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Effect of global climate change on insect populations, distribution, and its dynamics

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ABSTRACT

Insects are vital to various ecosystems as pollinators, decomposers, and food sources for many organisms. They dominate diverse terrestrial (e.g., glassland) and aquatic (lakes, oceans, rivers, etc.) ecosystems. Previous studies report that more than half of the estimated 2.0 million species of living organisms identified on our planet are insects. However, global climate change (GCC), characterised by rising temperatures and altered precipitation patterns, significantly impacts their populations worldwide. We reviewed the literature to provide an overview of GCC events in insects. Collectively, the study findings reveal that global temperature and precipitation change are among the extreme GCC events affecting more than 30% of insect population, distribution, physiology, feeding habits, interactions, migration, and communication across the globe. The climate change intensifies insect cycles and insect damage in agroecosystems. In response, insect species alter their geographic ranges and phenology, changing population dynamics and interactions. GCC also influences reproductive patterns, including mating behaviour and breeding synchrony. Warmer global temperatures might advance or delay insect emergence, causing mismatches with food availability or pollination partners. While some insect populations may adapt, extreme heat events or prolonged droughts exceeding their physiological tolerance result in population declines or local extinctions. Predictions suggest that up to 65% of insect populations could face extinction within the next century due to increasing climate change. Thus, understanding these impacts is essential for predicting the ecological consequences of the GCC and developing effective conservation strategies to mitigate such impacts and protect insect biodiversity and ecosystem services.

Introduction

Our planet contains a high biodiversity of insects distributed over a wide range of habitats (Eickermann et al., 2023; Marschalek and Deutschman, 2022; Montagna et al., 2012). They dominate diverse terrestrial (*e.g.*, forests, savannas, etc.) and aquatic (lakes, oceans, rivers, etc.) ecosystems (Arnold et al., 2021; Minachilis et al., 2021). Previous studies report that more than half of the estimated 2.0 million species of living organisms identified on our planet are insects (Marschalek and Deutschman, 2022). Some of these insects are either beneficial or harmful (non–beneficial) to humans and ecosystems (Arnold et al., 2021; Erenler et al., 2020; Ojija et al., 2023). Beneficial insects include, for instance, pollinators, which contribute to crop, vegetable, fruit, and honey production (Bezerra et al., 2019; Buckner and Danforth, 2022; Chain-Guadarrama et al., 2019; Ojija and Adam Silabi, 2024), and decomposers of organic matter that play an essential role in soil nutrient cycling and aeration (Jacobsen et al., 2017; Mabika et al., 2014; Marschalek and Deutschman, 2022; Noriega and Scholwalter, 2024). It is thought that beneficial insects are the major players in ensuring environmental sustainabilityand maintaining biodiversity and ecosystem health (Arnold et al., 2021; Noriega et al., 2028; Ojija et al., 2023). On the other hand, non–beneficial insects to humans include insect pests

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that destroy food crops, vectors for disease-causing microbes, or directly cause some illness (Skendžić et al., 2021; Subedi et al., 2023). Besides, some insect species are natural enemies; thus, they are considered the biological control of pests (Hatting, 2017; Judt et al., 2023; Lundin et al., 2015). Whether beneficial or harmful to human and ecosystem sustainability, insects may be adversely impacted by global climate change (GCC) (Bezerra et al., 2019; Buckner and Danforth, 2022; Harvey et al., 2023; Huang et al., 2022).

Climate change significantly impacts insect populations, distribution, and dynamics (Cardoso, et al., 2020). Rising temperatures generally lead to faster development and increased survival of insects in mid to high latitudes, resulting in range expansions and shifts in species distributions (Stange and Ayres, 2010). These changes can alter insect–plant interactions, pest damage to crops, and food security (Sharma, 2014). Temperature increases may also affect insect voltinism, fecundity, and dispersal, potentially causing rapid and large–scale effects on population dynamics (Stange and Ayres, 2010; Karuppaiah and Sujayanad, 2012). Additionally, elevated CO_2 levels can influence pest abundance by altering plant nutritional value and increasing herbivore consumption rates (Karuppaiah and Sujayanad, 2012). Climate change may also impact the efficacy of pest control measures and increase problems with insect–transmitted diseases (Sharma, 2014). These effects are species–specific and can vary across distributions, growing seasons, and crop types, making their study complex (González-Varo et al., 2013; Ojija and Nicholaus, 2023).

Previous studies state that the GCC is of great concern because it threatens world biodiversity, including insects (Decourtye et al., 2019; González-Varo et al., 2013; Ojija and Nicholaus, 2023; Peters et al., 2019). It impacts animal species over space and time (Fig. 1), consequently influencing their population dynamics and distribution patterns (Chain-Guadarrama et al., 2019; Dzekashu et al., 2022; Erenler et al., 2020a; Rafferty, 2017; Wyver et al., 2023). Unfortunately, when some scientists, ecologists, or conservationists think of the impact of GCC on animals and their conservation, most of the species that quickly come to mind are such as lions, cheetahs, leopards, hippopotamus, rhinoceros, elephants, buffalo, and the like (Eickermann et al., 2023). Yet, many species of animals that GCC threatens are invertebrates, particularly insects (Gorostiague et al., 2018; Harvey et al., 2023; Huang et al., 2022). Insects are the most affected due to their cold–blooded nature, which makes them live in areas with temperatures that are suitable for their biological processes, for instance, reproduction, growth, development, and survival (Harvey et al., 2023; Huang et al., 2022). The most known GCC's environmental factors—temperatures, precipitation, and atmospheric carbon dioxide (CO_2)—are thought to have paramount impacts on insect biodiversity (Buckner and Danforth, 2022; Classen et al., 2020; Duffy et al., 2022; Ojija and Nicholaus, 2023; Thibaudon et al., 2020). They are considered the main driving forces for the decline of global insect biodiversity (Decourtye et al., 2019; Duffy et al., 2022; Harvey et al., 2023; Vasiliev and Greenwood, 2021). A change in these factors (*i.e.,* too low or too high) can impact insects in multitudes of ways (Fig. 1), including their physiology, reproduction, growth, behaviour, and physical features, as well as relationships with other species (Classen et al., 2020; Eickermann et al., 2023; Gorostiague et al., 2018; Rafferty, 2017; Thibaudon et al., 2020).

Global climate changemay cause insects to change their interactions between and within species (Fig. 1), with host plants, animals, and/or natural enemies (Gorostiague et al., 2018; Harvey et al., 2023; Proesmans et al., 2021). A persistent GCC can cause some insects to turn into potential pests and/or invasive species so that they can adjust to the changing climate or weather (Proesmans et al., 2021; Skendžić et al.,

