock grazing has driven tree mortality (Penuelas and Sardans, 2021)."

Insect outbreaks are currently poorly presented in Earth System Models

"Continued climate change substantially increases risk of carbon stored in the biosphere being released into the atmosphere due to increases in processes such as wildfires, tree mortality, insect pest outbreaks, peatland drying and permafrost thaw (high confidence). These phenomena exacerbate self-reinforcing feedbacks between emissions from high-carbon ecosystems (that currently store ~3030–4090 GtC) and increasing global temperatures. Complex interactions of climate change, land use change, carbon dioxide fluxes, and vegetation changes, combined with insect outbreaks and other disturbances, will regulate the future carbon balance of the biosphere, processes incompletely represented in current earth system models."

"Shifts in terrestrial biome and changes in ecosystem processes in response to climate change are most frequently projected with dynamic global vegetation models (DGVMs), or land-surface models that form part of Earth System Models, which use gridded climate variables, atmospheric CO2 concentration and information on soil properties as input variables. Since AR5, most of DGVMs have been upgraded to capture carbon-nitrogen cycle interactions (e.g. Le Quéré et al., 2018), many also include a representation of wildfire, and fire-vegetation interactions (Rabin et al., 2017), and a small number now also accounts for land management (such as wood removal from forests, crop fertilisation harvest of irrigation (Arneth et al., 2017). Other forms of disturbance, such as tree mortality in response to, for example, episodic weather extremes or insect pest outbreaks, are relatively poorly represented, or not at all, although they demonstrably impact calculated carbon cycling (Pugh et al., 2019a)."

Uncertainly of the future of the global land carbon sink as complex interactions between changing climate, atmospheric CO2 levels and events such as pest and disease outbreaks are not captured

"The future of the global land carbon sink (Section 2.4.4.4) nevertheless remains highly uncertain because (i) of regionally complex interactions of climate change and changes in atmospheric CO2 with vegetation, soil and aquatic processes, (ii) episodic events such as heat-waves or droughts (and related impacts through mortality, wildfire or insects, pests and diseases, (Section 2.5.5.2, 2.5.5.3) so far are only incompletely captured in carbon cycle models.

Source: Bezner Kerr, R., T. Hasegawa, R. Lasco, I. Bhatt, D. Deryng, A. Farrell, H. Gurney-Smith, H. Ju, S. Lluch-Cota, F. Meza, G. Nelson, H. Neufeldt, and P. Thornton, 2022: Food, Fibre, and Other Ecosystem Products. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.

forests and tree mortality rather than on agricultural production. Relevant messages are extracted from the report and presented in quotation marks verbatim in Box 4 (next two pages).

2.2 Climate change impacts on non-locust pests and pathogens

Concerning other pests, climate change can directly alter the dynamics of agricultural insect pests, in terms of reproduction, development, survival and geographical dispersal.[21] In terms of indirect effects, climate change affects the relationships between pests, their environment and other insect species such as natural enemies, competitors, vectors and their mutation.

Insects are classified as poikilothermic organisms, meaning that the temperature of the environment regulates their degree of activity. Thus, temperature is probably the most important climatic factor that affects their behaviour, development, reproduction and geographical distribution.

The findings of Chaloner et al. (2021)[22] reveal that "temperature-dependent infection risk ... for 80 fungal and oomycete (fungus-like) crop pathogens will track projected yield changes in 12 crops over the twenty-first century".[23] At higher latitudes, both yields and infection risk are likely to increase for many crops, whereas in the tropics, productivity growth is likely to remain static owing to temperature rise[24] and infection risk could decline. The authors conclude that "the United States, Europe and China may experience major changes in pathogen assemblages. The benefits of yield gains may therefore be tempered by the greater burden of crop protection due to increased disease and unfamiliar pathogens."

21 Kocmánková, E.; Trnka, M.; Juroch, J.; Dubrovský, M.; Semerádová, D.; Možný, M.; Žalud, Z.; Pokorný, R.; Lebeda, A. Impact of climate change on the occurrence and activity of harmful organisms. Plant Prot. Sci. 2010, 45, S48–S52.
22 Chaloner, T.M., Gurr, S.J. & Bebber, D.P. Plant pathogen infection risk tracks global crop yields under climate change. Nat. Clim. Chang. 11, 710–715 (2021). https://doi.org/10.1038/s41558-021-01104-8
23 It is also noted that fungal infections are also humidity dependent, so that in drier (wetter) regions, infections could decrease (increase).

It is highly probable that the main drivers of climate change that all lead to higher temperatures, especially through increased atmospheric CO2, and the concomitant effects of decreased soil moisture[25], could significantly affect the population dynamics of invasive insect pests and thus the percentage of crop losses.[26]

To substantiate this, Figure 2, from the report (2021) of the Intergovernmental Panel on Climate Change (sixth assessment)[27], hereon IPCC-AR6, foresees global temperature rises, based on the following scenarios - “Shared Socioeconomic Pathways” (SSPs) - in order of hierarchal negative impact[28]:

SSP1. Sustainability – Taking the Green Road (low challenges to mitigation and adaptation). The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development, driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2. Middle of the Road (medium challenges to mitigation and adaptation). The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines.

SSP3. Regional Rivalry – A Rocky Road (high challenges to mitigation and adaptation). A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP4. Inequality – A Road Divided (low challenges to mitigation, high challenges to adaptation). Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labour intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels, but also low-carbon energy sources.

25 Zeng, X., Reeves Eyre, J. E. J., Dixon, R. D., & Arevalo, J. (2021). Quantifying the occurrence of record hot years through normalized warming trends. Geophysical Research Letters, 48, e2020GL091626. https://doi.org/10.1029/2020GL091626

26 Changes in soil moisture – either drier or wetter, can influence insect breeding, geographical range and behaviour.

27 Fand, B.B.; Kamble, A.L.; Kumar, M.Will climate change pose serious threat to crop pest management: A critical review. Int. J. Sci. Res. 2012, 2, 1–14.

28 IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

28 Adapted from https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change

Environmental policies focus on local issues around middle and high income areas.

SSP5. Fossil-fuelled Development – Taking the Highway (high challenges to mitigation, low challenges to adaptation). This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

The scenarios range from 1.4 to 4.7 degrees of warming by 2100 (SSP1-1.9 and SSP5-8.5, respectively). Taking the median representative pathway (SSP2-4.5), the world is expected to undergo a temperature increase of 2.75 degrees by 2100.

Predictions of climate change are not uniform across continents. Therefore, a geographical representation of where temperature increases are expected to be experienced the most (latitude extrema, altitudes and the tropical belt) are also depicted in Figure 2 (next page).

Augmenting the overview provided in Box 1 for the purposes of further precision, Skendžić et al. (2021)[29] provide a taxonomy of possible climate change impacts on insect pest and crop disease dynamics. These are summarised in the following subsections.

2.2.1 Response of insect pests to increased temperature

Many researchers[30] have demonstrated that the physiology of insects is particularly sensitive to changes in temperature. Increases in temperature tend to accelerate their metabolism, growth and mobility. In turn, these changes are heavily influential to population dynamics by way of reproductivity, survival, life-cycle stage, population size and geographic range.

All things being equal, pest insects (lower in the trophic level) breed faster and therefore can adapt or evolve faster than their amphibian, bird, mammal, and reptile predators, so insect pests could be more successful than their predators.[31] However, a study in 1952[32] showed that aphids increase their production of offspring with increasing temperature. The predatory ladybirds increased their consumption of aphids at an even faster rate with increasing temperature, indicating that in this case insect predators would be more efficient and pest problems could decrease with increasing temperatures. Further research is needed to affirm either hypothesis. Those species that are not amenable to temperature adaptation and evolution will tend to undergo a decline in population, while other species that are, could thrive, reproduce rapidly and migrate or

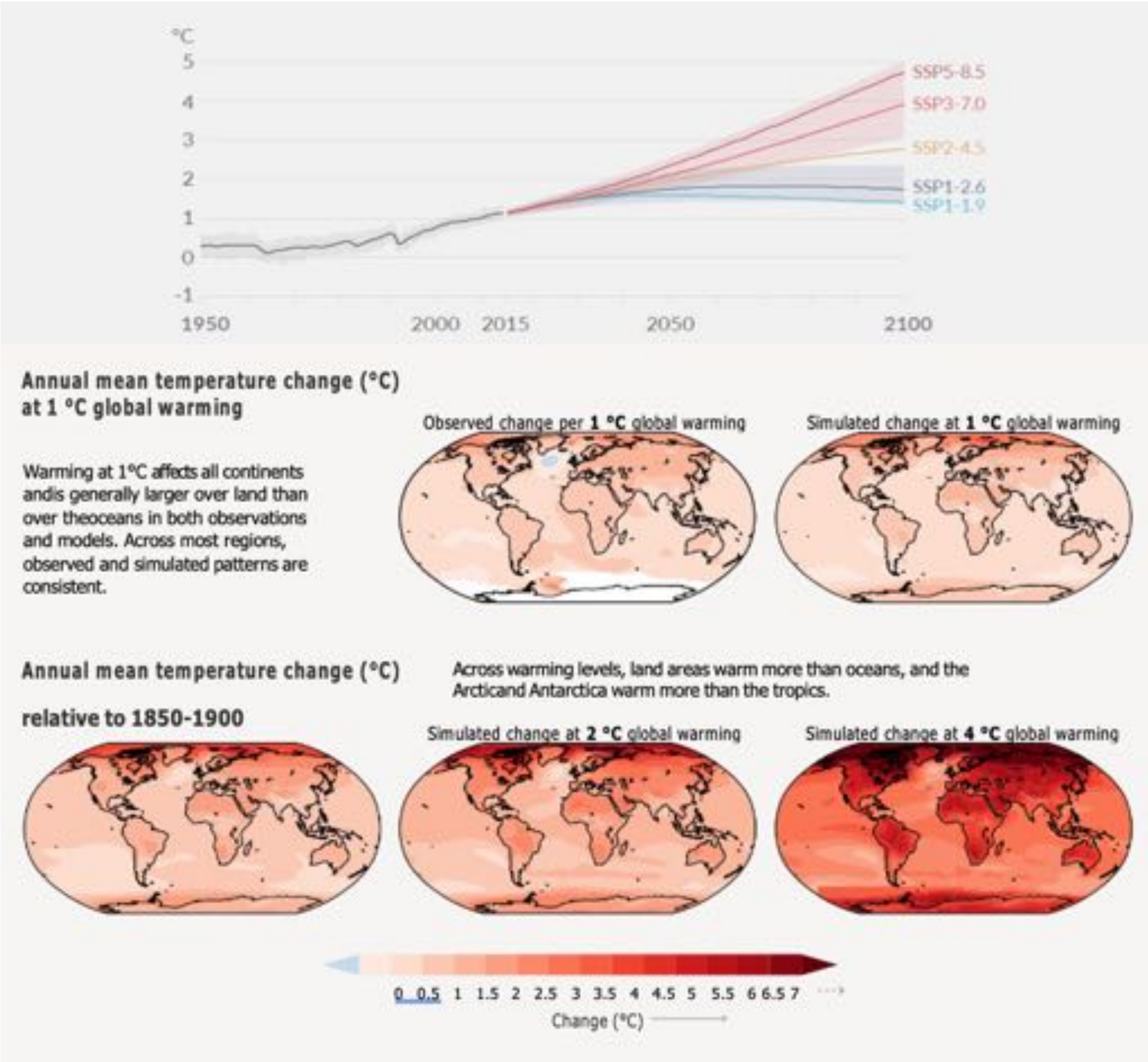
29 Skendži´c, S.; Zovko, M.; Živkovi´c, I.P.; Leši´c, V.; Lemi´c, D. The Impact of Climate Change on Agricultural Insect Pests. Insects 2021, 12, 440. https://doi.org/10.3390/insects12050440

30 E.g., DeLucia, E.H.; Casteel, C.L.; Nabity, P.D.; O'Neill, B.F. Insects take a bigger bite out of plants in a warmer, higher carbon dioxide world. Proc. Natl. Acad. Sci. USA 2008, 105, 1781–1782.

