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(Review Article)

Impact of climate change on insect biology, ecology, population dynamics, and pest management: A critical review

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Abstract

The purpose of this paper is to review and assess published literature on impact of climate change on insects. A systematic approach was used to accumulate research works of literature on "Impact of climate change on insects." A total of forty-three (43) research papers published between the years 1908 to 2023 were accumulated and used for this review. Tables were used to present all results. A subjective approach was used to select the topics: impact of climate change and insects. In this paper, twenty-three (23) possible impacts of climate change on insects were evaluated and presented. Impact of extreme weather conditions on insects, challenges faced with pest management and strategies to mitigate the effects of climate change were also discussed. The published papers established that temperature, increasing level of carbon dioxide gas (CO_2) in the atmosphere and precipitation all contribute to the changing climate that are affecting insect biodiversity, geographical distribution, behavioural preferences and pests' outbreaks that are negatively impacting the agriculture sectors in many countries. This review highlights that more studies should be done in neotropical countries since there is a dearth and demand for research and published data in these biodiversity rich regions.

Keywords: Climate Change; Insects; Global Warming; Greenhouse Effect; Pests

1. Introduction

Climate change is a long-term alteration in the statistical distribution of meteorological conditions across periods of time ranging from decades to millions of years. An urgent issue affecting the entire world, it comprises both anthropogenic and natural environmental changes [73] [101]. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO_2) levels in the atmosphere have increased as a result of human activity since the pre-industrial era. This is the main cause of climate change. These gases maintain the earth's temperature and contribute to the greenhouse effect. Both natural and human activity contribute to global warming [33] [49] [73]. The last three decades have generally become warmer, with the 2000s decade being the warmest, according to the Intergovernmental Panel on Climate Change (IPCC) [64] [73].

Global change is the collective term for all ongoing human-induced changes to the biotic and abiotic elements of the planet's homeostasis. One of these disruptions is global climate change [18] [206] [212]. Climate change has been proven to be a reality, and its effects on animals have been predicted by science. At present, every country on every continent on earth is being affected. Since data have been kept since 1850, each of the last three decades has been warmer than the decade before it [61] [212]. Sea levels are rising, weather events are growing more extreme, and greenhouse gas emissions are at their highest points ever. Weather patterns are also shifting. Without intervention, the average surface temperature of the planet is probably going to rise above 3 degrees Celsius this century [61] [191] [207] [212].

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Agriculture ecosystems are anticipated to be impacted by global climate change, which is brought on by increased greenhouse gas emissions, in a variety of ways, the results of which rely on the combined influences of climate (temperature, precipitation), and other worldwide changing components. With an estimated further increase in mean global temperatures of 0.80^{C} over the next 100 years, the biosphere can be expected to experience broad climate-related changes. The occurrence of insect pests could be impacted by these changes. Insects may respond to climate change in a variety of ways [33] [97] [219]. Crop patterns and intensity may change due to altered climatic circumstances, and to adapt, new kinds may be introduced that could either benefit or harm insect pests. Pest colonization and establishment will have greater opportunities when climatic disturbances become more severe and some pests may spread to higher latitudes and altitudes. When interacting species react to warming differently, relationships between predators and prey and between plants and insects may be affected [97] [219].

Various global climate models and development scenarios predict that Earth could warm by 1.4 to 5.8 degrees Celsius over the next century [73] [131]. Even little differences in temperature, relative humidity, CO_2 and O_3 concentrations, wind currents, and annual average precipitation can have an impact on insect behaviour [44] [88] [97]. Various effects on agricultural productivity are anticipated as a result of changes in pest activity brought on by climate change [73] [177]. Both the agricultural crops and the pests connected to them are greatly impacted by climate change, both directly and indirectly. Pest reproduction, development, survival, and dispersal are directly impacted, whereas climate change has indirect effects on pest insect relationships with their environment and relationships with other insect species, such as natural enemies, vectors, and competitors [73] [146].

2. Material and Methods

The topic of “impact of climate change on insects” was the subject of a systematic review using “Google Scholar,” a web-based search engine which provides a quick and easy way to search and access published literature from articles, journals and books. Thematic search terms such as impact, climate change, insects were used in the search.

The subjects that were evaluated in this research were chosen using an approach that involved looking at the related works of literature. Publications between the years 2000 to 2023 were acquired for this review. However, not all of the articles that were reviewed, were used in this study because the major objective was to assemble data from recent research (past 10 to 20 years) on impact of climate change on insects. However, papers that contained pertinent literature from as far back as the 1900’s and the 2000’s were also utilized. Forty-three (43) research articles were included in this review.

The search yielded different results: Some articles had all the thematic keywords and some were obtained that were specific to adaptation and mitigation measures to combat the impact of climate change, while others were specific on the impact of climate change on specific insect species and insect families.

3. Results

When searching "Google Scholar" for information on impact of climate change on insects, a total of 46,800,000 was retrieved. Among the results obtained from the search, a total of 37,300 were published within the years 2000-2023, 48,100 were published between the years 2010-2023 and 39,700 were published within the years 2015-2023. 22, 200 publications between the years 2010-2023 reviewed the impact of climate change on insects.

However, not all the results retrieved for this research focused on the impact of climate change on insects. Some focused solely on climate change on insects, while others evaluated possible adaptation and mitigation measures to combat the impact of climate change and were specific on the impact of climate change on specific insect species and insect families. Others focused on the effects of globalization and climate change on forest insect and pathogen impacts. Further, some papers focused on plant chemical ecology, tri-trophic interactions and food production, insect-human interactions and scientists’ future prediction as it relates to climate change and global warming.

4. Discussion

4.1. Major climatic factors affecting insects

4.1.1. Rise in Temperature

Temperature rise brought on by climate change may have varied effects on crop pest insect populations. A rise in temperature may have an impact on an insect's survival, growth, geographic range, and population number. The physiology or existence of hosts may have an indirect or direct impact on insect development and physiology due to temperature. Temperature can have a variety of effects on an insect species depending on how that species plans to evolve [44] [85] [88] [97]. An insect's reproductive biology may be impacted both favorably and unfavorably. Climate change will very certainly have an impact on these creatures since temperature and precipitation, in particular, have a significant impact on the growth, reproduction, and survival of insect pests [44] [85] [88] [97].