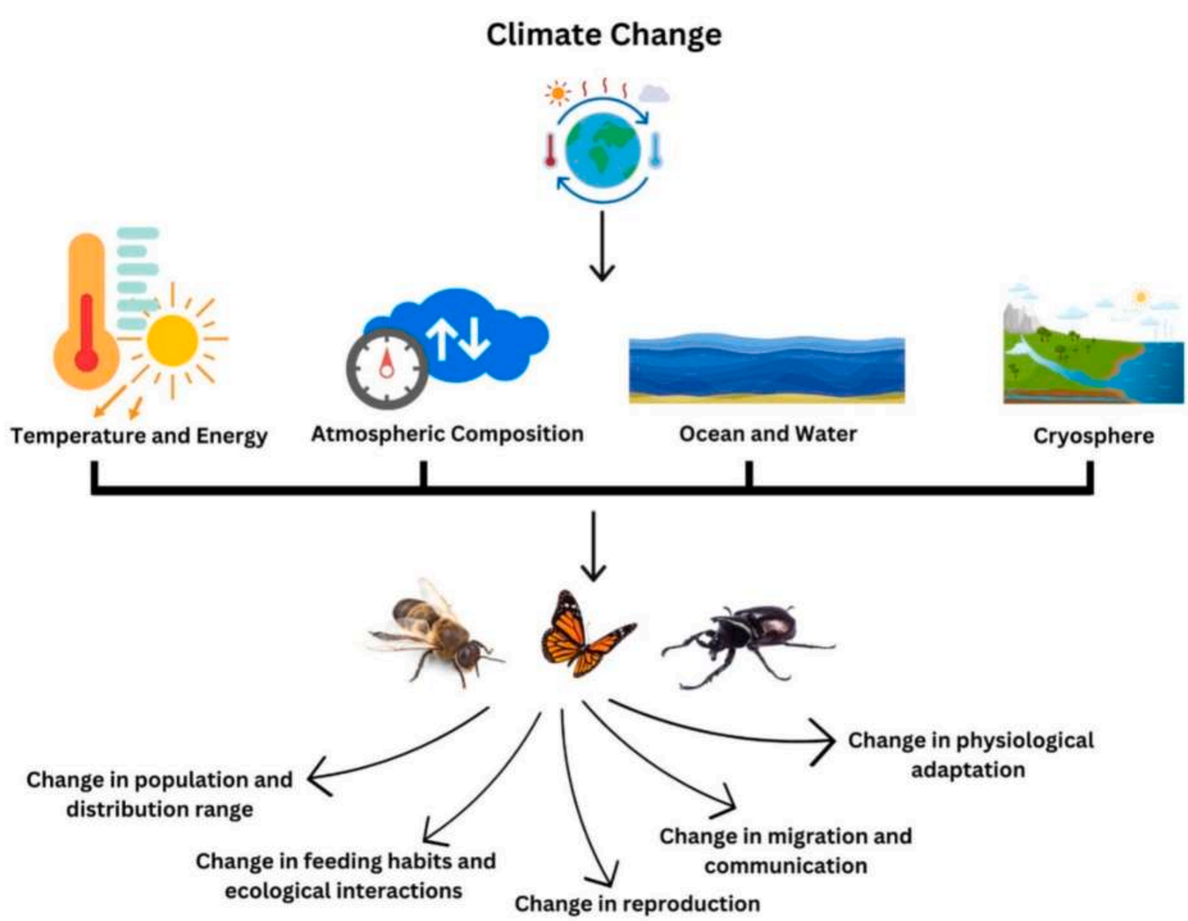

Fig. 1. The impact of global climate change on insect population and its dynamics pests (Source: Recreated with paid icons from https://www.freepik.com/).

2021; Subedi et al., 2023). The increase in global temperature and precipitation patterns has been shown to affect the reproduction pattern of insects, their distribution, and their population size (Fig. 1), *i.e.,* abundance and diversity (Huang et al., 2022; Zhao et al., 2023). This is because the insects could be forced to relocate to suitable habitats or expand their geographic range (Wang et al., 2023). This occurs because insects are ectotherms and, thus, sensitive to changes in ambient temperature and precipitation (Duffy et al., 2022; Harvey et al., 2023). Although there is widespread interest in the impact of GCC on insect biodiversity, such interest is limited in some parts of the world due to the paucity of studies (Decourtye et al., 2019; Eickermann et al., 2023; Rafferty, 2017). Consequently, there has not been much information on how climate change has affected, continues, and will affect insect biodiversity (Duffy et al., 2022; Rafferty, 2017). This knowledge about the relationships between GCC and insect biodiversity is vital because it provides critical information that would aid in their conservation initiative. Therefore, our review provides evidence and highlights the impact of GCC and associated extreme events *(i.e.,* high temperatures, droughts, heavy rainfall, and flooding) on insect populations and distribution ranges, feeding habits and ecological interactions, reproduction, physiological adaptation, migration, and communication.

Review methodology and focus

To ensure transparency and replicability, a comprehensive search strategy was developed using a combination of climate– and insect–related terms. The search was conducted across major academic databases (e.g., Scopus, Web of Science, and Google Scholar), targeting peer-reviewed literature published in English. Searches were performed using Boolean operators ("AND", "OR") and quotation marks to retrieve exact phrases. The terms were searched within the title, abstract, and keywords fields. The search strings included combinations of the following terms:

Climate–related terms: "climate change", "global climate change", "rising temperatures", "altered precipitation patterns", "extreme precipitation", "heavy rainfall", "droughts", "flooding", "high temperatures", "global change".

Insect–related terms: "insects", "insect behaviour", "insect population", "insect distribution range", "insect biodiversity", "insect pollinators", "plant–insect interactions".

Combined search phrases: "climate change impact on insects", "climate change and insects", "global climate change and insect biodiversity", "effects of temperature on insects", "effects of precipitation on insects", "global change and biodiversity loss", "insect pollinators and extreme temperature", "insects and droughts", "impact of extreme precipitation on insects", "impact of climate change on plant-insect interactions", "insects and heavy rainfall".

An example of a typical search string used in databases was: ("climate change" OR "global climate change" OR "rising temperatures" OR "heavy rainfall" OR "droughts" OR "flooding") AND ("insects" OR "insect biodiversity" OR "insect pollinators" OR "insect population" OR "plant–insect interactions").

No date restriction was applied to ensure a broad scope of literature, but only publications in English were included. Duplicates were removed, and articles were screened based on relevance to the review's objectives. Furthermore, unpublished materials and potentially predatory journals and publishers (*i.e.,* those listed and not listed here at https://beallslist.net/) were removed. In total, 109 literature sources were reviewed as part of this study.

Impact of global climate change on insect population and distribution range

The population size and distribution range of insects can be limited or facilitated by GCC (Bezerra et al., 2019; Buckner and Danforth, 2022; Dzekashu et al., 2022). Rafferty (2017) reports that shifts in the distribution of insects are among the most significant consequences of GCC (Fig. 2). The GCC extreme weather events (*i.e.,* severe droughts, heat waves, and flooding) associated with increasing global temperature, and precipitation have been claimed to affect the population of insects directly (Eickermann et al., 2023; Harvey et al., 2023; Ojija and Nicholaus, 2023; Vasiliev and Greenwood, 2021). This is because they can negatively affect the insects' reproduction rate (*i.e.*, by lowering their fecundity and growth rate) and survival (*i.e.,* by causing death due to drying or drowning) (Filazzola et al., 2021; Walker et al., 2019). For instance, a study conducted in China found that temperature and precipitation were the potential environmental factors for threatening current and future distribution of *Frankliniella occidentalis* (Pergande, 1895) (Wang et al., 2023). Evidence from preceding studies has also predicted that increased global temperatures and precipitation variability can affect insect species' distribution range, abundance, and diversity (Buckner and Danforth, 2022; Decourtye et al., 2019; Sánchez-Bayo and Wyckhuys, 2019). It was asserted further that as global temperatures increase, certain species of insects may lose their original or native habitat while others may expand their home range into new habitats (Bezerra et al., 2019; Huang et al., 2022). For instance, Huang et al. (2022) found that the specialist bee *Macropis nuda* (Provancher, 1882) changed its distribution range in the United States due to increased greenhouse gas emissions and temperature.