31 Laws, A. Climate change effects on predator–prey interactions, Current Opinion in Insect Science, Volume 23, 2017, https://doi.org/10.1016/j.cois.2017.06.010. (https://www.sciencedirect.com/science/article/pii/S2214574516301286)

32 Dunn, J. A. 1952. The effect of temperature on the pea aphid-ladybird relationship. Ann. Rept. Nat'l. Veg

Figure 2. Global surface temperature change relative to 1850-1900 (IPCC-AR6)



Source: IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, p.16.

spread to even more supportive ecological environments.

At the world's tropics, many insects are already at the upper limits of their thermal tolerance to current temperatures. Consequently, populations of insect pests are predicted to undergo a decrease in growth rate as a warming climate will push temperatures higher. However, it is well known that crops and other plants are equally sensitive to temperature changes.[33,34] For instance, in tropical regions the area suitable to cultivate crops such as coffee and cocoa is expected to rapidly diminish owing to temperature increases.[35]

Insect pests, faced with declining supplies of food as well as temperature stress beyond the optimum threshold for their physiology, will likely migrate to cooler zones to search for food, enabling their survival and hence establishment. Nevertheless, their

33 Kaushal, Bhandari, Siddique & Nayyar. (2016). Food crops face rising temperatures: An overview of responses, adaptive mechanisms, and approaches to improve heat tolerance, Cogent Food & Agriculture.
34 A. Wahid, S. Gelani, M. Ashraf, M.R. Foolad, Heat tolerance in plants: An overview, Environmental and Experimental Botany, Volume 61, Issue 3, 2007
35 https://www.theguardian.com/news/2022/jan/11/climate-change-insect-world-global-heating-species

survival could be threatened on the emergence of new or existing predators, competitors and other ecological factors.

On the other hand, insect pest populations established in temperate zones are anticipated to experience an increase in growth rate.[36] These authors conclude that "crop losses will be most acute in areas where (the scope for) warming increases both population growth and metabolic rates of insects". These conditions are centred primarily in temperate regions, where much of world's grain is produced. A group of researchers calculated that yields of the three most important grain crops – wheat, maize and rice – lost to insect pests will increase by as much as 25 percent for every degree Celsius of warming, with countries in temperate areas hit the hardest.[37]

Takeaway message 1: There is a high degree of certainty that temperature rise will greatly affect the tropics, which could lead to diminished pest pressure since the temperature-pest nexus is already at a near optimum threshold. However, in temperate zones there is moderate certainty that with increased warming, existing pests will thrive given the window for larger temperature increase. Temperate zones are also likely to attract new pests from areas where heat stress is too severe, forcing their migration. However, the survival and establishment of existing and new temperate insect pests will depend on many factors such as predator populations.

2.2.2 Response of insect pests to increased temperature

As carbon (and water) are essential for plant growth, as well as soil nutrients, increased CO2 concentration under climate change (see Figure 3) enables plants to grow faster owing to more rapid carbon assimilation.[39]

Although higher CO2 concentrations, prima facie, could increase crop yields, the magnitude of the effect on particular plant species is uncertain. Of note, maize, sorghum and sugarcane, which all are highly important food staples of tropical origin, are plant taxa (C4), which means they are more sensitive to photosynthesis for growth, i.e., have higher photosynthetic efficiency.[40]

That increasing photosynthetic activity, resulting in better growth and higher plant productivity, would in turn affect the herbivory (feeding habits) of insects by changing both the quantity and quality of plants and vegetation. A shared trait of plants grown under elevated CO2 levels, is a change in the chemical composition of leaves, which affects the nutrient quality of foliage and the feeding habits of leaf-consuming insects.[41] Scientists have found that CO2 can reduce the

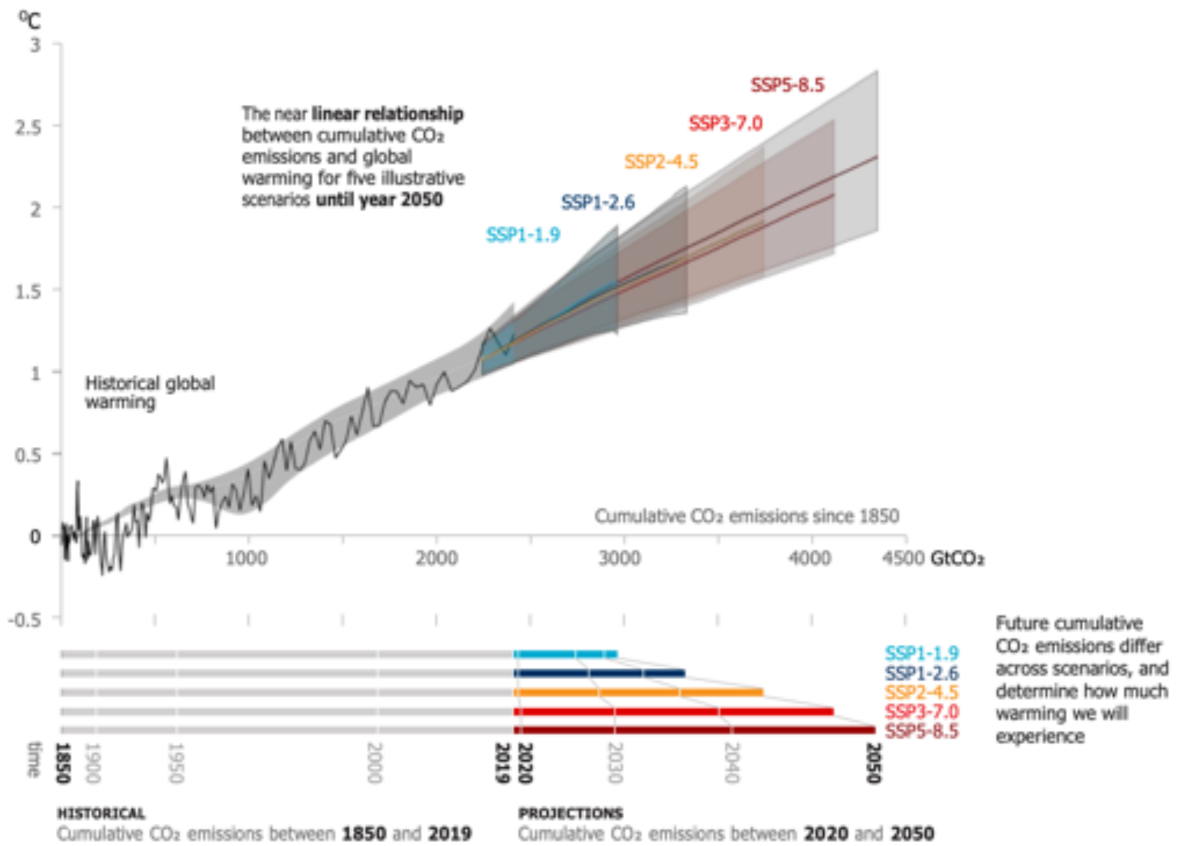
36 Deutsch, C.A.; Tewksbury, J.J.; Tigchelaar, M.; Battisti, D.S.; Merrill, S.C.; Huey, R.B.; Naylor, R.L. Increase in crop losses to insect pests in a warming climate. Science 2018, 361, 916–919.
37 Deutsch CA, Tewksbury JJ, Tigchelaar M, Battisti DS, Merrill SC, Huey RB, Naylor RL. Increase in crop losses to insect pests in a warming climate. Science. 2018 Aug 31;361(6405):916-919. doi: 10.1126/science.aat3466.
38 CO2 is a chemical compound critical for photosynthesis, a process in which water and CO2 are converted into sugars and starch, which is powered by solar energy. Photosynthesis is the central process of all primary production in the biosphere. The earth's entire biomass, the entirety of atmospheric oxygen and all the fossil fuel comes about through photosynthesis. Currently, there is a total of around 7000 bn tons of CO2 in the atmosphere and photosynthesis absorbs more than 100bn tons annually (15%). The amount of CO2 used by the photosynthetic apparatus forms the basis of crop production and, therefore, of all animal and human food.
39 The main effects of elevated CO2 levels on plants include a reduction in transpiration (water loss) and the rate of carbon dioxide uptake through the leaf (stomatal conductance), improved water and light-use efficiency, and thus an increase in photosynthetic rate. As a consequence, higher atmospheric CO2 concentrations could have a direct impact on ecosystems by stimulating plant development and growth, including weeds.
40 Only 3% of all flowering plant species are C4 plants and yet they account for about 50 percent of the 10,000 grass species. C4 plants have about 50 percent higher photosynthetic efficiency than C3 plants (e.g., rice, wheat, soybean and potato), indicating that their productivity is very high.
41 Lincoln, D.E. The influence of plant carbon dioxide & nutrient supply on susceptibility to insect herbivores. Vegetatio 1993, 104, 273 280.
42 https://www.theguardian.com/news/2022/jan/11/climate-change-insect-world-global-heating-species

nutritional value of plants, providing insects with a meal of empty calories lacking elements such as zinc and sodium.[42]

With higher atmospheric concentration of CO2, many crops accumulate more sugars and starches in their leaves, lowering the nitrogen to carbon ratio.[43] Since nitrogen is key for insects' growth and development, therefore they must consume more plant tissue to obtain an optimum level of nitrogen. This is a primary mechanism through which crops may be more susceptible to damage under rising CO2 levels. This being said, under higher CO2 concentration, plants may produce more defensive chemicals (typically carbon-based), that would deter and lower the performance of the insect pests, e.g., through slower growth, smaller size or lower fecundity.

Takeaway message 2: Higher CO_2 atmospheric concentrations are likely to increase yields for staple crops, but will also give rise to weed pressure, owing to enhanced photosynthesis efficiency. However, plants' sugar-nitrogen ratio will likely increase, leading to pests devouring more plant material to maintain nitrogen intake – a key regulator of insect growth and development. Plants, however, may counter this threat through increasing defence mechanisms.

Figure 3. Global surface temperature rise (OC) as a function of cumulative CO_2 emissions (GtCO2) - IPCC-AR6 2



Source: IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, p.28

43 Cotrufo, M.F.; Ineson, P.; Scott, A. Elevated CO2 reduces the nitrogen concentration of plant tissues. Glob. Chang. Biol. 1998, 4, 43–54.