In temperate settings, larger numbers and more diverse species of insects will emerge from warming temperatures. Some insects' lifecycles last for several years. Over the course of their life history, these insects (arctic moths, cicadas) will typically tend to moderate temperature variability. Some crop pests exhibit a 'stop' and 'go' response to temperature. During periods of time with optimal temperatures, they grow more quickly [44] [85] [88] [97]. These species of insects will develop more quickly in warmer environments, possibly producing more generations annually. For instance, in North America, synchronous, uni-voltine populations of bark beetles converted a thermal habitat that had not been adopted into an adoptive thermal habitat when the mean annual temperature was raised by 30°C [44] [85] [88] [97]. An increase in the number of generations may necessitate more controls, which would raise crop damage, farmer losses, and crop protection costs. It might also produce in problems like insecticide resistance. Some minor pests may develop into major ones, for example, species belonging to the family Pentatomidae; it is expected that with each 10°C increase will result in a 15% decrease in the winter mortality of adults from the family Pentatomidae of *Nezara viridula* Linnaeus (southern green stink bug) and *Halyomorpha halys* Stal (brown marmorated stink bug). Insects that migrate may arrive early in a region where they can overwinter [44] [85] [88] [97] [118].

Temperature can alter the gender ratios of some pest species, potentially reducing their ability to reproduce, especially thrips. Because soil offers an insulating layer that tends to buffer temperature changes more than air, insects that spend significant portions of their life cycles in the soil may be more progressively affected by temperature changes than those that are above ground [44] [85] [88] [97]. Winter temperature increases may aid in the continuation of some bugs' life cycles. Increased bug populations may be aided by lower winter insect mortality brought on by warmer winter temperatures. Greater temperature may lead to more insect species attacking more hosts in temperate regions because the diversity of insect species for an area tends to decline with increasing latitude and altitude [44] [85] [88] [97] [118].

Tropical insects that are sensitive to even small changes in temperature may be more at risk due to global warming [33] [97] [219]. With a temperature increase of 2–4°C, they risk going extinct, example; the highest temperature in the tropics has already reached 330^{C}, whereas the pod-sucking bug's critical range is 15–320^{C}. Such insects might find it challenging to adapt to temperature increases [33] [97] [219]. With a slight climate shift, insects that transmit plant illnesses could become dangerous. An effort has been made to thoroughly detail the potential changes that insects may experience in different parts of the world under climate change scenarios and projections, as supported by literature. As cold-blooded creatures, insects have bodies that are roughly the same temperature as their surroundings [97] [219]. Since temperature affects insect behaviour, dispersal, development, survival, and reproduction, it is likely the most significant environmental component. Predictions of insect life stages are frequently made using accumulated degree days from a base temperature and biofix point. According to estimates, insects may go through 1–5 more life cycles per season with a temperature increase of 20^{C} [97] [219]. Other researchers have discovered that the effects of moisture and CO_2 on insects can be a potentially significant factor in the context of global climate change [44] [88] [97].

Temperature is the most significant abiotic factor known to directly affect insects that feed on plants. Almost all insects will be impacted by temperature changes to some degree, and there may be numerous effects on insect life cycles as a result [23] [33] [73] [85] [35]. For every 2°C rise in temperature, insects are predicted to experience one to five extra life cycles per season [73] [85] [135] [219]. Insect metabolic rates often double with a 10°C increase because their physiology is sensitive to temperature changes [23] [33] [58] [73] [85] [135].

Numerous studies have shown that increasing temperatures tend to hasten insect growth, consumption, and movement in this environment. By impacting fecundity, survival, generation time, population size, and geographic spread, this may have an effect on population dynamics (Figure 1) [14] [15] [23] [33] [73] [85] [135]. It is anticipated that insect populations in tropical regions will see a decline in growth rate as a result of climate warming because the current temperature is already quite close to the ideal for pest formation and growth [23] [33] [52] [73] [85] [135].

Some insects have a close relationship with a chosen group of host crops. Insect pest populations unique to certain crops would diminish if temperatures rose to the point where farmers stopped growing the host crop. The same environmental conditions that affect insect pests also affect their parasites and insect predators, as well as the disease organisms that infect the pests. As a result, insect populations are under more attack. Aphids have been proven to be less sensitive to the aphid alarm pheromone they generate when being attacked by parasitoids and insect predators at warmer temperatures, which opens the door for increased predation [23] [33] [44] [85] [88] [97] [135].

In contrast, it is anticipated that insect populations in temperate regions will develop more quickly. Early infestations by species belonging to the family Noctuidae; *Helicoverpa zea* Boddie (corn earworm) in North America (EPA, 1989) and *H. armigera* Hubner (cotton bollworm) in North India [170] [171] led to increased crop loss as a result of global warming. New niches for insect pests will become available as a result of rising temperatures. The viability and incubation duration of *H. armigera* Hubner eggs are influenced by temperature [56].