The insects disrupt their population size and community composition by changing or expanding the home range in response to varying temperatures and precipitation (Gonzalez et al., 2021; Vasiliev and Greenwood, 2021). Because of this, their abundance, diversity, and distribution range are likely to change, *i.e.,* decline or increase (Zhao et al., 2023). However, it is essential to note that the GCC–specific impacts on insect population and distribution range are species-specific, meaning that they can vary depending on the species traits and their ecological requirements (Bezerra et al., 2019; Minachilis et al., 2021; Nielsen et al., 2017; Subedi et al., 2023). In Vestfold County in Norway, for instance, a study showed that the honeybees were more sensitive to varying ambient temperature and future GCC than bumblebees (Nielsen et al., 2017). Frequent droughts or irregular precipitation affect habitats and food resources available for insects (Skendžić et al., 2021), thereby causing their demise or forcing them to redistribute or relocate to other areas (Erenler et al., 2020; Kolanowska et al., 2021). Previous studies reported that the population of insect pollinators could be impacted when increases in global temperatures or precipitation reduce or alter the pollen or nectar quality (Kolanowska, 2021; LeBuhn and Vargas Luna, 2021; Rafferty, 2017). The insects might be forced to relocate to areas with quality food resources, *i.e.*, pollen or nectar (Kolanowska et al., 2021a, 2021b; Travis et al., 2013).

Shifts in precipitation patterns (*i.e.,* limited rainfall or too high rainfall leading to flooding) can significantly affect the water sources available for insects, subsequently impacting their reproduction and survival (Wang et al., 2023). Flooded areas due to high rainfall or those with a limited amount of rainfall might become inhabitable for insect species, making them relocate to other habitats or die (Parmesan and Yohe, 2003; Subedi et al., 2023; Walther et al., 2002). The relocation or migration of insects to new habitats can lead to changes in their distribution range, community composition, and population size in their original and new habitats (Vasiliev and Greenwood, 2021; Wang et al., 2023; Zhao et al., 2023). A change in population size resulting from the death, relocation, or migration of insects might eventually lead to the extinction of insect species and other indirect consequences on ecosystem integrity (Gonzalez et al., 2021; Harvey et al., 2023). The evidence from existing studies (Table 1) has also shown that the decline of the insect population due to GCC is threatening some species to extinction (Buckner and Danforth, 2022; Harvey et al., 2023; Zhao et al., 2023). For instance, Duffy et al. (2022) reported that over the next century, 65 % of the population of insects might go extinct due to increasing global climate change. Another study found that GCC may lead to changes in the natural ranges of Xylocopa bees in the Neotropics

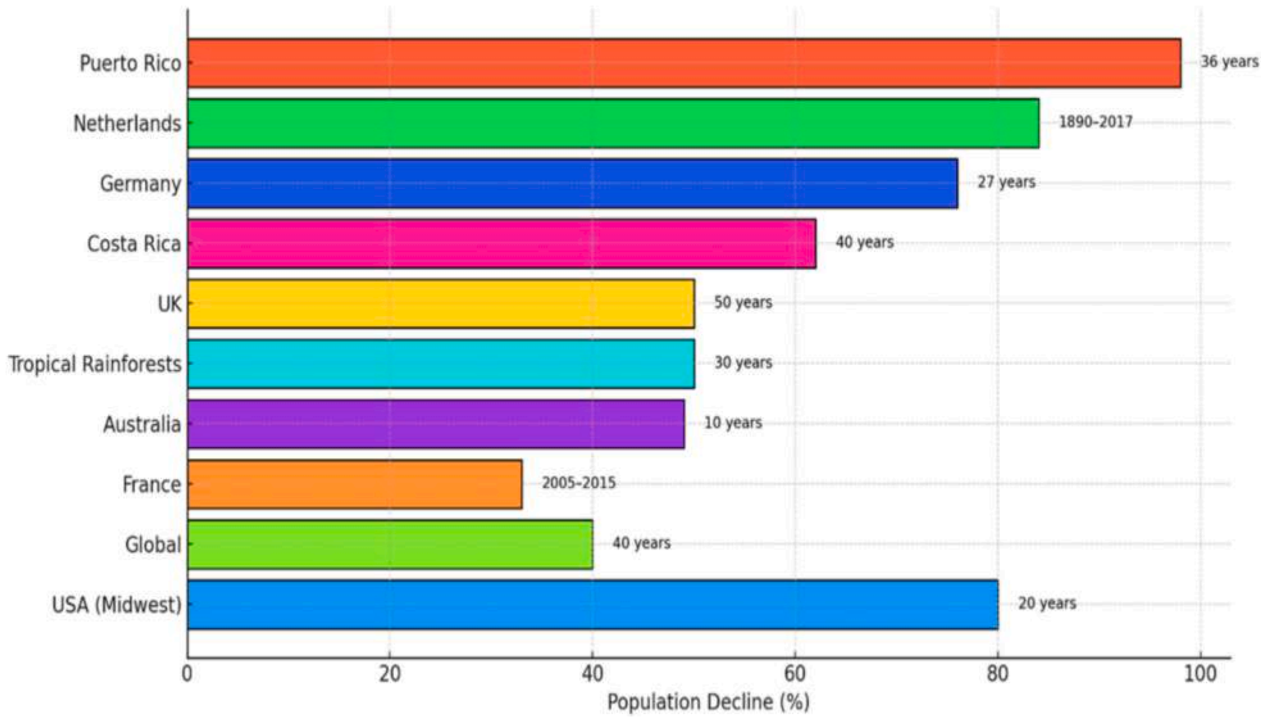

Fig. 2. The percentage declines of insects across among countries represented by the bar lengths, and the time frames for each region are displayed at the ends of the bars.