2.2.3 Response of insect pests to changeable precipitation patterns

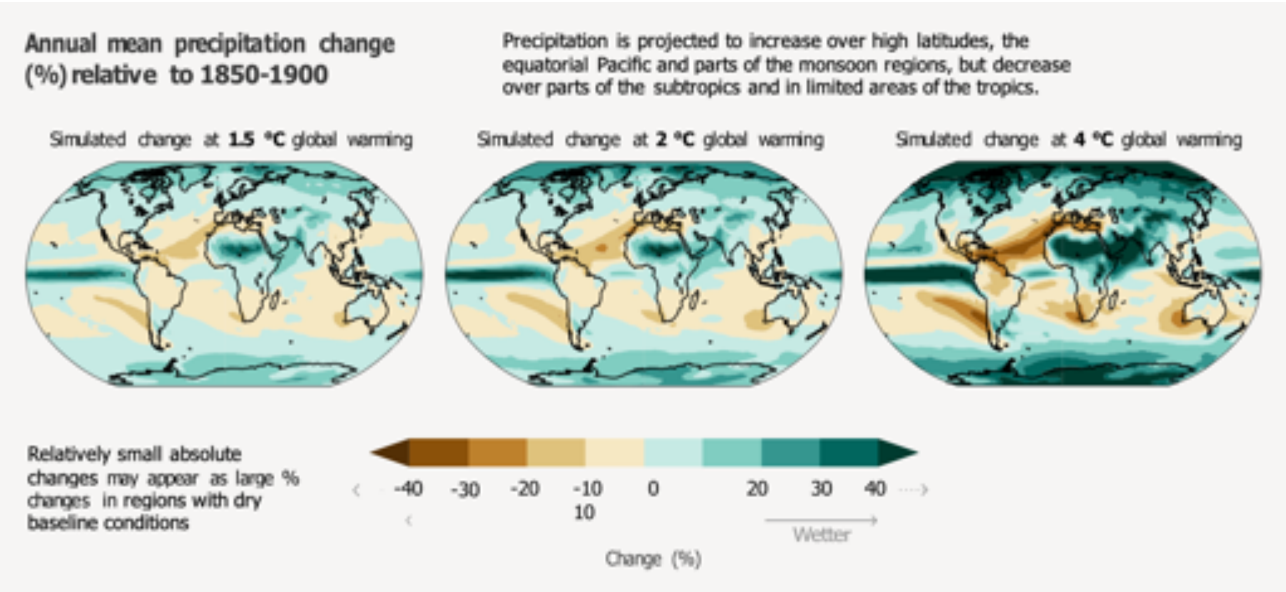
Owing to climate change, a global trend has emerged in which the frequency and amount of precipitation has decreased in certain parts of the world, while in other regions, the intensity and occurrence of rainfall has increased, with trends set to intensify (see Figure 4).

Insect species that overwinter – survive during cold seasons in the soil – are greatly influenced by rainfall patterns. Heavy rainfall can lead to flooding and prolonged stagnation of water, and can threaten insect survival as well as their dormancy. The abundance of precipitation can also lead to insect eggs and larvae being washed away, as well as small-bodied pests such as aphids and mites.

As for drought, plants become highly vulnerable through several mechanisms (Skendži´et al., 2021);

- dry climates provide suitable environmental conditions for insect development and growth
- drought-stressed plants attract some insect species, e.g., when plants lose moisture through the process of transpiration, columns in the water transportation structure of the plant break apart or "cavitate", producing an ultrasonic acoustic emission that is detected by harmful insects, especially leaf beetles[44]
- plants stressed by drought are more susceptible to insect attack because of a decrease in the production of secondary metabolites that provide a defence function.

Figure 4. Projected precipitation changes (IPCC-AR6)



Source: IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berge, p. 29.

44 e.g., Colorado beetle and the Cereal Leaf beetle

Takeaway message 3: Increased rainfall in and around the equatorial belt and mountainous regions lead to vulnerability of insect populations, especially those that overwinter (in the larval stage). However, in subtropical regions, especially those in Latin America and Southern Africa could see greater insect pestilence owing to increased aridness. Crops become highly stressed when relative water availability falls and attract more herbivorous insects.

2.2.4 Increased overwintering survival

Insects fall into the class of poikilothermic or cold-blooded animals and have few response mechanisms to changes in ambient temperature. However, many species, including at the larval stage, have evolved a variety of strategies to stay alive under thermally stressful environmental conditions.[45]

Unsurprisingly, the most critical season for many insect pests is winter, as low temperatures including frost, can significantly increase mortality and thus reduce populations in the following season.[46]

The IPCC (2007)[47] supported by several other studies has shown that climate change will likely be most pronounced in winter (in temperate zones) and at high altitudes and latitudes. Therefore, insects that undergo winter dormancy – or diapause[48]– are likely to experience the greatest changes in their thermal environment.

Concerning overwintering strategies, insects are generally classified into two groups: freeze-tolerant and freeze-avoidant. The first group utilises a physiological adaptation strategy in the form of diapause, while the second group employs a strategy in the form of behavioural avoidance or migration.[49] With respect to the first group, there are two types of diapause, which include heat-associated "aestivation" and cold-associated hibernation. In other words, aestivation allows insects to survive in environments with higher temperatures, while hibernation keeps insects alive at lower temperatures.

Diapause is a fundamental requirement for overwintering success of many species in temperate and colder climates, since it increases an organism's ability to survive at low temperatures, without the need of acclimation to low temperatures, such as the seasonal transition from spring to summer to autumn to winter.

When insects undergo diapause during the latent stages of development, insects experience a sharp drop in metabolic rate that is accompanied by an increase in resilience to cold temperatures.[50,51]

For numerous insect species, the duration of diapause is shorter at higher temperatures (aestivation). This is because warmer winter temperatures increase the metabolic rate of diapause, resulting in a shorter dormancy. Comparing metabolic rates

45 González-Tokman, D.; Córdoba-Aguilar, A.; Dáttilo, W.; Lira-Noriega, A.; Sánchez-Guillén, R.A.; Villalobos, F. Insect responses to heat: Physiological mechanisms, evolution and ecological implications in a warming world. Biol. Rev. 2020, 95, 802–821.

46 As an aside, this feature (insect pest mortality during winter) has been the hallmark of productivity growth and few losses to storage in temperate climes, permitting (now) developed countries to "power" industrial revolution centuries ago, allowing their economies to diversify away from agrarian-based ones, towards higher value-added sectors.

47 Pachauari, R.K.; Reisinger, A. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report on Intergovernmental Panel on Climate Change; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2007.

48 Diapause is a hormonally mediated state of low metabolic activity characterized by suppressed development, suspended activity, and increased resistance to adverse environmental extremes.

49 Bale, J.S.; Hayward, S.A.L. Insect overwintering in a changing climate. J. Exp. Biol. 2010, 213, 980–994.

50 Pullin, A.; Bale, J. Influence of diapause and temperature on cryoprotectant synthesis and cold hardiness in pupae of Pieris brassicae. Comp. Biochem. Physiol. Part A Physiol. 1989, 94, 499–503.

51 Bale, J.S.; Hayward, S.A.L. Insect overwintering in a changing climate. J. Exp. Biol. 2010, 213, 980–994.

and diapause duration under different environmental conditions suggests that diapause ends when the insect's energy reserves reach a critical point. When metabolic rate is high, energy reserves are depleted quickly, and when metabolic rate is low, this set point is reached much later, resulting in a longer diapause.[52]

Tougeron et al. (2017)[53] found that aphid parasitoids from mild winter climates are losing their winter diapause in France which has implications for pest control, implying "that diapause can be replaced by active adult overwintering, with potential consequences for species interactions, insect community composition, ecosystem functioning, and natural pest control." Tougeron (2019)[54] concluded that "potential modifications in overwintering strategies, either of the pests or their natural enemies, can destabilize food webs and modify (positively or negatively) the efficiency of biological control".

Consequently, climate change can disrupt the metabolic balance during diapause, which has the potential to significantly alter the timing of emergence. Hence, changes in spring temperatures could lead to a loss of synchrony with the host plant.[55] To give an example, many insects rely on synchrony between the timing of budding (or flowering) and their emergence for feeding. Under current predictions of climate change, synchrony between feeding stages could become uncoupled as a consequence of subtle environmental differences in the life cycle of individual species.

Under warmer winter conditions, non-diapausing, frost-sensitive species and those that can overwinter in their active stages are likely to have increased survival rates. These insect pests are anticipated to increase their populations and expand their geographic range, especially to higher latitudes and altitudes as average temperatures there are expected to increase.

By contrast, unseasonal low winter temperatures will lead to winter mortality, which is considered a key factor in reducing the population of many temperate insects, especially those that do not go into diapause. However, warmer winters or a reduction in the frequency of extreme cold periods may, therefore, improve the survival of such species, as they are not exposed to lethal cold temperature extremes. Consequently, increased survival during overwintering could lead to an increase in insect pest populations and therefore to a greater abundance of insects feeding on plants during the warmer periods of the year.

Furthermore, researchers[56] have shown that overwintering survival (a probable emerging phenomenon in temperate zones) can lead to pesticide resistance. Other mechanisms such as evolutionary natural selection and adaptation can also lead to resistance against chemical pesticides.

52 Hodek, I. and Hodková, M. (1988), Multiple role of temperature during insect diapause: a review. Entomologia Experimentalis et Applicata, 49: 153-165. https://doi.org/10.1111/j.1570-7458.1988.tb02486.x
53 Tougeron K, Le Lann C, Brodeur J, van Baaren J. Are aphid parasitoids from mild winter climates losing their winter diapause? Oecologia. 2017 Mar;183(3):619-629. doi: 10.1007/s00442-016-3770-7
54 Tougeron, K. (2019), Diapause research in insects: historical review and recent work perspectives. Entomol Exp Appl, 167: 27-36. https://doi.org/10.1111/eea.12753
55 Bale, J.S.; Hayward, S.A.L. Insect overwintering in a changing climate. J. Exp. Biol. 2010, 213, 980–994.
56 Ma, CS., Zhang, W., Peng, Y. et al. Climate warming promotes pesticide resistance through expanding overwintering range of a global pest. Nat Commun 12, 5351 (2021). https://doi.org/10.1038/s41467-021-25505-7

Takeaway message 4: Global warming could increase the build-up of insect pest populations, with high certainty in temperate zones that will endure milder winters. An increase in early emergence (shorter dormancy owing to accelerated metabolic rates attributable to higher temperatures) could result in pest populations being given a better chance to build up to damaging levels. These predictions hold true if pests are able to maintain synchrony with the growth cycle of the plants on which they feed. Of concern, overwintering survival has also been linked to increased resistance against pesticide application.