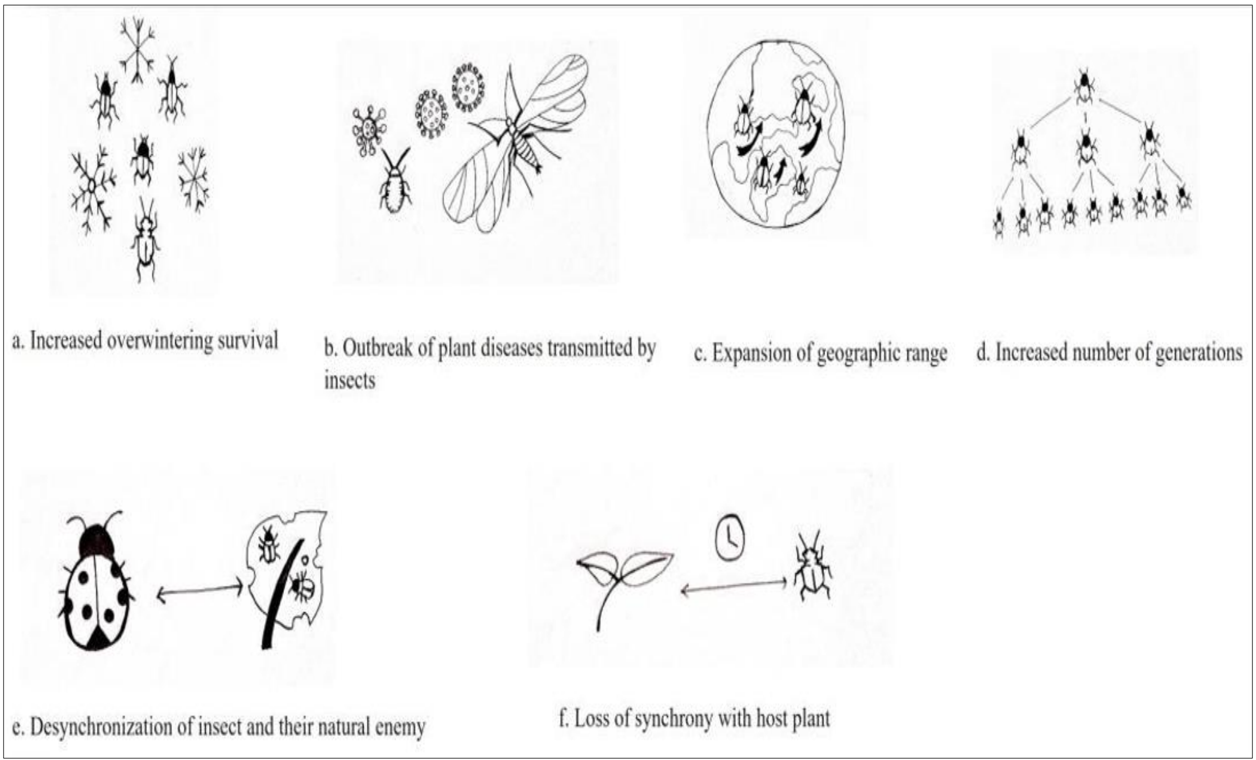

Figure 1 Several effects of increasing temperature on insects (Adapted from Ghosh & Debnath, 2023)

4.1.2. Increased levels of CO_2

The physiology of the crop is likely to be affected by increased photosynthetic activity as a result of elevated CO_2 levels. The changes in plant and vegetation quality as well as quantity will consequently have an indirect impact on insects. [23] [49] [73]. The growth of the *Maruca vitrata* Fabricius (bean pod borer) from the family Crambidae is accelerated by rising CO_2, which also alters the nutritional content of chickpea, increasing food consumption as well as larval weight gain, pupal weight gain, and overall larval duration [2] [23] [33] [73] [135].

Depending on the type of pest feeding, CO_2 fertilization has different effects. The number of thrips is growing [22] [23] [33] [73] [135]. Examples of phloem-feeding insect pests that show both an increase in population growth rates and a decrease in population density are whiteflies and aphids [23] [33] [73] [135] [192]. There is disagreement on the effects of rising CO_2 on sucking insects, despite the fact that in some cases abundance and fecundity may increase [23] [33] [73] [80] [81] [135]. In 2007, Stiling and Cornelissen used a meta-analysis to examine the indirect effects of a CO_2 increase on the life cycle characteristics of herbivores. They also evaluated the documentation of the studies that had been conducted. Their research showed that insect pests responded dramatically to rising CO_2, increasing their consumption rates by about 17%, decreasing their abundance by about 22%, and lengthening their development times by around 4%

when compared to ambient CO_2 (Figure 2). The relative growth rate fell by 4.9%. More so than other feeding guilds, such as sap-sucking herbivores (such as aphids, leafhoppers, and scale insects), chewers were found to be more substantially impacted by the increase in atmospheric CO_2.

In general, it is believed that CO_2 has indirect effects on insects and that changes in the host crop have an impact on insect damage. *Popillia japonica* Newman (Japanese beetle) from the family Scarabaeidae, *Empoasca fabae* Harris (potato leafhopper) from the family Cicadellidae, *Diabrotica virgifera virgifera* LeConte (western corn rootworm) from the family Chrysomelidae, and *Epilachna varivestis* Mulsant (Mexican bean beetle) from the family Coccinellidae caused 57% higher damage to soybean grown in an elevated CO_2 atmosphere. The extra insect eating may have been promoted by measured increases in the amounts of simple sugars in the soybean leaves. In order to get enough nitrogen for their metabolism, insects will occasionally eat more of the leaves with lower nitrogen concentrations [23] [44] [88] [97] [135]. Increased carbon-to-nitrogen ratios (C: N) in plant tissue brought on by higher CO_2 concentrations may impede insect growth and lengthen life phases that are vulnerable to parasitoid assault [23] [97] [135] [185].

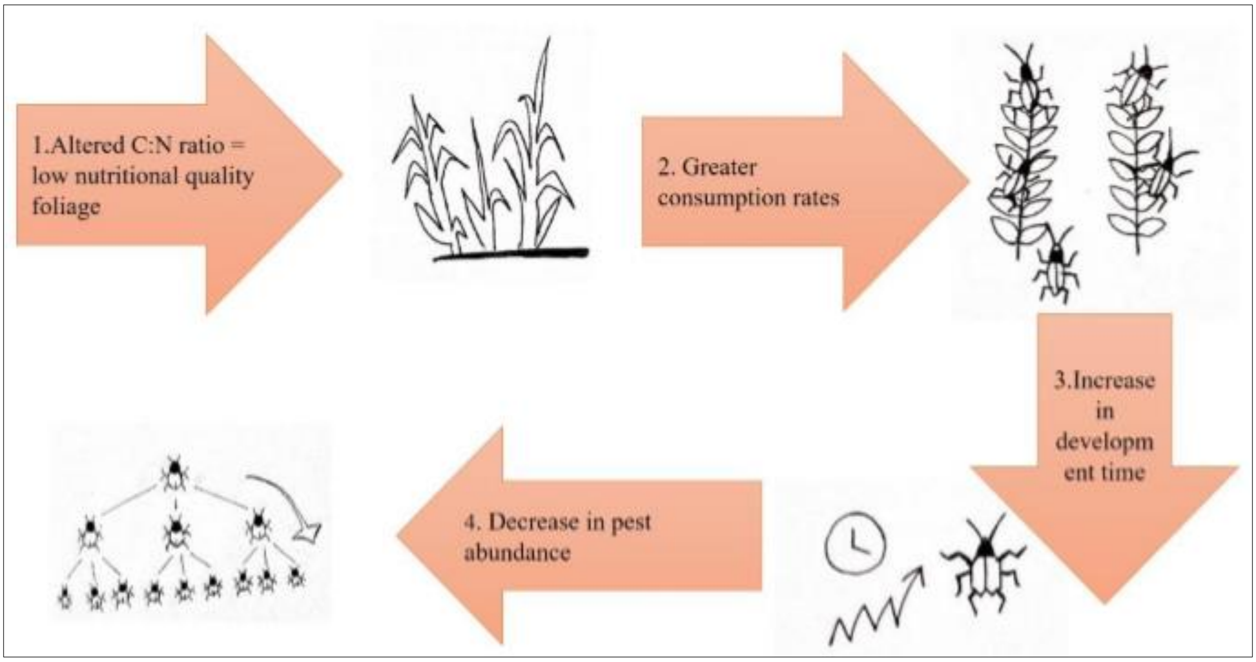

Figure 2 Effect of rising CO_2 on insects (Adapted from Ghosh & Debnath, 2023)