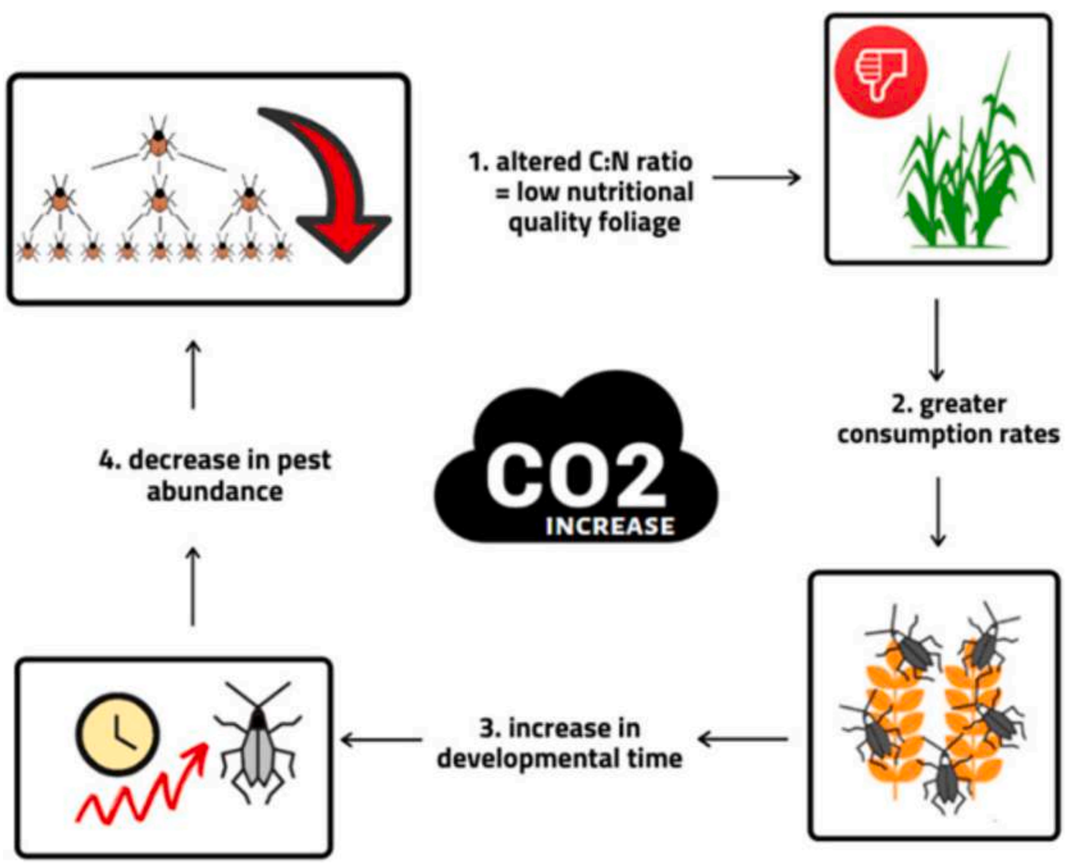

Fig. 3. Impact of heavy precipitation and drought on agricultural insect pests. pests (Source: Recreated with paid icons from https://www.freepik.com/).

Table 1
Evidence on the impact of global climate change on insect species.

GCC's impact on insect species	Place/country/ region	Source
Changes in spatial distribution or the natural ranges of Xylocopa bees	Neotropics	Bezerra et al. (2019)
Loss of habitable area of *Xylocopa frontalis*	Neotropics	Bezerra et al. (2019)
Natural range shifts of a rare specialist bee *Macropis nuda*	United States and Southern Canada	Buckner and Danforth (2022)
Change in the seasonal patterns of bee species in the Taita Hills region	Kenya	Dzekashu et al. (2022)
G.C.C. predicted a reduced distribution range of stingless bees	Colombia	Gonzalez et al. (2021)
Temperatures were predicted to affect the distribution range of *Apis dorsata*and *Apis laboriosa*	Nepal and China	Huang et al. (2022)
Increased temperature is predicted tocause redistribution of*Hippotiscus dorsalis* to suitable areas and a change in population density.	China	Zhao et al. (2023)
Distributions (both current and future) of *Frankliniella occidentalis*are likely to shift toward suitable areas due to varying temperature and precipitation patterns.	China	Wang et al. (2023)
Climate change was observed to affect insect–pollinator (bees, butterflies, and hoverflies) diversity and distribution on Mount Olympus.	Greece	Minachilis et al. (2021)
Ambient temperature affected the honeybees, suggesting they are more vulnerableto GCC	Norway	Nielsen et al. (2017)
Decline of non–migratory British butterfly species	Britain	Warren et al. (2001)

(Bezerra et al., 2019), *Apis dorsata* (Fabricius, 1793) and *Apis laboriosa* (Smith, 1871) in Nepal and China (Huang et al., 2022), and reduce the distribution ranges of stingless bees in Colombia (Gonzalez et al., 2021). Some of the evidence on the impact of GCC on insects worldwideis presented in Tables 1, 2 and 3.

Global climate change alters insect species' geographic ranges, resulting in range expansions, contractions, or elevational distributions (Buckner and Danforth, 2022; Forister et al., 2010; Rafferty, 2017). Also, insects tend tomigrate to new habitats with favourable climatic conditions, altering community composition and species interaction (Warren et al., 2001). However, GCC can benefit insects with enhanced thermal tolerance, resulting in individuals that can endure higher temperatures (Sunday et al., 2014).

Impact of global climate change on insects'feeding habits and ecological interactions

Insects may exhibit rapid evolutionary changes in response to climate–driven selection pressures on feeding strategies and ecological interactions (Kolanowska et al., 2021a; Parmesan and Yohe, 2003). Changes in temperature and precipitation can influence the abundance, distribution, and phenology of plants and animals, leading to mismatches in food availability for herbivores and their predators (Table 4). For instance, shifts in plant growth and insect emergence can create timing disparities, affecting species' ability to find suitable food (Visser and Holleman, 2001). Altered climate conditions can also impact the nutritional quality of host plants, influencing insect feeding preferences (Bale et al., 2002). Moreover, GCC can facilitate insect range expansions, leading to novel interactions, with some species becoming invasive (Chen et al., 2011; Ojija, 2024; Ojija et al., 2024). Additionally, changes in food availability may disrupt trophic interactions within food webs (Table 2). For example, insect prey population declines caused by climate-induced stressors like habitat loss and phenological mismatches can affect predator abundance (Deutsch et al., 2008; Harvey et al., 2023). As a result, insect herbivores may adjust their foraging behaviour, shifting their diets to include new plant species as traditional food

Table 2
Studies conducted to assess the impact of climate change in insect dynamics and their major findings.

Study	General observation	Study specific findings	References
Climate change impacts: insects	Climate change impacts insect populations, distribution, and dynamics through effects on survival, generation time, fecundity, and dispersal.	• Warmer temperatures have led to faster development and increased survival of insects in mid- to high latitude regions, resulting in observable shifts in insect species distributions. • Warmer temperatures have caused many insect species to advance the timing of their life cycle events, as they use temperature as a cue to synchronize their life history with seasonal changes. • Insects' short lifespans, high reproduction, and high mobility allow their physiological responses to warming temperatures to have particularly large and rapid impacts on their population dynamics.	Stange an Ayres (2010)
Impact of climate change on population dynamics of insect pests	Climate change, especially rising temperatures, can impact insect population dynamics through effects on survival, fecundity, voltinism, and distribution.	• Higher temperatures lead to decreased survival rates of certain insect pests, impacting their population dynamics in rice ecosystems. • Warming lead to changes in the number of generations per year (voltinism) of insect pests, benefiting multivoltine species and leading to changes in their geographical distribution. • Elevated CO_2 levels impacted population abundance of insect pests, potentially by altering the nutritional value of plants and leading to changes in insect	Skendžić et al. (2021)

(continued on next page)

Table 2 (*continued*)