2.2.5 Increased number of generations

Temperature change has been a recurrent theme throughout this paper, and remains the most important environmental factor for insects since it affects mainly their phenology.[57] Research suggests that growth and reproduction are greater where there is potential for temperature increase under climate change, especially in temperate zones, or when temperature increases do not impair insect physiology. Higher temperatures that are conducive to insects, will instigate higher population densities, making it possible for destructive insects to accelerate reproductive rates within a certain range, leading to an increase in the number of generations and to more crop damage.[58]

Skendžić et al. (2021)[59] highlight that of the many climate change impacts that can induce important phenological shifts, is the tolerance and development of insects to thermal changes. This can be measured by growing degree days (GDD) Simply put, GDD is a measure of heat accumulation that can used to predict pest development rates. Future temperature increases will affect temperate species of univoltine (one offspring per annum) and multivoltine (multi-breeding in one year) in different ways and to different extents. For multivoltine insects, such as aphids and some lepidopteran (butterfly and moth) species, higher temperatures, ceteris paribus, could foster faster development times that predictably allow for additional generations within a year.[60]

Insect species that persist in an annual life cycle generally develop more rapidly than those with longer life cycles. It has been extrapolated that a 2oC increase in temperature could result in one to five additional life cycles per year.[61] The most significant examples in this regard are aphids, which can be expected to produce four to five additional generations per year due to both their low developmental threshold and short generation time. Aphids may, therefore, be particularly sensitive indicators of temperature changes. Higher temperatures during their development have the beneficial effect of shortening the time in the larval and nymphal stages (when they are at risk from predators) and allowing species to become adults earlier.[62]

The anticipated responses of insects to a rise in temperature include an advance in the timing of adult emergence and an increase in flight

57 Phenology is the study of the timing of seasonal biological events (influenced by seasonal and interannual variations in climate), as well as habitat factors (e.g., altitude) such as the timing in the flowering of plants and the emergence of predatory insects.
58 Yamamura, K.; Kiritani, K. A simple method to estimate the potential increase in the number of generations under global warming in temperate zones. Appl. Entomol. Zool. 1998, 33, 289–298.
59 Skendži´c, S.; Zovko, M.; Živkovi´c, I.P.; Leši´c, V.; Lemi´c, D. The Impact of Climate Change on Agricultural Insect Pests. Insects 2021, 12, 440.
60 Bale, J.S.; Masters, G.J.; Hodkinson, I.D.; Awmack, C.; Bezemer, T.M.; Brown, V.K.; Butterfield, J.; Buse, A.; Coulson, J.C.; Farrar, J.; et al. Herbivory in global climate change research: Direct effects of rising temperature on insect herbivores. Glob. Chang. Biol. 2002, 8, 1–16
61 Yamamura, K.; Kiritani, K. A simple method to estimate the potential increase in the number of generations under global warming in temperate zones. Appl. Entomol. Zool. 1998, 33, 289–298.
62 Menéndez, R. How are insects responding to global warming? Tijdschr. Entomol. 2007, 150, 355.

duration. Since the insects fly earlier in the growing season, the individuals of the first generation could reproduce earlier. In addition, due to higher temperatures, faster larval development and growth occurs, so more individuals of the subsequent generation could develop when environmental conditions are still favourable, allowing them to develop directly in the same season rather than diapausing as larvae.[63]

Insect pests are widely diverse and there is no precise way to generalising the effects of climate change on all species. However, the documented changes in higher intra-year breeding confirm the high adaptability of insect pests to environmental change, which is why they are among the organisms that adapt to climate change.

Takeaway message 5: There is certainty that climate change and associated increased surface temperatures would lead to increased intra-year breeding, which would foster population growth and faster emergence and adult development, especially aphids, as long as they can adapt/evolve to the higher temperatures. However, with temperate zones yielding a higher temperature window within which insects can breed more and flourish, as opposed to temperature thresholds already reached in tropical zones, northern hemisphere crops could register a high increase in pestilence from dangerous aphids.

2.2.6 Expansion of insects' distribution

Ezcurra et al (1978)[64] posit a host of factors that determine the distribution of insect pests. These include (i) natural biogeography[65] ; (ii) crop distribution; (iii) agricultural practices (monocultures, irrigation, fertilizers, pesticides); (iv) climate; and (v) trade. The vast increase in global passenger travel presents yet another factor.

Climate change will have a major impact on the geographic distribution of insect pests. As mentioned in subsection 2.3.1, low temperatures are often more significant than high temperatures in determining migration routes and hence geographic distribution.

Farmers are set to bear new and severe pest problems, owing to the spread of insect pests to new areas, along with climate change induced shifts in growing areas of their host plants. Agro-ecology and edaphology (soil interaction) are also of importance in the distribution of pests.[66]

Insect pests, especially aphids, are expected to shift to both higher latitudes and altitudes in the coming decades, with an increase in the number of generations in certain parts of the world. In Europe for example, the European maize borer (Ostrinia nubilalis Hubner) is predicted to have migrated more than 1000 km northward since the 1990s.[67] Nevertheless, a decrease in the number of generations for this insect pest is anticipated for southern Europe due to temperature increase, which would

63 Altermatt, F. Climatic warming increases voltinism in European butterflies and moths. Proc. R. Soc. B 2010, 277, 1281–1287.
64 Ezcurra, E.; Rapoport, E.H.; Marino, C.R. The geographical distribution of insect pests. J. Bio.geogr. 1978, 5, 149.
65 Biogeography refers to the distribution of various species and ecosystems geographically and throughout geological time and space. Biogeography is often studied in the context of ecological and historical factors which have shaped the geographical distribution of organisms over time. Specifically, species vary geographically based on latitude, habitat, segregation (e.g., islands), and elevation. See https://biologydictionary.net/biogeography/
66 Lašt ° uvka, Z. Climate change and its possible influence on the occurrence and importance of insect pests. Plant Prot. Sci. 2010, 45, 53 S62.
67 Porter, J.; Parry, M.; Carter, T. The potential effects of climatic change on agricultural insect pests. Agric. For. Meteorol. 1991, 57, 221-240
68 Raza, M.M et al. Impact of global warming on insects. Arch. Phytopathol. Plant Prot. 2014

negatively affect populations. This implies that climate change will influence various species and regions differently.

Changes in frost pattern, are one of the drivers of the spread of frost-sensitive insect pests. The frequency of spring frosts decreases with increasing distribution of insect pests. Temperate climates are likely to be affected the most since temperature increase will facilitate migration and will lead to more generations of breeding. The lack of frost is another strong determinant in the rising prevalence of insect pests and their outbreaks.[68]

Raza et al. (2014) suggest that crop growers can in theory benefit from earlier seeding, but as a consequence these plants then become available to insect pests sooner, allowing them to begin feeding earlier and cause greater damage, as well as potentially producing additional insect generations during the typical growing season.

Takeaway message 6: Climate change will undoubtedly increase the distribution of insect pests. Temperate climates are likely to be affected the most since temperature increase will facilitate migration and will lead to more generations of breeding. The lack of frost is another strong determinant in the rising prevalence of insect pests and their outbreaks.

2.2.7 Increased risk of invasive alien insect species

Invasive alien species are defined as those that are introduced, outside their natural habitat, through a multitude of agents, e.g., food, crops, ornamental organisms, pets, livestock or simply via international travel and freight carriage (global trade). The commonality among these causal mechanisms is anthropogeny.

Invasive insects in agriculture are often vectors (carriers) of various diseases or parasites.[69] While many beneficial insect species are known to be highly sensitive to climate change (especially temperature), invasive inspect species can be resilient, usually have a wider range of tolerance or bioclimatic range than native insects, allowing them to find a wider range of suitable habitats.[70]

The Convention on Biological Diversity (CBD) describes invasive alien species as the greatest threat to global biodiversity.[71] There exists a generalised rule – colloquially known as the "rule of 10", which asserts that only a minor proportion of introduced invasive alien species establish themselves and only a small proportion of these species spread and become economic pests, namely, 1 in 10 of introduced species escape into the environment, and of those, 1 in 10 become established in the environment, and in turn, 1 in 10 of these established species become economic pests.[72]

Many recent studies predict expanded geographic range and increased population densities (via multiple generations of breeding) owing to climate change[73] that conceivably could lead to severe consequences for sustainable agricultural production.

69 Ward, N.L.; Masters, G.J. Linking climate change and species invasion: An illustration using insect herbivores. Glob. Chang. Biol. 2007, 13, 1605–1615.
70 Walther, G.R.; Roques, A.; Hulme, P.E.; Sykes, M.T.; Pyšek, P.; Kühn, I.; Zobel, M.; Bacher, S.; Botta-Dukát, Z.; Bugmann, H.; et al. Alien species in a warmer world: Risks and opportunities. Trends Ecol. Evol. 2009, 24, 686–693.
71 For further commentary, see Shrestha, S. Effects of climate change in agricultural insect pest. Acta Sci. Agric. 2019, 3, 74–80.
72 Vander Zanden, M.J. The success of animal invaders. Proc. Natl. Acad. Sci. USA 2005, 102, 7055–7056
73 For example, Hill, M.P.; Bertelsmeier, C.; Clusella-Trullas, S.; Garnas, J.; Robertson, M.P.; Terblanche, J.S. Predicted decrease in global climate suitability masks regional complexity of invasive fruit fly species response to climate change. Biol. Invasions 2016, 18, 1105–1119.
74 Shik JZ, Dussutour A. Nutritional Dimensions of Invasive Success. Trends Ecol Evol. 2020 Aug;35(8):691-703
75 Tobin, P.C.; Parry, D.; Aukema, B.H. The influence of climate change on insect invasions in temperate forest ecosystems. For. Sci. 2014, 81, 267–293

While higher temperature differentials often dictate the establishment of invasive species, the ability to adapt to new diets is another important trait responsible for invasion success.[74]

Climate change, however, could positively or negatively influence the transmission mechanisms of invasive alien species. All biological systems have thermal limits, therefore, while temperature increase will have significant impact on ecosystems and the species that dwell in them, the extent of virility in response to climate change is still largely unknown. This is because the process of insect invasion involves a chain of events that includes introduction and establishment, while dispersal could be positively or negatively influenced by climate change.[75]

This being said, extreme climatic events (e.g., storms, high winds and cyclones) could shift invasive pests to new geographic areas where they may find environmental conditions favourable for establishment. Simply, the more individuals introduced into an area, the greater the chance that they will successfully establish. Thanks to rising international trade in agricultural products, many of the most destructive pests and diseases have come from the Americas – the world's largest maize producing and exporting region – (e.g., the maize stem borer and fall armyworm), despite increasingly stringent phytosanitary requirements. Another established pathway of introduction is trade in tropical fresh fruit, which again contrary to stricter phytosanitary regulations, eggs or larval stage often go undetected, especially in exports from South East Asia.[76]

Takeaway message 7: Insects can be introduced to new geographical areas inadvertently through globalised trade and travel. They can also be dispersed by climatic events such as cyclones and storms. There is, however, uncertainty on whether invasive insect species can establish themselves in new environments, since much will depend on factors such as temperature and food supply. But researchers have predicted that selective processes could lead to survival and establishment. A case in point here is the spread of fall armyworm, which has demonstrated great adaptability to new environments.