4.1.3. Changing precipitation patterns

The distribution and regularity of rainfall may have a direct or indirect impact on the abundance of pests. Climate change was predicted to result in a drop in rainfall frequency while increasing rainfall intensity [23] [33] [73] [135] [141]. This would lead to both droughts and flooding on the one hand, as well as excessive rain and flooding on the other. Minor pests like aphids, jassids, whiteflies, mites, etc. may be washed away from crops and their occurrence may be reduced as a result of the heavy rains (Figure 3) [23] [33] [73] [135] [141]. BPH's abundance is discovered to be normal in the absence of precipitation, but it becomes numerous and multiplies dramatically in the presence of 10% more precipitation than is typical [23] [33] [49] [73] [135]. Staley *et al*. (2007) found that increased summer rainfall episodes caused wireworm populations to proliferate swiftly in the upper part of the soil, in contrast to ambient and drought conditions [77]. Plants under drought stress are more susceptible to insect attack because of decreased production of secondary compounds with a defense role (Figure 3) [23] [33] [73] [135] [220].

Due to their sensitivity to moisture, several insects are eliminated from crops by severe rainfall. Flooding the soil has been employed as a management method for some insects that overwinter in soil, such as the cranberry and onion insect pests. One could anticipate that the increased frequency and intensity of precipitation events anticipated by the climate will have a negative effect on these insects. Other insects, like *Acyrthosiphon pisum* Harris (pea aphids) from the family Aphididae, are not drought-tolerant. According to studies on *Nilaparvata lugens* Stal (brown plant hoppers) from the family Delphacidae, BPH populations rise with increases in precipitation up to 400 ppm and fall with precipitation levels over 500 ppm [23] [33] [44] [88] [97] [118] [135].

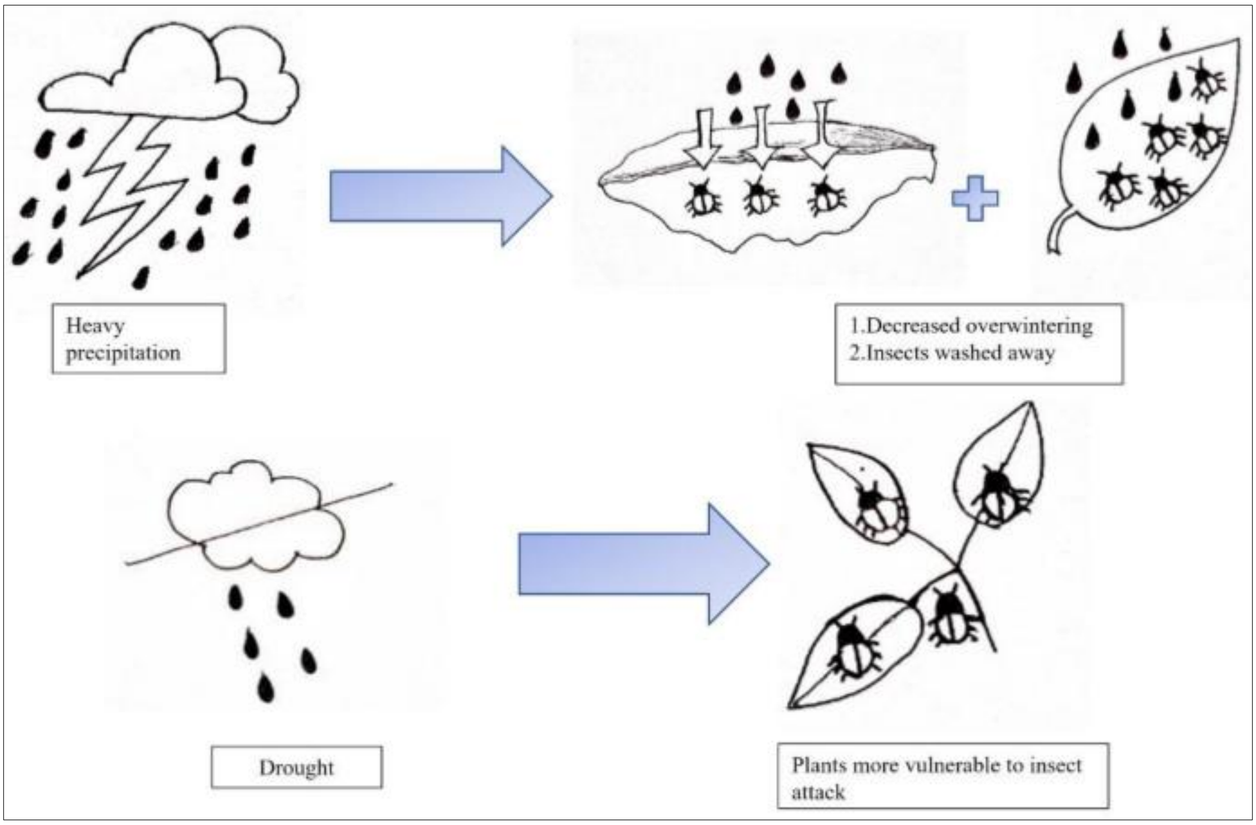

Figure 3 Effects of changing precipitation patterns on insects (Adapted from Ghosh & Debnath, 2023)

4.1.4. Combined effects of temperature and CO_2

An examination of prehistoric leaves reveals an increase in insect herbivores as a result of CO_2 and temperature increases. According to several research, when CO_2 levels are elevated at the same time as temperature increases, temperature may not have an impact on insect development. The development of moths (leaf miners), for instance, is accelerated by higher temperatures, but this is counterbalanced by higher CO_2 levels, which alter the nutritional composition of leaves and lead to smaller adult moths and poorer adult survival rates. In other words, it's important to keep in mind that some things may work to counteract climate change [33] [97] [185].