Study	General observation	Study specific findings	References
		abundance and consumption rates.	
Climate change effects on insects: implications for crop protection and food security	Climate change trigger major changes in insect diversity, abundance, distribution, and population dynamics, with implications for crop protection and food security.	• Climate change lead to major changes in arthropod diversity, insect pest distribution, and population dynamics. • Several insect pests observed to expand their range from tropical to temperate regions, causing increased damage to various crops. • The effectiveness of various pest management strategies, including host plant resistance, transgenic crops, natural enemies, and pesticides reported to likely decrease due to climate change.	Sharma (2014)
Insect pest management in the era of climate change	Climate change affects insect physiology, biogeography, and population dynamics, with major implications for agriculture.	• Found that Climate change can lead to changes in insect physiology, biochemistry, biogeography, and population dynamics, which can vary across different insect species, geographic regions, and crop types. • The impacts of climate change on insects are species-specific, making them challenging to study and understand. • Key effects of climate change on insect pests include changes in geographical distribution, asynchrony with host plants, increased voltinism (number of generations per year), enhanced pest damage to crops, changes in inter-species interactions, and impacts on invasive species, with some effects being more pronounced than others.	Mohd et al. (2021)
Impact of climate change on insect biology, ecology, population dynamics, and pest management: a critical review	Climate change impacts insect biology, ecology, population dynamics, and pest management, with a need for more research in neotropical countries.	• Climate change is affecting insect biology, ecology, population dynamics, and pest management in various ways. • Insects are responding to climate change through changes in their behavior, development, survival, and geographic distribution. • Calls for more research on the impact of climate change on insects, especially in the neotropical regions.	Lakhnarayan et al. (2023)
Direct impacts of recent climate warming on insect populations.	Climate change has complex effects on insect development, dispersal, and population dynamics.	• Climate change is inducing significant responses from insect species, including earlier flight periods, enhanced winter survival, and acceleration of development rates. • Climate change disrupted phenological synchrony between insects and their host plants, but adaptive genetic processes are likely to quickly restore this synchrony. • Climate change removed or relocated barriers that limit the current species' ranges, facilitating the establishment and spread of invasive alien species.	Robinet (2010)
The impact of climate change on agricultural insect pests	Climate change can affect insect pests by expanding their geographic range, increasing overwintering survival, and altering their interactions with plants and natural enemies.	• Climate change, including increased temperatures, rising atmospheric CO_2 levels, and changing precipitation patterns, had significant impacts on agricultural insect pests (Fig. 3). • Affected insect pests in several	Skendžić et al. (2021)

(*continued on next page*)

Table 2 (*continued*)

Study	General observation	Study specific findings	References
		ways, including expanding their geographic range, increasing overwintering survival, increasing the number of generations, altering interactions with host plants and natural enemies, and increasing the risk of invasive species and insect-transmitted plant diseases. • Adaptation strategies are needed to address the impacts of climate change on agricultural insect pests, including modified integrated pest management (IPM) practices, monitoring climate and pest populations, and using modeling prediction tools.	

sources diminish(Deutsch et al., 2008). As species search for suitable habitats due to shifting climate zones, novel species interactions, and competitive dynamics emerge in new communities (Harvey et al., 2023; Rafferty, 2017; Skendžić et al., 2021). Furthermore, some insect species may display phenotypic plasticity or genetic adaptation in response to these changes, but rapid climate shifts could overwhelm adaptive responses, disrupting ecological stability and resilience (Hoffmann, 2011). Previous studies have also reported that warmer temperatures can accelerate insect development, leading to earlier emergence of adults and changes in life cycle timing (Harvey et al., 2023; Parmesan, 2006; Subedi et al., 2023). This can cause insects to extend their activity periods or shift to different seasons due to changes in temperature and photoperiod (Harvey et al., 2023b; Parmesan, 2006).

The GCC poses complex challenges for insect feeding behaviours, affecting their ecological interactions and population dynamics (Table 4). However, some species can exhibit phenotypic plasticity in feeding behaviours, enabling them to cope with changing environmental conditions (Parmesan and Yohe, 2003). Thus, understanding these impacts is vital for predicting ecosystem responses and developing effective strategies for conservation and management in a changing world.

Impact of global climate change on insects' reproduction

With far-reaching effects on population dynamics, species interactions, and ecosystem health (Gonzalez et al., 2021; Zhao et al., 2023), the GCC also posessignificant challenges to the reproductive success and fecundity (the ability to produce offspring) of insects (Eickermann et al., 2023; Sharma, 2014). Changes in global temperatures and precipitation patterns can alter the developmental processes of insects, leading to changes in life cycle timing and the synchronization between insects and their environment (Filazzola et al., 2021; Parmesan and Yohe, 2003). For instance, warmer temperatures can accelerate the rate of insect development, causing earlier emergence of adults and shifting their reproductive cycles (Filazzola et al., 2021). These changes in phenology—seasonal life cycle events—can create divergences between the timing of insect reproduction and the availability of vital resources, *i.e.,* host plants for oviposition (egg-laying) and larval development (Forrest and Thomson, 2011; Sharma, 2014). As GCC alters environmental cues, insects might emerge or reproduce when conditions are not optimal for their survival or the survival of their offspring (Wyver et al., 2023). If, for example, adult insects emerge before their primary food sources or host plants are available, it can negatively impact reproductive success. This disparity may reduce the availability of suitable sites for oviposition and the availability of food for larvae, thus impairing their development and survival (Forrest and Thomson, 2011). Such disruptions can cascade through ecosystems, affecting insect populations and species that rely on them, including plants, pollinators, and predators (Wyver et al., 2023).

Global temperature fluctuations, especially extreme weather events like heat waves and droughts, can further exacerbate these challenges (Filazzola et al., 2021). Prolonged periods of excessive heat can directly affect insect reproductive physiology, influencing hormone regulation, gamete production, and mating behaviours (Table 3). Insects that rely on specific temperature cues for courtship, mating, or oviposition may be disrupted under changing climatic conditions (Jaworski and Hilszczański, 2013). Heat stress, for example, can impair the mating behaviours of insects, reducing the frequency of successful copulation and thereby decreasing overall reproductive output (Table 3). Similarly, drought conditions can limit the availability of water and food

Table 3
Insect population decline across regions as associated with climate change impacts.

Country	Time frame	Population decline (%)	Affected groups	Cause	Source
Puerto Rico	36 years	98 % decline in ground-foraging arthropods	Arthropods	Rising temperatures	Lister and Garcia, (2018)
Netherlands	1890–2017	84 % decline in butterflies	Butterflies	Habitat loss, climate change	Warren et al. (2021)
Germany	27 years	76 % decline in flying insect biomass	Flying insects	Intensive agriculture, pesticide use	Hallmann et al. (2017)
Costa Rica	40 years	62 % decline in butterfly species richness	Butterflies	Deforestation, rising temperatures	Hill et al. (2021)
UK	50 years	50 % decline in some moth species	Moths	Light pollution, habitat fragmentation	Boyes et al. (2021)
Tropical Rainforests	Past 30 years	40–60 % decline in insect biomass	Various insect taxa	Climate change, deforestation	Wagner et al. (2021)
Australia	Past decade	49 % decline in insect species abundance	Native insects	Urbanization, habitat loss	Sánchez-Bayo and Wyckhuys (2019)
France	2005–2015	33 % decline in bumblebee populations	Bumblebees	Pesticides, rising temperatures	Goulson et al. (2015)
Global	40 years	>40 % decline in insect species globally	Various insect taxa	Climate change, habitat destruction, pollution	Sánchez-Bayo and Wyckhuys (2019)
USA (Midwest)	20 years	80 % decline in monarch butterfly numbers	Monarch butterflies	Loss of milkweed, herbicide use	Pleasants and Oberhauser, (2013)

Table 4
Examples of the impact of global climate change on insect feeding behaviour and ecological interactions.