2.2.8 Reduced effectiveness of biological control agents—Natural enemies

A further impact of climate change on insects concerns their natural enemies. The dimensions of abundance, distribution and seasonal emergence of insect pests under climate change will also be consequential to their natural enemies. As a corollary, climate change is likely to change the degree of success of nature's biological control mechanisms. Indeed, crop pests also tend to thrive in simplified environments that have been stripped of their predators – another legacy of monocultural farming practices.[77]

An important concept in discussions of natural enemies of insects is "tri-trophism". This is simply the interaction between the natural enemy, the insect

76 Cini, A.; Anfora, G.; Escudero-Colomar, L.A.; Grassi, A.; Santosuosso, U.; Seljak, G.; Papini, A. Tracking the invasion of the alien fruit pest Drosophila suzukii in Europe. J. Pest. Sci. 2014, 87, 559–566.
77 https://www.theguardian.com/news/2022/jan/11/climate-change-insect-world-global-heating-species
78 Hance, T.; Van Baaren, J.; Vernon, P.; Boivin, G. Impact of extreme temperatures on parasitoids in a climate change perspective. Annu. Rev. Entomol. 2007, 52, 107–126.
79Welch, K.D.; Harwood, J.D. Temporal dynamics of natural enemy–pest interactions in a changing environment. Biol. Control 2014, 75, 18–27
80Hance, T.; Van Baaren, J.; Vernon, P.; Boivin, G. Impact of extreme temperatures on parasitoids in a climate change perspective. Annu. Rev. Entomol. 2007, 52, 107–126.

and the plant – the tri-trophic interaction.

The effects of climate change on this interaction are modulated in a variety of ways. Temperature changes can affect the biology of each component species of the tri-trophic system differentially, such as destabilizing their their population dynamics and causing temporal desynchronization . Natural enemies could, therefore, be decoupled from the synchronized dynamics between them and insect pests, and potentially negatively affecting the performance of biological control.[79]

Aphids are considered among the insect pests that are prone to control by many natural enemy species, such as parasitic wasps, which lay their eggs in the bodies of aphids, and predatory species, such as ladybirds. Of concern is that owing to temperature changes, natural enemies could start to emerge at a lower temperature than their prey (e.g., aphid) and develop faster than the prey when temperature increases. Therefore, a too early and warm spring leads to its early emergence and a high probability of death in natural enemy populations from a lack of prey.[80] If this phenomenon is repeated over several years, it may lead to the extinction of the natural enemy.[81] Indeed, one of the main defence mechanisms of the fall armyworm against predators is their ability to reach large numbers and migrate before seasonal conditions are suitable for predators.[82] Of course, there is the general possibility that pest and predator emerge in synchrony even in a changing climate.

With predicted geographical shifts in the cultivable range of crops owing to climate change, insect pests may migrate to areas, which may not be tracked by their natural predators, resulting in spatial desynchronization.[83]

Beyond temperature change, elevated CO2 concentration and changing precipitation patterns, will modify the life cycle of the plant (phenology) and plant productivity, which in turn will affect the growth and abundance of insects and consequently have an important bearing on the population of natural predators.[84]

However, the literature is sparse on how elevated CO2 concentration can affect predator efficiency. Ladybirds (Coccinelidae) constitute the largest insect group of predatory natural enemies of aphids. Research by Chen et al. (2005[85], 2007[86]) showed that the Asian ladybird preferentially preyed on aphids under elevated CO2 concentration. Despite this preference, predation levels were not affected by high CO2 concentrations.

Skendžić et al. (2021)[87] conclude that ultimately, climate change and climate change will affect higher trophic levels directly, by altering the behaviour of natural enemies, or indirectly, by altering physiological traits in host plants and behavioural traits in insect pests. The authors stress the need to assess the trophic system as a whole and highlight the challenge for future research to develop models based on knowledge of phenological processes obtained through long-term monitoring

80 Hance, T.; Van Baaren, J.; Vernon, P.; Boivin, G. Impact of extreme temperatures on parasitoids in a climate change perspective. Annu. Rev. Entomol. 2007, 52, 107–126.
81 Ibid.
82 Sparks, Alton N. (1979). "A Review of the Biology of the Fall Armyworm". The Florida Entomologist. 62 (2): 82–87. doi:10.2307/3494083
83 Hullé, M.; D'Acier, A.C.; Bankhead-Dronnet, S.; Harrington, R. Aphids in the face of global changes. C. R. Biol. 2010, 333, 497–503.
84 Thomson, L.J.; Macfadyen, S.; Hoffmann, A.A. Predicting the effects of climate change on natural enemies of agricultural pests. Biol. Control 2010, 52, 296–306.
85 Chen, F.; Ge, F.; Parajulee, M.N. Impact of elevated CO2 on tri-trophic interaction of Gossypium hirsutum, Aphis gossypii, and Leis axyridis. Environ. Entomol. 2005, 34, 37–46.
86 Chen, F.;Wu, G.; Parajulee, M.N.; Ge, F. Impact of elevated CO2 on the third trophic level: A predator Harmonia axyridis and a parasitoid Aphidius picipes. Biocontrol Sci. Technol. 2007, 17, 313–324.
87 Skendži´c, S.; Zovko, M.; Živkovi´c, I.P.; Leši´c, V.; Lemi´c, D. The Impact of Climate Change on Agricultural Insect Pests. Insects 2021, 12, 440

of insects, their associated natural enemies and host plants, and their response to current climate and climate change.

Takeaway message 8: There is considerable uncertainty about the synchronisation between natural enemies, insect pests and plants under climate change. Temperature changes, CO2 concentration levels and shifts in rainfall patterns can affect the biology of each component species differentially, such as destabilizing population dynamics and causing temporal desynchronization. This could lead to the loss of natural predators and rising populations of insect pests. However, there is a pressing need to develop models based on knowledge of phenological processes obtained through long-term monitoring of insects, their associated natural enemies and host plants, and their response to the current climate as well as predicted climate change.

2.2.9 Incidence of plant diseases transmitted by insect vectors and other means

It is well known that insects are important vectors that transmit a plethora of plant diseases such as viruses, phytoplasmas and bacteria.

Of these, viruses are considered a major cause of many plant diseases in global food production. Sastry and Zitter (2014)[88] estimated the overall economic loss from these diseases is in excess of USD 30 billion per year. Again, climate change may have a major impact on the epidemiology (the incidence, distribution, and the degree of control) of diseases borne from plant viruses.

Research into viruses is lagging. Of the 9,000 virus species that have been documented and described in detail, millions of other types of viruses exist in the environment (virtually in all ecosystems). Viruses[89] are the most numerous type of biological entity to be found on the planet.[90]

Since viruses, including agricultural viruses, are immobile, and can only be transmitted by their vector or host, e.g. an insect. Some agricultural viruses and vectors are host generalists and others are specialists with a specific mode of transmission, so the persistence, spread and prevalence of viruses depend on the particular vectors, their host plant and the climatic conditions in which they thrive.[91]

The majority of viruses that can be found in agricultural crop species are messenger RNA viruses and single-stranded DNA viruses.[92] Their main host-to-host transmission strategy is the use of insect vectors with mouthparts for infiltrating the plant.[93]

Climate change induced temperature rises could favour the occurrence of

88 Sastry, K.S.; Zitter, T.A. Plant Virus and Viroid Diseases in the Tropics. Volume 2: Epidemiology and Management, 1st ed.; Springer: Dordrecht, The Netherlands, 2014; ISBN 978-94-007-7820-7.
89 Not all viruses are harmful. Many are beneficial e.g., bacteriophages, pathogens of pests and some that confer adaptive benefits to plants such as drought, cold or soil salinity resistance [Roossinck, M.J. (2015), Beneficial viruses for crops. Molecular Plant Pathology, 16: 331-333. https://doi.org/10.1111/mpp.12241].
90 Lawrence CM, Menon S, Eilers BJ, Bothner B, Khayat R, Douglas T, Young MJ (May 2009). "Structural and functional studies of archaeal viruses". The Journal of Biological Chemistry. 284 (19): 12599–603
91 Trebicki, P. Climate change and plant virus epidemiology. Virus Res. 2020, 286, 198059.
92 When viruses exist in the form of independent particles, or virions, their genetic material is in the form of long molecules of DNA (a self-replicating material that is the carrier of genetic information) or RNA (a messenger carrying instructions from DNA for controlling the synthesis of proteins) that encode the structure of the proteins by which the virus infects.
93 Canto, T.; Aranda, M.A.; Fereres, A. Climate change effects on physiology and population processes of hosts and vectors that influence the spread of hemipteran-borne plant viruses. Glob. Chang. Biol. 2009, 15, 1884–1894.
94 Hance, T.; Van Baaren, J.; Vernon, P.; Boivin, G. Impact of extreme temperatures on parasitoids in a climate change perspective. Annu. Rev. Entomol. 2007, 52, 107–126.
95 Irwin, M.E.; Ruesink,W.G.; Isard, S.A.; Kampmeier, G.E. Mitigating epidemics caused by non-persistently transmitted aphidborne viruses: The role of the pliant environment. Virus Res. 2000, 71, 185–211.

insect-transmitted plant diseases owing to geographic expansion and increases in populations of insect vectors. The main order of insects that transmit plant viruses are the families of aphids, leafhoppers (Cicadellidae) and whiteflies (Aleyrodidae). Among these, aphids are the largest group of vectors, transmitting more than 275 virus species. The short time needed for development and their high reproductive capacity make aphids and whiteflies sensitive to changes in climate.[94]

When aphids encounter favourable thermal conditions, they can be "launched" upward and owing to winds, they have substantial potential for migration and long distance dispersal.

The severity of viral diseases is highly dependent on the timing of infection and the volume of inoculum (the virus material used to inoculate cell tissue), which is influenced by the overwintering of its insect vectors and their host plants.[95] Aphids are expected to have higher survival rates in milder winters, while higher spring/summer temperatures increase their development and reproduction rates. The final outcome is a higher incidence of viral disease transmission and spread.[96]

In a similar vein, some of the most serious plant pathogens are in the form of fungi, which rely on winds (including climate-induced cyclones and storm systems). With climate change, more frequent rainfall can allow airborne plant pathogens to spread, while cyclones can disperse fungal spores as has been the case with the spread of soybean rust from South America to North America. Also, international trade constitutes a primary mechanism for their dispersal and establishment in new areas. It is estimated that fungi are the highest threat for animal-host and plant-host species, representing the major cause (approximately 65 percent) of pathogen-driven host loss.[97] It is to be noted that animals are more affected than plants, and also that this figure includes all plant and animal species - not only agriculturally important ones.

The most economically devastating fungi are Magnaporthe oryzae, affecting rice, as well as UG99 affecting wheat in Africa (and pathogens in temperate climates that overwinter, e.g., late blight[98]), followed by Botrytis cinerea (see Box 1), while several high-value crops produced in the tropics, such as bananas, coffee, cacao, spices, mangos, and several nuts, are also affected by fungal infections, e.g., TR4 (Panama disease) in the case of bananas.[99]

With climate change and other anthropogenic causes, an increase in newly introduced insect-transmitted plant diseases as well diseases caused by fungal pathogens is expected. Therefore, it is of great importance to have diagnostic tools and appropriate personnel to detect pests and pathogens.

Takeaway message 9: Climate change may have a major impact on the epidemiology (the incidence, distribution and the degree of control) of diseases borne from plant viruses. Aphids are a prolific species in transmitting viruses. These insect pests could register higher survival rates in milder winters, while higher spring/summer temperatures will

96 Alonso-Prados, J.L.; Luis-Arteaga, M.; Alvarez, J.M.; Moriones, E.; Batlle, A.; Laviña, A.; García-Arenal, F.; Fraile, A. Epidemics of aphid transmitted viruses in melon crops in Spain. Eur. J. Plant Pathol. 2003, 109, 129–138.
97 Fisher, M. C., Henk, D. A., Briggs, C. J., Brownstein, J. S., Madoff, L. C., McCraw, S. L., et al. (2012). Emerging fungal threats to animal, plant and ecosystem health. Nature 484, 186–194. doi: 10.1038/nature10947
98 https://www.koppert.com/challenges/disease-control/phytophthora-blight/
99 https://www.frontiersin.org/article/10.3389/fmicb.2019.00214

increase their development and reproduction rates. The final outcome would be a higher incidence of viral disease transmission to crops. An overarching factor is our limited knowledge on viruses. Only 9,000 virus species have been documented and described in detail, but millions of other types of viruses exist. It is not known how these other viruses could respond under climate change – with the possibility of new endemics and pandemics affecting agriculture. Diagnostic tools are of the essence.