Table 1 Climate change and it's impacts on different groups of insects

Impacts	**Description of impacts**	**Author(s)**
Natural enemies	The degree of efficacy of biocontrol operations will change due to the significant impacts of climate change on the number, distribution, and seasonal timing of pests and their natural enemies. A too-early and warm spring may lead a natural enemy to emerge early and die for lack of prey, according to Hance *et al.*'s (2007) research. This is because the natural enemy starts to develop at a slightly lower temperature than the prey and develops faster than the prey when the temperature rises. If this incident repeats itself over a long period of time, the natural enemy may become extinct. The productivity and phenology of plants are impacted by rising temperatures, altered precipitation patterns, and increasing CO_2 concentrations. This in turn changes the number of herbivore populations (host insects), impacting the amount of prey and hosts available for predation or parasitism. The majority of insects are not harmful to agro-ecosystems, and there is strong evidence to support the idea that this is because of interspecific interactions between pest insects and their natural enemies, such as diseases, parasites, and predators. Due to the negative effects of prolonged drought on the activity and abundance of the natural enemies of this pest, oriental armyworm, *M. separata* Walker from the	(Price, 1987); (Lincoln, 1993); (Freier & Triltsch, 1996); (Sharma *et al.*, 2002); (Thomas & Blanford, 2003); (Dhillon & Sharma, 2007); (Thomson *et al.*, 2010); (Pareek *et* al., 2017); (Jastoria *et al.*, 2021); (Karthik *et al.*, 2021); (Skendžić *et al.*, 2021); (Ghosh & Debnath, 2023)

	family Noctuidae, populations rose during extended periods of drought (which is harmful to the natural enemies), followed by high rains. While aphid abundance rises as temperature and CO_2 levels rise, parasitism rates are unaffected by high CO_2. Coccinellids will be better able to manage aphids at temperatures up to 25°C. A parasitoid may be more likely to be killed by the host at higher temperatures. The caterpillar *Spodoptera littoralis* Boisduval (Egyptian cotton leafworm) from the family Noctuidae is less parasitized by the parasitoid *Microplitis rufiventris* Kokujev (braconid wasp) from the family Braconidae at 27°C (80.6°F) than it is at 20°C. High CO_2 levels have no impact on parasitism rates, although warmth and CO_2 levels both increase aphid abundance. In addition to affecting the rate of insect growth, temperature has a substantial effect on parasitoids' fertility and sex ratio.	
Pollinators	Pollinators are beneficial insects that gather pollen from the anther to the stigma of the same or other flowers as a necessary aspect of their survival. Honey bees, bumble bees, wasps, butterflies, flies, and other insects are examples of pollinators. Bees pollinate more than 73% of the world's cultivated crops, compared to flies, bats, wasps, beetles, birds, and butterflies and moths, which each pollinate 4%, 19%, 6.5 percent, 5%, and 5% of the world's crops. Nearly a third of the food produced worldwide is pollinated by insects. Significant pollinator species including bees, moths, and butterflies have unquestionably experienced declines in population size, geographic range, and pollination behaviour due to changing weather patterns. Essential plant life cycle events like flowering, pollination, and fruiting have been shown to be significantly influenced by temperature and water availability. For food security, species diversity, ecological stability, and climate change resilience, pollination quality and quantity have a variety of effects. A number of ecosystem functions depend on insects. For many commercially important crops, they are excellent pollinators. More than one-third of all food crops in the world depend on commercial bees for pollination. Climate factors including temperature and water availability have been found to have a major impact on key plant life cycle events like flowering, pollination, and fruiting. Many pollinators have modified their life cycles to correspond with plant phenological events. Impending climate change is expected to modify the phenological events that take place in plant-pollinator relationships, which is expected to have an impact on the amount of pollination. Asynchronies can hinder plant growth and diminish pollinator survival-related food sources' availability. Despite sustained synchronization between the plants and pollinators, the median flower abundances were reduced by 68% and the median number of interactions decreased by 73%. Butterflies are utilized for predicting various environmental changes and are thought to be indicators of ecosystem change. They are most likely to be impacted by global climate change because of their specialized biological needs, which include habitats for egg-laying and food plants with precise requirements for temperature and humidity. Early migration, latitudinal range shifts to the north, elevation range shifts to the up, population decrease, and species extinction have all been linked to climate change in studies of butterflies. Any impact on butterflies will cause disturbance in pollinator connections because they are an essential part of the ecosystem as pollinators. Butterflies suffer from reduced nectar supply caused by dry spells and drought on plant phenology. Butterflies in the Sikkim Himalayas already exhibit indicators of climate change. As a result of the changing climate, many species have expanded their geographic range. The elevational ranges of most butterflies are somewhat limited. Because of the increased reduction in their ranges caused by upward extension, they are now more vulnerable. In several parts of the world, butterfly elevational and latitudinal ranges have been found to shift upward and contract. Some of the species in Sikkim Himalayas showing elevational range shift due to climate change are *Troides helena* Linnaeus (common birdwing), *Papilio machaon*	(Haribal, 1992); (Parmesan *et al*., 1999); (Walther *et al*., 2002); (Forister & Shapiro, 2003); (Kudo *et al*., 2004); (Hickling *et al*., 2006); (Murugan, 2006); (Pounds *et al*., 2006); (White & Kerr, 2006); (Cleland *et al*., 2007); (Wilson *et al*., 2007); (Colwell *et al*., 2008); (González-Megías *et al*., 2008); (Food and Agriculture Organization, 2008); (Ricketts *et al*., 2008); (Sidhu & Mehta, 2008); (Abrol, 2009); (Forister *et al*. 2010); (Chettri, 2010); (Acharya & Vijayan, 2011); (Rákosy & Schmit, 2011); (Acharya & Chettri, 2012); (Pareek *et* al., 2017); (Young, 2016); (Karthik *et al*., 2021); (Dwarka *et al*., 2023); (Ghosh & Debnath, 2023)