GCC impact	Description	Source
Alter insect-plant interactions	Changes in plant phenology affecting the timing of insect-host interactions. Phenological mismatches between insect life stages and host plant availability	Visser and Holleman (2001); Wyver et al. (2023)
Increase herbivory	Warmer temperatures and elevated CO_2 levels lead to enhanced plant growth rates—higher consumption rates by herbivorous insects.	Bale et al. (2002)
Changes in feeding preferences	Altered host plant suitability and nutritional quality under changing climate conditions. Shifts in insect species composition and diet breadth.	Sharma (2014); Subedi et al. (2023); Walther et al. (2002)
Range expansion and colonization	Climate-driven shifts in geographic distributions of insect species. Expansion into new habitats and ecosystems.	Eickermann et al. (2023); Parmesan et al. (1999); Walther et al. (2002)
Changes insects' feeding behaviour	Behavioural flexibility enables adaptation to changing environmental conditions—variability in feeding strategies and resource utilization.	Bale et al. (2002); Eickermann et al. (2023); Harvey et al. (2023); Sharma (2014); Subedi et al. (2023)
Disrupts trophic interactions	They altered predator–prey dynamics due to changes in insect abundance and behaviour—cascading effects on food webs and ecosystem functioning.	Bale et al. (2002); Deutsch et al. (2008); Erenler et al. (2020); Sharma (2014); Subedi et al. (2023)
Infuence evolutionary responses to climate stress	Genetic adaptations in insect populations in response to climate-driven selection pressures. Rapid evolutionary changes in feeding-related traits.	Hoffmann and Sgrò (2011)
Impact on pollination dynamics	Changes in pollinator behaviour and efficiency due to altered climate conditions. Implications for plant reproductive success and diversity.	Burkey and Reed (2006)
Facilitates establishemnt of invasive species	Climate change facilitates the spread and establishment of invasive insect pests—competition for resources and disruption of native ecosystems.	Chen et al. (2011); Ojija (2024); Ojija et al. (2024)
Impact on disease vectors and transmission	Altered distribution and abundance of disease-carrying insect vectors. Changes in disease transmission dynamics and public health risks.	Eickermann et al. (2023); Skendžić et al. (2021); Subedi et al. (2023)
Disruption of mutualistic interactions	Climate-induced mismatches between insects and symbiotic partners (e.g., ants and aphids, wasps and trees). Consequences for ecosystem stability and plant-animal interactions.	Blanchard et al. (2019); Kikuchi et al. (2016); Vidal et al. (2021)

Table 5
Examples of the impacts of global climate change on insect reproduction.

Impact of climate change	Description	Source
Changes in phenology and timing	Warmer temperatures can accelerate insect development, leading to shifts in emergence timing and life cycle events.	Forrest and Thomson (2011); Parmesan (2006); Parmesan and Yohe (2003); Wyver et al. (2023)
Altered mating behaviour	GCC may disrupt mating behaviours due to temperature fluctuations and changes in seasonal cues.	Deutsch et al. (2008); Forrest and Thomson (2011)
Impact on fertility and egg production	Insects may experience reduced fertility and egg production under extreme heat conditions.	Visser and Holleman (2001)
Disruption of reproductive synchrony	Changes in temperature and precipitation patterns could disrupt synchrony between insects and host plants.	Forister et al. (2010); Rafferty (2017)
Increases stress and mortality	Extreme weather events like heatwaves or droughts can increase insect stress levels.	Harrington et al. (1999); Marschalek and Deutschman (2022); Navarro-Cano et al. (2015)
Impacts distribution range	Insects may shift their geographic ranges in response to changing climate conditions.	Walther et al. (2002)
Impacts on oviposition behavior	Climate change can alter oviposition behaviour, affecting the selection of suitable egg-laying sites.	Visser and Holleman (2001)
Changes reproductive physiology	Insects may undergo physiological changes in response to climate stress, affecting reproductive hormones.	Blanchard et al. (2019); Skendžić et al. (2021); Visser et al. (2006)
Disrupts symbiotic relationships	Climate change can disrupt symbiotic relationships between insects and their microbial or pollinator partners.	Burkey and Reed (2006); Kikuchi et al. (2016)
Impact on parental Care	Changes in climate conditions may affect parental care behaviours, such as the provisioning of offspring.	Gonzalez et al. (2021); Harrington et al. (1999); Navarro-Cano et al. (2015)
Adaptation through phenotypic plasticity	Some insects exhibit phenotypic plasticity in reproductive traits, allowing them to adapt to variable conditions.	Bale et al. (2002); Eickermann et al. (2023); Navarro-Cano et al. (2015)
Impacts on fecundity and offspring survival	Climate change can influence fecundity and offspring survival rates, affecting population growth.	(Deutsch et al., 2008)
Evolutionary responses to climate stress	Insect populations may undergo evolutionary changes in reproductive traits in response to climate change.	Harvey et al. (2023); Hoffmann and Sgrò (2011)
Impact on sperm viability and mating success	Climate factors can affect sperm viability and mating success in insects.	Eickermann et al. (2023); Hoffmann and Sgrò (2011)

resources, further affecting fecundity and the capacity of insects to produce viable offspring (Filazzola et al., 2021). In addition to reproductive physiology, temperature, and precipitation pattern shifts can modify the seasonal cues—such as temperature and photoperiod (day length)—that regulate insect breeding seasons (Bale et al., 2002; Navarro-Cano et al., 2015). Changes in these cues may lead to shifts in mating behaviours, courtship displays, and egg-laying timing (Table 5), all of which are crucial for reproductive success (Forrest and Thomson, 2011; Gonzalez et al., 2021). As breeding seasons become misaligned with environmental conditions, the survival rates of immature stages (*e.g.*, eggs, larvae) can be negatively impacted. For instance, if larvae hatch during food scarcity or extreme weather, their chances of reaching maturity may be drastically reduced, thus affecting population growth and long-term viability. Table 3 below provides examples of the impacts of GCC on insect reproduction, highlighting the complex interactions between environmental changes and reproductive biology.

One particularly concerning outcome of GCC is the disruption of mutualistic relationships between insects and other species (Harrington et al., 1999; Trunschke et al., 2024). For example, many insects are pollinators that rely on the timely blooming of flowering plants to obtain nectar and pollen. If climate change causes plants to bloom earlier or later than usual, this could reduce the availability of these essential resources for pollinators, potentially leading to declines in insect populations and, in turn, affecting plant reproduction (Rafferty, 2017; Trunschke et al., 2024). These shifts, whether caused by warming temperatures, altered precipitation patterns, or extreme weather events, can reduce reproductive success, compromise offspring fitness, and ultimately lead to population declines (Blanchard et al., 2019; Sharma, 2014). In the long run, these changes threaten the persistence of insect populations and the ecosystems that depend on their services, *i.e.*, pollination and pest control, under increasingly unpredictable climatic conditions (Deutsch et al., 2008; Forrest and Thomson, 2011; Navarro-Cano et al., 2015; Parmesan and Yohe, 2003).

Impact of global climate change on insects' physiological adaptation

The physiological adaptations of insects to GCC are vital for understanding how these organisms cope with rapidly shifting environmental conditions (Hill et al., 2021). Insects, being ectothermic, are particularly sensitive to changes in temperature, humidity, and other climatic factors, which directly influence their metabolic rates, survival strategies, and overall fitness (Harvey et al., 2020; Jaworski and Hilszczański, 2013). As global temperatures rise, insects are exposed to altered thermal environments that can challenge their capacity to regulate body temperature and maintain homeostasis (Jaworski and Hilszczański, 2013; Kovac et al., 2023). For instance, increases in temperature can push insects beyond their heat tolerance thresholds, forcing them to adapt or perish (Chown et al., 2010). This can result in physiological changes that include heightened metabolic rates, which, while necessary for survival in warmer climates, can also increase energy demands and alter resource utilization patterns (Kovac et al., 2023). GCC also affects humidity and precipitation patterns, critical factors in maintaining an insect's water balance and desiccation resistance (Kovac et al., 2023).