3 Mitigation measures

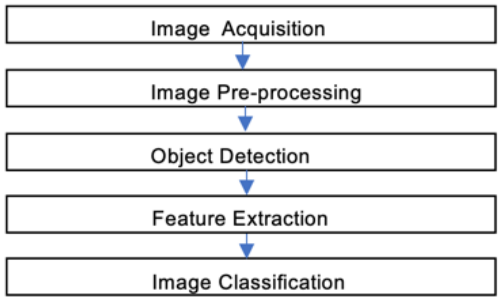
Insect pests and crop diseases are expected (with uncertainty) to establish themselves in new geographical locations as a result of climate change and other anthropogenic activity, such as rising world trade and air travel. These novel pests and diseases, by definition, will tend not to be immediately recognizable by farmers/ pastoralists or by agricultural extension workers. However, technology can play and is playing an important role in this regard. Innovation has been on the back of considerable progress in the use of ML in the realm of image recognition, towards Object Detection (mostly pests) and Image Classification (mostly crop diseases), using mobile phone technology.

3.1 Pest and disease identification

To provide some simplification, Figure 5 presents the stages involved in pest/disease identification under this innovative technology.

Such has been the technological advances in this discipline, it is well beyond the scope of this working paper to provide a comprehensive description of image recognition technologies to date.

Figure 5. The premise of image recognition in pest/disease identification



However, a glance into these technologies is provided in Annex 1[100]. Further to which, the taxonomy of machine/deep learning (ML-DL) approaches are listed in Figure 6 (next page).

Many of the algorithms to be found in the literature employ "machine learning" libraries from open-sources. Examples include AlexNet[101], GoogleNet[102], LeNet[103], SqueezeNet[104], VGGNet[105], U-Net[106], Inception[107], ResNet[108], DenseNets[109] and Google

100 Adapted and expanded from (i) Júnior & Rieder, Automatic identification of insects from digital images: A survey, Computers and Electronics in Agriculture, Volume 178, 2020; and (ii) Yuan Yuan, Lei Chen, Huarui Wu, Lin Li, Advanced agricultural disease image recognition technologies: A review, Information Processing in Agriculture, 2021
101 Convolutional neural network (CNN)
102 Convolutional neural network (CNN)
103 Convolutional neural network (CNN)
104 Deep neural network (DNN)
105 Convolutional Neural Network (CNN)
106 Convolutional Neural Network (CNN)
107 Convolutional Neural Network (CNN)

Tensor Flow[110]. Most of these employ Convolutional Neural Networks.

It is seen in Annex 1 that most of the 50 surveyed studies employing ML-DL reach a very high degree of precision in detecting and classifying the pest or disease. The mean accuracy of the surveyed studies was in the proximity of 92 percent, while the median accuracy was over 93 percent.

Many of the studies employed the "PlantVillage"[111]dataset. To date, this dataset has released over 54,000 expertly curated images on healthy and infected leaves of crops plants, and the database continues to grow over time

PlantVillage state that their dataset is "the beginning of an on-going, crowdsourcing effort to enable computer vision approaches to help solve the problem of yield losses in crop plants due to infectious diseases".

"Machines learn" and so with more images to process, precision tends to increase. Therefore, as more images on crop diseases and pests surface, precision rates in detection/ classification will increase further. The "business model" on which PlantVillage is premised is on the widespread distribution of smartphones among crop growers around the world. In the coming years global ownership of smartphones is expected to surpass 7 billion.[112]

PlantVillage do not restrict themselves in providing imagery data, but based on the work of Mohanty et al. (2016)[113] at Pennsylvania State University as well as FAO, and that of the International Institute of Tropical Agriculture (IITA) – part of the Consultative Group for International Agricultural Research (CGIAR) network, a ML-DL powered app named "Nuru" has been developed using Google Tensor Flow which embeds a generalised neural network (and can be downloaded on Android).

As an example, the App has been successful in identifying the highly damaging pest "fall armyworm" to maize cultivation in Ethiopia, when it was first discovered in the country in 2018. See Box 1.

Figure 6. Taxonomy of machine/deep learning (ML-DL) approaches

- ANN Artificial Neural Network
- CLS curvilinear structures
- CNN Convolutional Neural Network
- DCCN Densely Connected Convolutional Networks
- DCNN Deep/Densely Convolutional Neural Network
- DNN Dense Neural Network
- DT Decision Tree
- FNN Feed-Forward neural network
- FRST Fast radial symmetry transform feature extraction from image classification
- IP Image processing KNN K-Nearest Neighbours
- LPSA Line Profile-based Segmentation Algorithm
- LTSM Long Short Term Memory (
- MLE Maximum Likelihood Estimator
- OPA Object Proposal Algorithm
- R-FCN Region-based Fully Convolutional Networks
- RCNNN Region-based Convolutional Neural Network
- RNN Residual Neural Network
- RPN Region Proposal Network
- RTBnet RetinaNet and MobileNet based
- SDAE Stacked Denoising Auto-Encoders
- SSD Single Shot Multibox Detector
- SVM Support Vector Machine
- SWCNN Sliding-Window-based Convolution Neural Network
- VGGD/VDCN Very Deep Convolutional Networks
- VGGN Convolutional Network for Classification and Detection
- YOLO You Only Look Once
- ZL Zeiler and Fergus Model

108 Residual Neural Network
109 Convolutional neural network (CNN)
110 Generalised neutral network
111 See https://www.kaggle.com/abdallahalidev/plantvillage-dataset for the contents of the dataset.
112 https://www.bankmycell.com/blog/how-many-phones-are-in-the-world
113 Mohanty SP, Hughes DP, Salathé M. Using Deep Learning for Image-Based Plant Disease Detection. Front Plant Sci. 2016

4. Towards a Holistic Early Warning System for Pest and Disease Detection and Control Mitigation measures

The "blueprints" for an Early Warning System (EWS) for desert locust outbreak prevention and control have been set out in a separate TMG Working Paper (available upon request). However, the aim of this section is to examine ways to integrate an EWS for migratory pests and crop diseases with that of the central system for desert locusts. This task is seemingly not so onerous given that the technologies of Table 2 for pest and crop disease detection/classification are well-established, standalone and self-supporting (thanks to machine/deep learning) with little need for additional resources, either human or IT infrastructure. A high dependency on automation is foreseen. Again, however, communication, co-ordination, partnerships under the rubric of governance are challenges that seemingly need to be addressed, but as described below an existing mechanism of governance is at hand.

The TMG EWS, in its function, would incorporate and process information from satellites and weather intelligence for ML-driven prediction and

Box 5: 4 IGAD Climate Prediction and Application Centre, Disaster Operations Centre

The Intergovernmental Authority on Development (IGAD) is a Regional Economic Community (REC) of the African Union for Easter Africa region with 8 member states; namely: Djibouti, Eritrea, Ethiopia, Kenya, Somalia, South Sudan, Sudan and Uganda. The IGAD regional strategy promotes sustainable and resilient development, peace and security, and regional integration in the east Africa region. The IGAD Climate Prediction and Application Centre (ICPAC) is one of the specialized institutions of IGAD with a mandate to lead the climate, disaster risk management and food security agendas in the region. ICPAC is a designated Regional Climate Centre by the World Meteorological organization (WMO).

ICPAC has established and officially launched a regional Disaster Operation Centre Situation room in its Nairobi headquarters in November 2021. This Centre was established following the endorsement by the IGAD Heads of State who also proposed to establish the IGAD Disaster Operations Centre (IDOC) in December 2020. The center has a Situation Room that monitors major hazards and issues regional early warning information and it is anchored under the IGAD Disaster Risk Management (DRM) Program at ICPAC – a specialized institution of IGAD on Climate risks and Disaster Risk Management. The main goal of the IDOC is to provide people-centered multi-hazard early warning information and strengthen early action in the IGAD region. This is achieved through the following core functions;

1) Monitor major hazards and issue early warning information for the region.

2) Coordination with the national focal institutions on early action.

3) Rapid mapping of affected areas and impacts of disasters.

4) Strengthen capacity of the member states to anticipate risk and offer technical support to the Africa Union early warning situation room.

High-impact hazards being monitored currently by the Centre are drought, floods, tropical cyclones, food insecurity, and coastal sea waves. The IDOC also anticipates looking at forest fires, landslides, pandemic/epidemics, pests, and diseases. The IGAD DRM program also aims at establishing Nation early warning situation rooms that will feed the regional IDOC with information such as disaster impact data, ongoing responses in the country, and any other relevant information.

Box 6: The *One Health* concept

The "One Health" concept summarises an idea that has been known for more than a century: animal health, human health, and environmental health are intrinsically intertwined and interdependent. The health of one affects the health of all (The World Organisation for Animal Health, OIE)[115]

Insights from the One Health concept could be drawn upon to further progress early warning systems and early action for transboundary crop pests and diseases. One Health recognizes the interdependence of human, animal and environmental health. Historically, the approach has largely been defined around zoonotic diseases and sharing the infrastructure of human and animal health systems. An illustrative example of cooperation linking the health triad, humans-animals-environment is the World Health Organisation (WHO), whom working with the Food and Agriculture Organisation of the United Nation (FAO) and OIE is promoting multi-sectoral responses to food safety hazards, risks from zoonoses, and other public health threats at the human-animal-ecosystem interface and is providing guidance on how to reduce these risks.[116]

Under the One Health approach, systems that integrate data from across human, animal and the environmental sectors are more and more needed. In this context, the revamped World Animal Health Information System, OIE-WAHIS, launched earlier this year brought a key contribution to the provision of enhanced data analysis of the domestic animal and wildlife health sector. [117] OIE-WAHIS is a comprehensive database through which information on the animal health situation worldwide is reported and disseminated throughout the world. Guaranteeing transparency is a core mission of the OIE. To fulfil this mandate, OIE-WAHIS comprises key essential elements:

(i) An **early warning system** for the immediate management of alert notices for OIE-listed diseases and emerging diseases.

(ii) A **monitoring system** to manage six-monthly information updates on all OIE-listed diseases.