	Linnaeus (yellow swallowtail), *Princeps helenus* Hubner (red helen), *Princeps nephelus* Boisduval (yellow helen), *Ixias pyrene* Linnaeus (yellow orangetip), *Delias descombesi* Boisduval (redspot jezbel), *Eurema brigitta* Stoll (the small grass yellow, *Taraka hamada* Druce (forest pierrot), *Curetis dentate* Moore (angled sunbeam), *Heliophorus brahma* Moore (golden sapphire), *Jamides alecto* Felder (metallic cerulean), *Abisara fylla* Westwood (dark judy), *Melantis leda* Linnaeus (common evening brown), *Lethe mekara* Moore (common red forester), *Orsotrioena medus* Fabricus (nigger), *Hestina nama* Westwood (circe), *Phalanta alcippe* Stoll (large yeoman), *Cyrestis thyodamas* Doyere (common map), *Limentis daraxa* Doubleday (green commodore), *Tanaecia julii* Lesson (common earl) and *Cethosia biblis* Drury (red lacewing). It is evident that low to mid-elevation biodiversity is more affected by climate change than biodiversity at higher elevations, where the effects of climate change and habitat disturbance are greatest. Unusual weather conditions have negatively impacted the potential habitat of butterflies at lower elevations, posing a major threat to them. In addition, Haribal (1992) found that Sikkim's butterfly population was declining, primarily as a result of human activity. The warmer temperatures are good for many behavioural activities such as flight, feeding, mud-plugging, migration, etc., hence climate change has some beneficial effects on butterflies. Early butterfly emergence benefits from early flowering of feeding plants or early leafing of egg-laying plants. However, these short-term advantages can eventually work against the survival of butterflies or their young.	
Invasive (alien) insect species	Important environmental factors including temperature and precipitation, the frequency of extreme weather events, as well as air quality and land cover, are all being affected by climate change. Temperature, atmospheric CO_2 content, and the availability of nutrients are the primary determinants of an organism's ability to survive. Changes in these factors are most likely to stress ecosystems and increase the likelihood of invasions. According to the Convention on Biological Diversity (CBD), invasive alien species are thought to represent the biggest danger to biodiversity loss globally and cause significant financial harm to agricultural, forestry, and aquatic ecosystems by altering their geographic structure, function, and variety. Insect physiology and behaviour are directly impacted by climate change, while biotic interactions have an indirect impact. The main contributors to anthropogenic and global climate change are predicted to be the introduction, establishment, dispersion, impact, and changes in the efficacy of mitigation measures of invasive insect species. By altering phenological events, such as flowering periods, particularly in temperate species of plants because many tropical plants can endure the phenological shifts, global warming is projected to worsen ecological repercussions such as the introduction of new pests. The main factor encouraging the adoption of cultivars or crops that are insect vulnerable is the incursion of new insect pests. For instance, between 2018 and 2019, the recently introduced invasive insect known as the autumn armyworm, *Spodoptera frugiperda* Smith from the family Noctuidae, spread to various nations including India, Thailand, Myanmar, China, Republic of Korea, Japan, Philippines, Indonesia, and Australia. The biology, distribution, and abundance of an organism are mostly impacted by the link between temperature and the pace of development. Since insect development takes place within a specific temperature range, a change in temperature will inevitably have an impact on the rate of development, the length of the life cycle, and ultimately the likelihood of survival. Insects' metabolism and activity increase when the surrounding temperature rises to levels close to their thermal optimum. A desert locust outbreak (*Schistocerca gregaria* Forskal from the family Acrididae) has posed a serious threat to food security and way of life in many East African countries from the end of 2019 to the beginning of 2020. Climate changes, such as rising temperatures and precipitation over dry regions, strong winds in conjunction with tropical cyclones, can provide new conditions for pest reproduction, growth, and migration. This indicates that global warming	(Barnett *et al.*, 2005); (Roxy *et al.*, 2014); (Karthik *et al.*, 2021); (Skendžić *et al.*, 2021); (Bhat *et al.*, 2022)

	contributed to the development of the circumstances necessary for the locust's growth, breakout, and survival. 90% of the heat produced by humans is absorbed by the oceans and in the tropical Ocean system's western Indian Ocean, there is the fastest warming, with summertime average temperatures rising by 1.2 °C. Due to increased frequency and severity of extreme weather events in the surrounding areas, the locust epidemic has been more likely to spread to nations like Pakistan, India, etc.	
Impact on beneficial insects	The natural enemies of the insect pest are impacted by climate change in many different ways. greater temperatures, greater CO_2 levels, and lesser precipitation on plants create a variety of nutritional options for diverse insect pests, which ultimately affects the fitness of parasitoids and predators that feed on insect pests. Although there are many different host and parasitoid species, variations in precipitation are the main factor influencing how different caterpillar parasites behave. In cassava, *Manihot esculenta*, water stress mixed with dry circumstances reduces mealy bug parasitism. Natural enemies track their prey based on their host's tolerance for environmental extremes in relation to their movement as herbivore hosts. When pea plants are grown in environments with high CO_2 levels, predatory insects like *Oechalia schellenbergii* Guerin (Schellenberg's soldier bug) from the family Pentatomidae have been reported to be more successful in eradicating cotton bollworm larvae (*Helicoverpa armigera* Hubner) from the family Noctuidae. *Harmonia axyridis* Pallas (Asian ladybeetle), a coccinellid predator belonging to the family Coccinellidae, was also found to be more successful at feeding on the aphid, *Aphis gossypii* Glover from the family Aphididae, at greater CO_2 levels. Ladybird beetles (*Coccinella septempunctata* Linnaeus from the family Coccinellidae) are more effective at reducing the English grain aphid (*Sitobion avenae* Fabricus from the family Aphididae) populations in hot summers than in cool summers. Increased temperatures have an impact on plants' ability to produce and release additional floral nectar and volatile chemicals. These secretions aid the insects' defense against natural predators. After surviving temperature extremes, natural enemies must adapt to climate change in order to procreate; they must effectively find hosts via a wide range of temperature and humidity settings. At temperatures above 35 °C, the egg parasite *Trichogramma carverae* Oatman and Pinto is unable to recognize hosts and becomes less fertile at 30 °C. Some parasitoids undergo rapid evolutionary change in response to temperature changes and frequently participate in the extinction of the parasitoid population when the hosts are absent. As host species emerge and pass through the vulnerable phases swiftly before parasitoids appear, the rate of insect parasitism will decrease with higher temperatures. In temperate climates, mild winters let parasitoids survive. For instance, aphid parasitoids from cereal crops become active in the winter and lower aphid populations in the spring. The temperature has a significant impact on how ants forage. In general, chemically recruited ants favor cooler eating temperatures than non-chemically recruited ants. Increased temperature consequently causes pheromone degradation, which alters the trail left behind and is harmful to ant feeding activities. Sometimes small predators and parasitoids of hymenopterans contribute to temperature increases. The populations of host insects and natural enemies may react differentially to temperature variations. According to Awmack *et al*. research in 1997, aphids may be more susceptible to natural enemies as a result of climate change. If host populations develop and go through critical life stages before parasitoids do, parasitism may be minimized. At warmer temperatures, hosts may transition through sensitive life stages more quickly, narrowing the window for parasitism. Increased temperatures may harm sensitive natural enemies like small predators and parasitoids of the Hymenoptera. For instance, at 400^{C}, BPH was 17 times more tolerable than its predators *Cyrtorrhinus lividipennis* Reuter (rice bug) from the family Miridae, whereas the spider *Paradosa pseudoannulata* Bosenberg and Strand (wolf spider) from the family Lycosidae was more tolerable.	(Scott e*t al*., 1997); (Skirvin *et al*., 1997); (Ruano *et al*., 2000); (Harrington *et al*., 2001); (Thomson *et al*., 2001); (Calatayud *et al*., 2002); (Coviella *et al*., 2002); (Legrand *et al*., 2004); (Chen *et al*., 2005); (Hance *et al*., 2007); (Coll & Hughes, 2008); (Van Oudenhove *et al*., 2011); (Kambrekar *et al*., 2015); (Marshall *et al*., 2020); (Karthik *et al*., 2021)