With changing moisture availability, many insect species may experience increased stress from dehydration, limiting their ability to thrive in their once–occupied habitats. For example, species adapted to humid environments may struggle as conditions become more arid, leading to shifts in their geographic range or even local extinctions (Bowler and Terblanche, 2008). This interplay between temperature and water availability can reshape insect communities by influencing both survival and reproduction, thereby affecting the broader ecosystem (González-Tokman et al., 2020; Walker et al., 2019).

In aquatic habitats, where insects depend on dissolved oxygen, rising temperatures complicate survival further (Silberbush et al., 2015; Sundar and Muralidharan, 2017). Warmer water holds less oxygen, limiting oxygen and imposing additional stress on aquatic insects that rely on efficient oxygen transport for survival (Sundar and Muralidharan, 2017; Verberk et al., 2016). These physiological constraints can drive significant evolutionary changes (Table 4). Insects may respond to these challenges through phenotypic plasticity—the ability to adjust their physiological traits within a single generation—or through long-term genetic adaptation, where populations evolve to tolerate new environmental conditions (González-Tokman et al., 2020; Hoffmann and Sgrò, 2011). Such adaptations may manifest in traits like altered metabolic rates, improved water conservation, or enhanced oxygen transport efficiency. Behavioural adaptations also play a crucial role in how insects respond to GCC (Walker et al., 2019). As global temperatures rise and environmental cues shift, insects may change their foraging patterns, shift their activity to cooler times of the day, or modify their mating behaviours to improve their chances of survival and reproduction (González-Tokman et al., 2020; Kingsolver, 2009). For example, insects may begin foraging earlier in the morning or later in the evening to avoid the hottest parts of the day, a behavioural shift that can influence their interactions with predators, prey, and competitors (Filazzola et al., 2021; Thorat and Nath, 2018). Table 6below summarizes the diverse impacts of climate change on insects' physiological adaptation.

Global climate change further influences life history traits, *i.e.*, developmental rates, reproduction, and lifespan (Larson et al., 2019; Walker et al., 2019). Warmer temperatures can accelerate development, leading to faster maturation and shorter life cycles (Table 6). While this might increase the number of generations per year, it can also disrupt the reproduction timing and lead to food availability mismatches (Table 4), potentially reducing reproductive success (Deutsch et al., 2008; Walker et al., 2019). In some cases, insects that rely on specific

Table 6
Impacts of global climate change on insect physiological adaptation.

GCC impact	Description	Source
Changes temperature tolerance	GCC alters temperature regimes, affecting insects' thermal tolerance and response to temperature stress	Chown et al. (2010); González-Tokman et al. (2020)
Metabolic rate changes	Rising temperatures can increase insect metabolic rates, impacting energy allocation and resource utilization.	Filazzola et al. (2021); Harvey et al. (2023); Skendžić et al. (2021)
Changes water balance and desiccation resistance	Changes in humidity levels affect insects' water balance, influencing desiccation resistance and survival.	Bowler and Terblanche (2008); Guedes et al. (2015); Thorat and Nath (2018)
Impact on respiratory mechanisms	Insects face oxygen limitation in warmer environments, particularly in aquatic habitats where oxygen levels decrease.	Silberbush et al. (2015); Sundar and Muralidharan (2017); Verberk et al. (2016)
Changes evolutionary responses	Insects exhibit phenotypic plasticity or genetic adaptation in response to climate change, altering physiological traits.	Hoffmann and Sgrò (2011)
Impact on behavioural adaptations	Insects change foraging patterns or mating behaviours in response to climate shifts.	Filazzola et al. (2021); Harvey et al. (2023); Kingsolver (2009)
Impact on water regulation	Climate change affects insect osmoregulation and water balance, influencing survival in changing moisture conditions.	Chown et al. (2010); Filazzola et al. (2021); Hoffmann and Sgrò (2011); Kovac et al.(2023)
Effects on developmental rates	Temperature shifts influence insect developmental rates, impacting life cycle timing and population dynamics.	Deutsch et al. (2008); Filazzola et al. (2021)
Effects on physiological stress responses	Insects exhibit stress responses to climate change, including altered hormone levels and immune function.	Harvey et al. (2020); Wang et al. (2022)
Impact on feeding behaviour	Changes in temperature influence insect feeding behaviour, affecting nutrient acquisition and dietary preferences	Harvey et al. (2023); Walker et al. (2019)
Effects on flight performance	Temperature variations impact insect flight performance, influencing dispersal abilities and population dynamics.	Harvey et al. (2020); Travis et al. (2013)
Alteration of adaptation of thermal tolerance	Insects may evolve thermal tolerance mechanisms in response to climate change, altering physiological limits.	González-Tokman et al. (2020); Harvey et al. (2020); Kovac et al.(2023)
Impact on reproductive fitness	Climate change affects reproductive fitness in insects, influencing fecundity, mating success, and offspring survival.	Filazzola et al. (2021; Visser and Holleman (2001)
Effesct on genetic adaptation and selection	Insect populations undergo genetic adaptation and selection in response to climate change-driven environmental shifts.	Hoffmann and Sgrò (2011); Walker et al. (2019)

seasonal cues for reproduction may find their breeding cycles misaligned with environmental conditions, reducing offspring survival (Boullis et al., 2016; Harvey et al., 2023). These physiological and behavioural adaptations to GCC highlight the complexity of the challenges insects face (González-Tokman et al., 2020). The ability to adapt—either through plasticity, behavioural shifts, or genetic changes—will determine the resilience of insect populations (Filazzola et al., 2021; Harvey et al., 2023; Thorat and Nath, 2018). However, not all species will be able to adapt quickly enough, potentially leading to declines or extinctions of vulnerable species (Eickermann et al., 2023b; Hoffmann and Sgrò, 2011; Ojija and Nicholaus, 2023). Understanding these adaptations is crucial for predicting how insect populations respond to ongoing environmental changes and developing effective conservation and management strategies. As GCC continues to reshape ecosystems, interdisciplinary research that combines insights from physiology, ecology, and evolutionary biology will be essential for mitigating the impacts on insect populations and the ecosystems they support.

Impact of global climate change on insects' migration and communication

Global climate changehas profound effects on the geographic ranges of insects, forcing shifts in their migration patterns and distribution (Forister et al., 2010; Parmesan, 2006; Travis et al., 2013). As temperatures rise and weather patterns become more unpredictable, insects adjust their ranges to seek suitable climates, often moving to higher altitudes or latitudes (Parmesan and Yohe, 2003). These changes are not just limited to geographic shifts but also affect the timing of insect migrations (Stevens et al., 2013), as seasonal cues such as temperature and day length are altered (Chapman et al., 2011; Gienapp et al., 2007; Parmesan et al., 1999). This disruption of insect phenology can result in mistimed migrations, affecting the coordination of critical life cycle events, *i.e.*, mating and feeding (Gienapp et al., 2007; Larson et al., 2019). Variations in temperature and wind patterns can further influence flight behaviour, either aiding or hindering migration efforts (Wagner et al., 2021), affecting population survival and movement across regions (Chapman et al., 2011). Global climate change impacts where and when insects migrate and their ability to disperse effectively (Travis et al., 2013). Shifts in climatic conditions can limit or enhance dispersal opportunities, altering population dynamics and potentially reducing genetic diversity in isolated populations (Larson et al., 2019). As insects are forced into new habitats, they must adapt to unfamiliar conditions, which may require changes in their physiological and behavioural traits (Parmesan et al., 1999). Successful adaptation to these new environments is critical for the survival of many species, as failure to adjust may lead to population declines or even extinctions.