(iii) **Further information** provided by National Authorities through annual reports.[118]

While examples such OIE-WAHIS illustrate significant achievements in improving the efficiency and rapidity of animal disease information exchange, especially for early warning purposes, one must note that crop agriculture is missing in the equation. In other words, since One Health began as a collaboration between veterinarians and public health scientists, crop health within the One Health approach remains a relatively unexplored area. Nevertheless, looking beyond zoonotic diseases, it is clear that human and animal health are closely linked to crop health for multiple reasons. In the context of transboundary crop pests and diseases, one can list at least four reasons:

(i) Food security – enough food to feed people (ii) Feed security – enough feed to feed animals

(iii) Food and feed safety – plant products free from toxins, pesticide residues and human/animal disease contaminants

(iv) Livelihoods – agriculture is fundamental for economic growth in developing countries.[119]

The climate crisis provides further impetus to embrace the essential components of healthy plants, healthy animals and healthy people for a complete and balanced One Health initiative. Climate change is causing changes in the range of crop pests and diseases, livestock disease, as well as human and animal vector borne diseases such as malaria, leishmaniasis, Rift Valley Fever, tick-borne encephalitis and many more. This means more pesticides, insecticides, fungicides and antimicrobials could be used to control pests, vectors and diseases, consequently bringing wider health and environmental impact. Importantly, as more and more agents are deployed in control, there is a profound danger that pests and diseases could evolve to become increasingly resistant to these control measures.

Finally, many lessons can be drawn from the global COVID-19 response in shaping transboundary pest and disease management systems. The urgency of the COVID-19 pandemic led to important information sharing, data analytics, and modelling in how the disease could spread. These tools could also be leveraged to help build resilience to future plant pest/disease outbreaks – from identifying risks in global crop trade networks to local "citizen science" in monitoring through IT applications.

forecasting, especially in identifying desert locust breeding grounds and other transboundary threats. Given that the Horn of Africa is a hotspot for such threats, the Intergovernmental Authority on Development (IGAD, Nairobi), has recently opened a regional Disaster Operation Centre Situation room in its Nairobi headquarters. In partnership with IGAD, the TMG EWS would synergise with efforts by IGAD to harness weather intelligence in the monitoring of high-impact hazards such as drought, floods, tropical cyclones, food insecurity and coastal sea waves, many of which are relevant to the potential of plant pest and disease outbreaks. The IGAD Disaster Operations Centre also anticipates monitoring pandemics/epidemics as well as pests and diseases in the near future (see Box 5 on page 29).

Clearly, strong benefits will transpire in strategically aligning with IGAD's mandate, vision and initiatives. If threats escalate to potential transboundary events, even to epidemic or pandemic proportions, intra-regional communication co-ordination, would be critical and would need to be supported by an effective governance model. In this respect, TMG and IGAD could gather insights from the "One Health"[114] initiative (see Box 6 on previous page).

5. Concluding remarks

This working paper has introduced and elaborated on the formal linkages between climate change and other consequences of anthropogenic activity from an increasingly globalised world on the adaptation, intensification, migration and establishment of transboundary crop pests and diseases. The potential rapid evolutionary pace of invasive species and their adaptation to a changing climate constitute the primary drivers of the risks that they pose.

The latest IPCC assessment (AR6 Working Group II)[120] paints a pessimistic scenario in our ability to reign-in climate change impacts. This spells certainty for the emergence of new pests and pathogens, but uncertainty as to where, when and how exactly they are likely to transpire. However, in its synthesis of current research, this paper foresees that for desert locusts, there is a likelihood that climate change could render new breeding grounds – further south in Africa, further east in Asia and northwards to Southern Europe, notwithstanding that desert locust outbreaks are set to gain more traction in frequency and in intensity in established zones.

Concerning other pests, biological and phenological mechanisms could foster the migration and expansion of insect pest populations and disease prevalence owing to the direct effects of climate change on temperature (including overwintering), CO2 concentration, changing rainfall patterns, the degree of synchrony

114 https://www.cdc.gov/onehealth/index.html
115 One Health - OIE - World Organisation for Animal Health
116 One Health (who.int)
117 One Health Archives - OIE - World Organisation for Animal Health
118 World Animal Health Information System - OIE - World Organisation for Animal Health
119 Including plant health in the 'one health' concept - CABI.org
120 https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

between plant-pest-predator, the newfound risk of the establishment of invasive alien insect species and the threat to natural enemies of insect pests. Finally, the degree to which viruses (bringing about crop disease) can be introduced through insect species, especially through elevated and geographically expanded aphid populations, needs to be further elaborated.

Again, while the science is known and well understood, much uncertainty abounds these mechanisms when climate change is introduced, and it is not known with sufficient precision how a changing climate will exactly alter pest and disease dynamics. This uncertainty is partly due to the fact that it is not only the pests and diseases that respond to changes but also their host plants and natural enemies.

This all being said, the balance of evidence suggests that temperate regions could be at most risk of increased pestilence and disease pressure, for the simple reason that climate change could affect these regions the most with rising temperature, since this is a major driver of increased prevalence of insect pests and crop diseases. Overwintering survival of pests that could feature more in temperate zones, is also linked with a greater resistance to pesticide applications.[121]

If many of the predicted changes were to manifest, this would be deeply troubling because temperate zones supply a significant percentage of the world's grain, oilseeds and other staple foodstuffs. In contrast, tropical zones may confront lower pest and disease pressure, owing to the fact that a further temperature increase would disrupt their physiology leading to lower prevalence, while at the same time crop yield growth is expected to stall or even decline.

Of note, at the time of writing this paper, several crucial developments in the context of crop pests and diseases and food insecurity have occurred. In spring 2022, East Africa has seen an outbreak of fall armyworm, which has been attributed to the climate crisis. Insect invasion such as fall armyworm or locust species adds to strains on Africa's food crisis creating yet another challenge of availability of fresh food.[122] Furthermore, in May 2022, Sardinia has reported an invasion of Moroccan locusts.[123] This outbreak has been named as the worst invasion of locusts in 60 years in the Italian island[124] and seems to continue unabated well into July 2022.[125] Russia's war in Ukraine is further jeopardising our already vulnerable global food systems. Russia and Ukraine being major exporters of agricultural products, and more importantly Russia supplying the world with synthetic fertilisers, leaves us, and particularly importers in the Global South painfully exposed to shocks. With climate crisis on top, we simply cannot afford to proceed with "business as usual".

A call is made for deeper research using models to simulate the effects of climate change on pest and disease distribution and migration. This will inevitably be a difficult task given the sheer complexity in how insect pests, their natural enemies, viral, bacterial and fungal pathogens and their

121 Ma, CS., Zhang, W., Peng, Y. et al. Climate warming promotes pesticide resistance through expanding overwintering range of a global pest. Nat Commun 12, 5351 (2021). https://doi.org/10.1038/s41467-021-25505-7
122 https://www.theeastafrican.co.ke/tea/science-health/fall-armyworm-spark-fears-of-food-insecurity-uganda-3784062
123 Locust swarms destroy crops in Sardinia's latest infestation | Italy | The Guardian
124 Worst invasion of locusts in 60 years hits Sardinia | News | DW | 11.06.2019
125 https://www.agrodolce.it/news/invasione-cavallette-sardegna-problema-endemico/

vectors, interact with, and respond to a changing climate.

The value and urgency of these tasks should not be underestimated, given that between 20 to 40 percent of all crops are reported to be lost to insect pests and diseases, which could drastically increase in the future therefore heightening both national food insecurity and impairing the role of international markets in supplying food.

The world cannot wait for science to catch up to provide more evidence. Urgent action is needed. Therefore, we propose to build on the existing knowledge and start necessary action while science and all forms of knowledge accompany the efforts to set up a "holistic early warning system" under partnership with IGAD, and galvanising upon IGAD's mandate for transboundary pest control. Using technologies such as image recognition (employing ML), this system will cover all threats related to destructive pests (e.g., aphids and fall armyworm) and crop diseases (e.g., blast, rusts and other fungal pathogens). Of parallel concern is the rapid evolution of resistant strains of pathogens and pests to conventional chemicals (i.e., insecticides, fungicides and antimicrobials) giving rise to more aggressive variants, necessitating a research gap to be bridged. Thus, given the expected prolificacy and adaptability of new and emerging threats, (i) it is important that the monitoring of pests and diseases and their successful identification collectively uses data and common methodology from a diverse set of databases, which could be in the international, regional, national and sub-national domains; and (ii) the need to start monitoring key interactions rather than only monitoring target pests, since by adding monitoring of interactions (e.g., predation pressure on pests), we would assist the scientific community in better formulating the 'right' measures to deal with the complex problems we face. Without this knowledge, we might use methods that counteract the goal of reduced pest impact and hence the long-term resilience of food systems.

In this vein, few pests and diseases are routinely monitored, e.g., locusts, wheat rust and TR4[126] in the cases of banana, but many are not. This underscores the said holistic early warning system to embody specific/targeted and passive surveillance mechanisms, risk modelling and assessment, diagnostics, collective data sharing and communications – global to regional to local and local to regional to global – for all pest and pathogen threats, including potential pests and diseases currently unknown to cause crop damage. Consequently, a newfound form of governance emerges as a global imperative. This imperative resonates the call for transdisciplinary collaboration between science and action, and partnerships (in scientific research and technology), including co-ordination among countries (and especially for regional transboundary threats). With IGAD as the conduit, the aforementioned One Health initiative could provide valuable lessons in these regards.

126 Black Sigatoka disease afflicting bananas has emerged as a more worrying threat.

Annexes

Annex 1. Innovations in pest and disease image recognition.

#[112]	Study	Algorithm	Type	(Disease) Classes	% Detection	Dataset	Image	Crop
1	Akintayo et al. (2018)	CNN	Obj. detect.	2	96	644	Nematode eggs	Soyabean
2	Alemayehu et al. (2016)	SVM	Img. classif.	4	93.3	900	Insect on plant	Teff, Wheat, Sorghum, Barley, Maize
3	Avila-George et al. (2018)	ANN	Img. classif.	3	97.2	40	Leaf disease	Tobacco
4	Bakkay et al. (2018)	IP	Img. classif.	3	77	100	Insect on field trap	-
5	Basati et al. (2018)	DT	Img. classif.	2	90.2	16	Wheat grains	Wheat
6	Bisgin et al. (2018)	SVM	Img. classif.	15	85	6900	Insect	-
7	Chen et al. (2018)	CNN	Segm.	2	95.6	68	Insect on leaf	Pakchoi
8	Cheng et al. (2017)	CNN	Img. classif.	10	98.6	550	Insect on leaf	-
9	Cruz et al. (2017)	CNN	Img. classif.	3	98.6	224	Leaf disease	Olive
10	Ding and Taylor (2016)	CNN	Img. classif.	2	93.1	177	Insect on field trap	Tomato
11	Espinoza et al. (2016)	ANN	Img. classif.	2	96	3185	Insect on sticky trap	Banana
12	Fuentes et al. (2017)	CNN	Obj. detect.	9	83	5000	Leaf disease	Tomato
13	Kalamatianos et al. (2018)	CNN	Obj. detect.	2	91.5	542	Insect on field trap	Olive
14	Li et al. (2019a)	CNN	Obj. detect.	2	88.5	1228	Insect on plant	Wheat
15	Li et al. (2019b)	MLE	Img. classif.	6	74.7	700	Maize grains	Maize
16	Liu et al. (2016)	CNN	Obj. detect.	12	95.1	5000	Insect on plant	Rice
17	Liu et al. (2019)	CNN	Obj. detect.	16	75.4	88670	Insect on field trap	-