Parasitoids	Higher trophic levels are predicted to have worse problems. The majority of the impact will presumably be felt by parasitoids among insects. Together, parasitoids, herbivores, and plants have developed in a climate that is rather stable. In order to live, parasitoids frequently have a lower temperature tolerance than their hosts. The most vulnerable species to extinction are those who depend on a tight synchronization with their host. Higher temperatures may improve the likelihood that a host may eliminate its parasite, according to some studies. For instance, the parasitoid *Microplitis rufiventris* Kokujev (braconid wasp) from the family Braconidae is less effective in parasitizing the caterpillar *Spodoptera littoralis* Boisduval (Egyptian cotton leafworm) from the family Noctuidae at 27°C (80.6°F) than it is at 20°C (68°F). Extreme weather conditions and shifting climate can potentially disturb parasitoid populations. Increased climatic variability is associated with lower parasitism rates, according to significant global research of caterpillars that were collected in the field. Reduced parasitism rates are probably caused by "increased lags and disconnections between herbivores and their carnivores that occurs as climatic variability increases". Tachinid flies and parasitic wasps both attacked caterpillars. Tachinids were able to adapt to climatic change, while parasitic wasps with a narrow host range did not. Field crops like maize that rely on biological management from host-specific parasitoids like *Trichogramma spp*. are anticipated to experience an upsurge in pest attacks if the weather patterns become more unpredictable.	(Karban 1998); (Thomas & Blanford 2003); (Stireman, 2005); (Hance *et al*., 2007); (Kambrekar *et al*., 2015)

Table 2 Climate change and it's impacts on insect biology, ecology, behaviour, population dynamics, abundance and distribution

Impacts	Description of impacts	Author(s)
Biology and phenology of insects	The biology and phenology of insect pests are significantly impacted by climate change and weather changes. Insect pests react differentially to various climate change conditions as typically adaptive creatures. Insect population dynamics, nocturnal activity, growth rate, reproduction, winter performance, and diapause are all complexly impacted by these changes. Through altering host plants and rivals, they also have an indirect impact on insects. Because tropical regions have historically experienced less climatic variability and because tropical insects are already more prone to harmful thermal maxima than temperate insects, research suggests that tropical insects are more vulnerable to warming conditions. Climate change has an impact on insect pests both directly and indirectly. Indirect effects include alterations to the host plant they feed on as well as interactions with natural enemies, other insect species, competitors, and the environment. Direct consequences include variations to the pests' biology, phenology, and distribution. Different species react differently to climatic fluctuation even within the same landscape, notwithstanding the difficulty of predicting the precise impact of climate change on insect biology and phenology.	(Bale *et al*., 2002); (Deutsch *et al*., 2008); (Stange & Ayres, 2010); (Prakash *et al*., 2014); (Garcia-Robledo *et al*., 2016); (Pareek *et* al., 2017); (Nice *et al*., 2019); (Marshall *et al*., 2020); (Jastoria *et al*., 2021); (Skendžić *et al*., 2021); (Chandrakumara *et al*., 2023); (Hassan *et al*., 2023)
Insect ecology	Different parts of insect ecology are predicted to be significantly impacted by climate change. It may foster circumstances that enable pests to flourish and widen their range. Each stage of an insect's life can react differently to environmental conditions. It's possible that some pests, which are currently confined to small areas or low densities, will be able to take advantage of the shifting conditions and spread more broadly, resulting in harmful population numbers. The synchronization within and between insect species can be impacted by climate change. Although parasitoids adapt to climate change in a manner similar to herbivores, host-parasitoid synchrony and population cycles are difficult to predict in a changing climate due to their intimate interaction with their hosts and unique life	(Porter *et al*., 1991); (Bale *et al*., 2002); (Kingsolver *et al*., 2020); (Tougeron *et al*., 2020); (Chandrakumara *et al*., 2023); (Hassan *et al*., 2023)

	cycle. Changes in temperature and humidity may also have an effect on insect communication, which depends on volatile chemicals. These modifications may have an impact on how these substances are produced, released, and detected, which may have an impact on how insects behave and survive. It's crucial to comprehend these potential effects in order to create efficient insect pest management tactics.	
Distribution: Geographic range expansion and migration behaviour	The width and range of an insect species' occurrence are greatly determined by the local climate. Therefore, an unfavourable environment is one of the elements that determine the limits of an insect species' range. For their growth and survival, insects must have climates that are peculiar to their species. Low temperatures are frequently more important in determining an insect species' geographic range than high temperatures, and climate change may have a considerable impact on the geographic distribution of insect species. A species' range is constrained by upper latitudinal boundaries because of the comparatively chilly temperature. Since the range border is defined by climate extremes rather than mean temperatures, insect species whose expansions were formerly constrained by extreme low temperatures are expanding toward polar regions. Many insect species are expected to move their northern and southern ranges up to higher altitudes and elevations. Many of the species that are increasing their geographic range are thermal generalists, and the decrease in winter mortality is what is causing their expansions. The distribution, geographic ranges, and migration patterns of insect species will be impacted by predicted changes in temperature, CO_2, and precipitation patterns brought on by climate change. Insect pests may have opportunities to spread across geographic and political boundaries as a result of these changes, which may also establish new ecological niches and eliminate low-temperature barriers, endangering food security. It is anticipated that an overall global pattern of expanding latitudinal and altitudinal range of agricultural pests will arise from climate change and the consequent changes in land usage. Insect species in their current environment may react differently to changing climates over longer time periods. They may undergo genetic, physiological, or behavioural changes to adapt to new climatic conditions in their current habitats. Alternately, they might expand their range to remain inside the current climatic envelope while adapting to new climatic conditions in their current range. Additionally, populations may fail to adjust to the shifting local climatic conditions and completely change their range to remain inside their ideal climatic envelope or go locally extinct, which would result in the population's eventual extinction. Numerous life history traits will determine a species' capacity to adapt to rising temperatures and widen its range, making the potential response extremely different among species.	(Parmesan & Yohe, 2003); (Battisti *et al.*, 2005); (Menéndez, 2007); (Food and Agriculture Organization, 2008); (Gregory *et al.*, 2009); (Ramamurthy, 2009); (Subrahmanyam *et al.*, 2009); (Stange & Ayres, 2010); (Fand *et al.*, 2012); (Andrew & Terblanche, 2013); (Lynch *et al.*, 2014); (Barzman *et al.*, 2015); (Lancaster *et al.*, 2016); (Pareek *et* al., 2017); (Marshall *et al.*, 2020); (Jastoria *et al.*, 2021); (Skendžić *et al.*, 2021); (Bhat *et al.*, 2022); (Chandrakumara *et al.*, 2023); (Hassan *et al.*, 2023)
Population dynamics and voltinism	Insect species can develop and reproduce more quickly when the average temperature rises, which leads to shorter life cycles, more larvae on a single host plant, and more outbreaks on a regular basis. Numerous insect groups are anticipated to see an increase in population size and pest activities as a result of this change in population dynamics brought on by climate change. Insects' voltinism (the number of generations they produce in a year) and survival and development rates can also be impacted by temperature changes, which can have an impact on population size, genetic composition, and the amount of damage they cause to host plants. According to the population model of the grape berry moth *Paralobesia viteana* Clemens from the family Tortricidae, a temperature increases of more than 2°C may have a significant effect on its voltinism and cause a change in the timing of its ovipositional period, which is currently regulated by photoperiod-induced diapause. With fewer cohorts in low-temperature regions and more in warmer ones, *Spodoptera eridania* Stoll (Southern armyworm) belonging to the family Noctuidae exhibited	(Bale *et al.*, 2002); (Jönsson *et al.*, 2007); (Tobin *et al.*, 2008); (Puri & Ramamurthy, 2009); (Stange & Ayres, 2010); (Jastoria *et al.*, 2021); (Sampaio *et al.*, 2021); (Bapatla *et al.*, 2022); (Chandrakumara *et al.*, 2023); (Hassan *et al.*, 2023)