Another significant consequence of GCC is the disruption of insect communication systems, which are essential for survival and reproduction (Boullis et al., 2016; Cusano et al., 2016). Rising global temperatures, along with increased atmospheric levels of carbon dioxide (CO_2) and ozone (O_3), are likely to impact pheromone-mediated communication in insects significantly (Boullis et al., 2016; Knaden et al., 2022). Pheromones, chemical signals used for communication, play a vital role in many insect species' behaviours, *i.e.*, mating, territory marking, and social organization (Boullis et al., 2016). Temperature affects the production, release, and detection of pheromones, as these chemicals are often volatile and sensitive to environmental conditions (Boullis et al., 2016; Knaden et al., 2022). Elevated temperatures can accelerate the evaporation of pheromones, potentially reducing their effectiveness and the distance over which they can be detected (Boullis et al., 2016; Conrad et al., 2017). This may disrupt mating patterns and social interactions, leading to population declines in some species (Boullis et al., 2016; Cardé and Haynes, 2004). Similarly, increased CO_2 levels can alter plant-insect interactions, as plants often release volatile organic compounds (V.O.C.s) in response to herbivory (Knaden et al., 2022). These compounds can interfere with insect pheromone signals, leading to miscommunication (Conrad et al., 2017). Additionally, elevated O_3 levels can degrade pheromones in the atmosphere, reducing their efficacy (Knaden et al., 2022). Ozone can break down these chemical signals, making it difficult for insects to locate mates or coordinate social activities. In addition, a previous study shows that climate-driven changes in acoustic signalling—used by many insect species for mate recognition and coordination of reproductive activities—can interfere with these vital behaviours (Table 7), potentially reducing reproductive success (Conrad et al., 2017; Cusano et al., 2016). For instance, a previous study showed that acoustic communication, *i.e.*, the percent time calling and buzz duration of insect species in the subfamily Conocephalinae, decreased with increased temperature (Cusano et al., 2016). Table 7summarizes the diverse impacts of climate change on

Table 7
Impacts of Global climate change on migration and communication of insects.

GCC impacts	Description	Source
Changes in range and distribution	GCC alters insect geographic ranges, leading to shifts in migration patterns and distribution	Parmesan (2006); Parmesan and Yohe (2003)
Impact on phenology and timing	Changes in seasonal cues affect insect phenology, disrupting migration timing and coordination.	Filazzola et al. (2021); Gienapp et al. (2007)
Impact on flight behaviour	Variations in temperature and wind patterns influence insect flight behaviour during migration.	Chapman et al. (2011); Travis et al. (2013)
Changes in dispersal ability	Climate-driven changes affect insect dispersal ability, impacting population dynamics and habitat colonization.	Filazzola et al. (2021); Travis et al. (2013)
Influence on the ability to adapt to novel habitats	Insects may adapt to new habitats and migration routes in response to climate-induced changes.	Parmesan et al. (1999)
Disruption of pheromone signaling	Temperature fluctuations disrupt pheromone signalling, affecting mate attraction and reproductive behaviour.	Boullis et al. (2016); Cardé and Haynes (2004)
Changes in acoustic signalling	GCC alters acoustic signalling in insects, impacting mate recognition and species interactions.	Cusano et al. (2016)
Effects on visual communication	Shifts in light availability influence insect visual signaling, affecting communication and courtship displays.	Conrad et al. (2017); Hausmann et al. (2021)
Impact on vibrational communication	Changes in substrate vibrations disrupt vibrational communication in insects.	Cocroft (2001); Leith et al. (2021)
Disruption of chemical cues	Climate change affects the dispersion and detection of chemical cues used in insect communication.	Boullis et al. (2016); Conrad et al. (2017)
Effect on multimodal signals	Insects integrate multiple sensory signals to compensate for climate-induced changes in communication channels.	Conrad et al. (2017)
Impact on adaptive responses to communication disruption	Insects evolve adaptive strategies to cope with communication disruption caused by climate change.	Cocroft (2001); Knaden et al. (2022)
Infuence ecological consequences of communication changes	Climate-driven alterations in insect communication have cascading effects on species interactions and community dynamics.	Knaden et al., (2022); Leith et al. (2021)
Changes population migration	Changes in migration behaviour influence population structure and genetic diversity in insect populations.	Leith et al. (2021); Stevens et al. (2013)

insects' migration and communication.

Furthermore, shifts in light availability and quality, which can result from altered weather patterns, may affect visual communication cues (Table 7), disrupting courtship displays and other forms of signalling necessary for species interactions (Conrad et al., 2017; Hausmann et al., 2021). Similarly, changes in substrate conditions due to climate factors can affect vibrational communication (Cocroft, 2001; Leith et al., 2021), which many insects rely on for coordinating behaviours, *i.e.*, foraging or mating (Table 5). The ability to detect and respond to chemical cues—another critical aspect of insect communication—is also vulnerable to GCC (Knaden et al., 2022; Leith et al., 2021). Variations in temperature, humidity, and wind patterns can alter the dispersion of these chemical signals, making it more difficult for insects to locate mates, food, or suitable habitats (Conrad et al., 2017; Jaworski and Hilszczański, 2013). In response to these challenges, insects may evolve adaptive strategies, *i.e.*, integrating multiple sensory signals (chemical, visual, vibrational) to compensate for disruptions in individual communication channels (Cocroft, 2001). However, the success of these adaptations will vary across species and ecosystems, and not all insects can cope with such rapid environmental changes.

The cascading effects of climate-induced disruptions in communication and migration behaviours can have broader ecosystem implications (Table 7). Changes in migration patterns may alter population structures, potentially reducing genetic diversity as populations become fragmented or fail to disperse effectively (Stevens et al., 2013). This can weaken populations' resilience to environmental changes and increase the risk of local extinctions (Harvey et al., 2023, 2020; Parmesan, 2006). Moreover, the breakdown in insect communication can disrupt species interactions, *i.e.*, pollination, predator–prey relationships, and resource competition, ultimately affecting entire ecosystems. Thus, understanding the multifaceted impacts of G.C.C. on insect migration and communication is essential for predicting how species will respond to ongoing environmental shifts (Mclaughlin and Zavaleta, 2012). These insights are also critical for developing conservation strategies to mitigate the ecological consequences of GCC.

Conclusion and future prospects

This review provides valuable insights into the relationship between insects and GCC, illustrating how changing environmental conditions reshape insect populations, distribution, feeding habits, interactions, reproduction, physiology, migration, communication, and overall ecosystem health. G.. alters migration timing and routes, disrupting population connectivity and dispersal patterns. Consequently, some migratory insect species may face barriers or encounter novel habitats, affecting their population dynamics and genetic diversity. To effectively address these challenges, conservationists and researchers must adopt interdisciplinary approaches that integrate ecological, physiological, and behavioural perspectives. These insights could highlight the urgent need to address GCC and prioritize the protection of insect populations, which play vital roles in sustaining biodiversity and maintaining ecological balance. Overall, the complex and interconnected nature of GCC-induced changes to insect reproduction highlights the vulnerability of insect populations to environmental stressors.

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Fredrick Ojija: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Marco Mng'ong'o:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Becky N. Aloo:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Gabriel Mayengo:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Mlyashimbi Helikumi:** Writing – review & editing, Visualization, Methodology, Conceptualization.

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