[112] **1.** Akintayo, A., Tylka, G.L., Singh, A.K., Ganapathysubramanian, B., Singh, A., Sarkar, S., 2018. A deep learning framework to discern and count microscopic nematode eggs. Sci. Rep. 8 (1).; **2.** Alemayehu, D.M., Mengistu, A.D., Gebeyehu, S., 2016. Computer vision for ethiopian agricultural crop pest identification. Indonesian J. Electric. Eng. Comput. Sci. 3 (1), 209–214.; **3.** Avila-George, H., Valdez-Morones, T., Espinosa, H., Acevedo, B., Castro, W., 2018. Using artificial neural networks for detecting damage on tobacco leaves caused by blue mold. Int. J. Adv. Comput. Sci. Appl. 9, 579–583.; **4.** Bakkay, M.C., Chambon, S., Rashwan, H.A., Lubat, C., Barsotti, S., 2018. Automatic detection of individual and touching moths from trap images by combining contourbased and region-based segmentation. IET Comput. Vision 12 (2), 138–145.; **5.** Basati, Z., Rasekh, M., Abbaspour-Gilandeh, Y., 2018. Using different classification models in wheat grading utilizing visual features. Int. Agrophys. 32 (2), 225–235.; **6.** Bisgin, H., Bera, T., Ding, H., Semey, H.G., Wu, L., Liu, Z., Barnes, A.E., Langley, D.A., Pava-Ripoll, M., Vyas, H.J., Tong, W., Xu, J., 2018. Comparing SVM and ANN based machine learning methods for species identification of food contaminating beetles, Sci. Rep. 8 (1).; **7.** Chen, J., Fan, Y., Wang, T., Zhang, C., Qiu, Z., He, Y., 2018. Automatic segmentation and counting of aphid nymphs on leaves using convolutional neural networks. Agronomy 8 (8).; **8.** Cheng, X., Zhang, Y., Chen, Y., Wu, Y., Yue, Y., 2017. Pest identification via deep residual learning in complex background. Comput. Electron. Agric. 141, 351–356.; **9.** Cruz, A.C., Luvisi, A., De Bellis, L., Ampatzidis, Y. X-fido: An effective application for detecting olive quick decline syndrome with deep learning and data fusion. Front. Plant Sci. 8.; **10.** Ding, W., Taylor, G., 2016. Automatic moth detection from trap images for pest management. Comput. Electron. Agric. 123, 17–28.; **11.** Espinoza, K., Valera, D.L., Torres, J.A., López, A., Molina-Aiz, F.D., 2016. Combination of image processing and artificial neural networks as a novel approach for the identification of *bemisia tabaci* and *frankliniella occidentalis* on sticky traps in greenhouse agriculture. Comput. Electron. Agric. 127, 495–505.; **12.** Fuentes, A., Yoon, S., Kim, S.C., Park, D.S., 2017. A robust deep-learning-based detector for real-time tomato plant diseases and pests recognition. Sensors (Switzerland) 17 (9).; **13.** Kalamatianos, R., Karydis, I., Doukakis, D., Avlonitis, M., 2018. Dirt: The dacus image recognition toolkit. J. Imaging 4 (11).; **14.** Li, W., Chen, P., Wang, B., Xie, C., 2019a. Automatic localization and count of agricultural crop pests based on an improved deep learning pipeline. Sci. Rep. 9 (1).; **15.** Li, X., Dai, B., Sun, H., Li, W., 2019b. Corn classification system based on computer vision. Symmetry 11 (4).; **16.** Liu, Z., Gao, J., Yang, G., Zhang, H., He, Y., 2016. Localization and classification of paddy field pests using a saliency map and deep convolutional neural network. Sci. Rep. 6 (1), 20410.; **17.** Liu, L., Wang, R., Xie, C., Yang, P., Wang, F., Sudirman, S., Liu, W., 2019. Pestnet: An end-to-end deep learning approach for large-scale multi-class pest detection and classification. IEEE Access 7, 45301–45312.

Annex 1. Innovations in pest and disease image recognition (continued).

#[113]	Study	Algorithm	Type	(Disease) Classes	% Detection	Dataset	Image	Crop
18	Mousavi et al. (2016)	SVM	Img. classif.	5	90	100	Leaf disease	Maize
19	Nazri et al. (2018)	CNN	Img. classif.	2	95	687	Insect on sticky trap	Rice
20	Partel et al. (2019)	CNN	Obj. detect.	2	80	800 + 8000	Insect on field trap	Citrus
21	Picon et al. (2018)	CNN	Img. classif.	3	87	8178	Leaf disease	Wheat
22	Ram and Rodríguez (2016)	IP	Img. classif.	2	88.1	260	Cell nuclei	-
23	Ramcharan et al. (2017)	ANN	Img. classif.	6	93	2756	Plant disease	Cassava
24	Roldán-Serrato et al. (2018)	ANN	Img. classif.	2	88	200	Insect on leaf	Potato and bean
25	Shen et al. (2018)	CNN	Obj. detect.	6	88	739	Insect on lab trap	Stored grains
26	Sun et al. (2018)	CNN	Obj. detect.	6	74.6	2183	Insect on field trap	Pine
27	Tan et al. (2016)	CNN	Img. classif.	4	97.5	250	Fruit disease	Melon
28	Wen et al. (2015)	SDAE	Img. classif.	9	96.9	728	Insect on sticky trap	Fruit
29	Xia et al. (2018)	CNN	Obj. detect.	24	89.2	660	Insect on leaf	-
30	Zhong et al. (2018)	CNN, SVM	Img. classif.	6	90.1	3000	Insect on field trap	-
31	Mohanty et al. (2016)	CNN	Img. classif.	26	99.35	54306	Leaf disease	14 Crops
32	Brahimi et al. (2017)	CNN	Img. classif.	9	99	14828	Leaf disease	Tomato
33	Durmus et al. (2017)	CNN, DNN	Img. classif.	10	95.65	54309	Leaf disease	Tomato

[113] **18.** Mousavi, S.A., Hanifeloo, Z., Sumari, P., Arshad, M.R.M., 2016. Enhancing the diagnosis of corn pests using gabor wavelet features and svm classification. J. Sci. Ind. Res. 75 (6), 349–354.; **19.** Nazri, A., Mazlan, N., Muharam, F., 2018. PENYEK: Automated brown planthopper detection from imperfect sticky pad images using deep convolutional neural network. PLoS ONE 13 (12).; **20.** Partel, V., Nunes, L., Stansly, P., Ampatzidis, Y., 2019. Automated vision-based system for monitoring Asian citrus psyllid in orchards utilizing artificial intelligence. Comput. Electron. Agric. 162, 328–336.; **21.** Picon, A., Alvarez-Gila, A., Seitz, M., Ortiz-Barredo, A., Echazarra, J., Johannes, A., 2018. Deep convolutional neural networks for mobile capture device-based crop disease classification in the wild. Comput. Electron. Agric.; **22.** Ram, S., Rodríguez, J.J., 2016. Size-invariant detection of cell nuclei in microscopy images. IEEE Trans. Med. Imaging 35 (7), 1753–1764.; **23.** Ramcharan, A., Baranowski, K., McCloskey, P., Ahmed, B., Legg, J., Hughes, D.P., 2017, Deep learning for image-based cassava disease detection. Front. Plant Sci. 8.; **24.** Roldán-Serrato, K.L., Escalante-Estrada, J., Rodríguez-González, M., 2018. Automatic pest detection on bean and potato crops by applying neural classifiers. Eng. Agric. Environ. Food 11 (4), 245–255.; **25.** Shen, Y., Zhou, H., Li, J., Jian, F., Jayas, D.S., 2018. Detection of stored-grain insects using deep learning. Comput. Electron. Agric. 145, 319–325.; **26.** Sun, Y., Liu, X., Yuan, M., Ren, L., Wang, J., Chen, Z., 2018. Automatic in-trap pest detection using learning for pheromone-based Dendroctonus valens monitoring. Biosyst. Eng. 176, 140–150.; **27.** Tan, W., Zhao, C., Wu, H., 2016. Intelligent alerting for fruit-melon lesion image based on momentum deep learning. Multimedia Tools Appl. 75 (24), 16741–16761.; **28.** Wen, C., Wu, D., Hu, H., Pan, W., 2015. Pose estimation-dependent identification method for field moth images using deep learning architecture. Biosyst. Eng. 136, 117–128.; **29.** Xia, D., Chen, P., Wang, B., Zhang, J., Xie, C., 2018. Insect detection and classification based on an improved convolutional neural network. Sensors 18 (12), 4169.; **30.** Zhong, Y., Gao, J., Lei, Q., Zhou, Y., 2018. A vision-based counting and recognition system for flying insects in intelligent agriculture. Sensors 18 (5), 1489.; **31.** Mohanty SP, Hughes DP, Salathé M. Using Deep Learning for Image-Based Plant Disease Detection. Front Plant Sci. 2016 ; **32.** Brahimi M, Boukhalfa K, Moussaoui A. Deep learning for tomato diseases: classification and symptoms visualization. Appl Artif Intell 2017;31(4):299–315; **33.** H. Durmuş, E. O. Güneş and M. Kırcı, "Disease detection on the leaves of the tomato plants by using deep learning," 2017 6th International Conference on Agro-Geoinformatics, 2017.

Annex 1. Innovations in pest and disease image recognition (continued).

#[114]	Study	Algorithm	Type	(Disease) Classes	% Detection	Dataset	Image	Crop
34	Amara et al. (2017)	CNN	Img. classif.	3	92–99	3700	Leaf disease	Banana
35	Shijie et al. (2017)	VDCN	Img. classif.	11	89	7040	Leaf disease	Tomato
36	Yuan et al. (2018)	CNN, VDCN	Img. classif.	8	95.93	2430	Leaf disease	Rice, Cucumber
37	Wang et al. (2018)	CNN	Img. classif.	8	90.84	2430	Leaf disease	Rice, Cucumber
38	Xu et al. (2021)	CNN	Img. classif.	4	90	3852	Leaf disease	Maize
39	Luna et al. (2018)	CNN	Img. classif.	2	91.67	4923	Leaf disease	Tomato
40	Ferentinos (2018)	CNN	Img. classif.	58	99.53	87848	Plant disease	25 crops
41	Zhang et al. (2018)	CNN, RNN	Img. classif.	9	97.28	5550	Leaf disease	Tomato
42	Zhang et al. (2019)	CNN	Img. classif.	2	99.6	1200	Leaf disease	Cherry
43	Lin et al. (2019)	CNN	Img. classif.	2	96.08	50	Leaf disease	Cucumber
44	Barbedo et al. (2019)	CNN	Img. classif.	79	75–100	46409	Leaf disease	14 crops
45	Liang et al. (2019)	CNN, SVM	Img. classif.	2	95.83	5808	Plant disease	Rice
46	Selvaraj et al. (2019)	CNN	Img. classif.	18	90	18000	Plant disease	Banana
47	Qiang et al. (2019)	CNN	Img. classif.	unknown	95.8	unknown	Leaf disease	Multiple
48	Too et al. (2018)	DCCN	Img. classif.	26	99.75	54306	Plant disease	14 crops
49	Wang et al. (2019)	CNN	Img. classif.	15	96.61	4394	Plant disease & weeds	Cucumber, Rice, Maize
50	Verma et al. (2020)	CNN, RNN	Img. classif.	3	87.6	1076	Leaf disease	Grape
51	Tabar et al. (2021)	CNN+LSTM, FNN	Img. classif.	1	88-89	21000	Desert Locust	Multiple

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TMG Research

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