	voltinism and has been reported to range from 2.9 to 9.2 generations in Brazil's current climate, and under climate change scenarios, this number was projected to rise significantly. In one study from India, the annual *Helicoverpa armigera* Hubner (cotton bollworm) generation increased to 12.9, 13.3, 13.8 and 14.2 respectively, with mean temperatures anticipated to rise by 0.51 °C, 1.03 °C, 1.57 °C and 2.1 °C in climate years 2030, 2050, 2070 and 2090. Future climate years in India will see a 3-12% increase in *H. armigera* Hubner generations.	
Growth rate, reproduction and abundance	As long as species growth maximum are not exceeded, insects' reactions to higher temperatures can be beneficial, such as greater reproductive potential. Under scenarios of global warming, the abundance of insects is anticipated to rise as ambient temperatures typically rise toward the ranges necessary for the growth and development of many insect species, thus reducing thermal limitations on population dynamics. Because nitrogen is necessary for insect growth, higher CO_2 levels alter the C: N ratio of plants, increasing the number of plants that insect pests consume. Due to the necessity for insects to consume more plant tissue in order to receive the same amount of energy, this increased consumption may cause more plant damage. Leaf feeders up their intake rates to make up for nutrient deficiencies when nitrogen levels fall as expected as a result of CO_2 fertilization. The growth period of the gypsy moth *Lymantria dispar* Linnaeus from the family Erebidae significantly reduced in their laboratory experiment as a result of an increase in temperature, demonstrating that the developmental periods of the egg, larva, and pupal stages shorten under conditions of increased temperature. Insects' life cycles are shortened by warmer weather, leading to more generations and shorter life spans. More generations are produced as a result, which can exacerbate the pest complex. Due to their rapid development, insects spend less time exposed to harmful elements including cold temperatures, parasite and predator attacks, and entomopathogens. Many bug species may experience reproductive success as a result of this brief exposure. For many species, however, breaching a particular optimal temperature range might result in slower growth, less fecundity, and higher mortality rates.	(Bezemer *et al.*, 1998); (Hamilton *et al.*, 2005); (Rouault *et al.*, 2006); (DeLucia *et al.*, 2008); (Puri & Ramamurthy, 2009) (Skendižić *et al.*, 2021); (Chandrakumara *et al.*, 2023); (Hassan *et al.*, 2023)
Increased number of generations of insects/ pests	By studying the phenology of insects and pests, we can quickly examine the effects of climate change. With shorter life cycles, the larval stages pass more quickly and transformation is getting simpler. According to research, the timing of pest appearances is also affected by climate change. with instance, with every 1 ˚C rise in temperature, potato aphids (*Myzus persicae* Sulzer belonging to the family Aphididae) were visible two weeks sooner than usual. Insect populations' metabolic processes are actually sped up by warmer temperatures, and this tendency to decrease diapause times suggests that insect activity will be higher. In general, higher temperatures cause population sizes to increase, which in turn causes a greater number of species to exist in dynamic equilibrium. Higher temperatures during the developmental phases have the positive consequence of shortening the larval and nymphal stages, particularly when they are seriously threatened by predators, and enabling species to mature earlier. An earlier adult emergence and longer flights are two reactions that insects should predict in response to temperature rise. Due of the rapid growth and development of larvae caused by high temperature ranges, more members of the next generation can be created while the photoperiod and temperature are still favourable. This prevents them from going through diapause as larvae and enables them to develop immediately in the same season.	(Harrington *et al.*, 2001); (Harrington *et al.*, 2007); (Menéndez, 2007); (Menéndez *et al.*, 2007); (Altermatt, 2010); (Pathak *et al.*, 2012); (Skendžić *et al.*, 2021); (Bhat *et al.*, 2022); (Hassan *et al.*, 2023)
Tritrophic (interspecific) interaction and	With modifying trophic relationships and community composition, climate change is transforming ecosystems. Climate change may lead to more heat stress exposure as well as morphological and phenological mismatches with lower trophic levels. The physiology of insects is significantly	(Caulfield & Bunce, 1994); (Coviella & Trumble, 1999); (Gouinguené &

chemical ecology	influenced by rising temperatures and CO_2, which can have a considerable impact on interactions between crops and herbivores. Natural enemies are impacted by changes to the availability of prey and hosts as a result of changes to plant phenology, which also impacts the growth and quantity of herbivores that consume these plants. Since an increase in plant foliage and variations in herbivore life cycles can have a substantial impact on their availability as prey, changes in plant phenology may lead to a reduction in predation and parasitism by natural enemies. Insect host plant associations and their tri-trophic interactions may become of balance because of changes in the flowering and growth patterns of the host plant brought on by climate change. Insects change in time with their host plant while also adjusting to the climatic factors. The production of secondary metabolites and the defensive characteristics of host plants can change in response to changes in temperature, CO_2, precipitation, relative humidity, and other environmental factors, which can have a significant impact on insect-plant interactions, according to a number of controlled studies. These modifications may weaken a plant's ability to protect itself from insect pests, leaving it more susceptible to harm. Additionally, increased temperatures and CO_2 concentrations may have an impact on the olfactory perception of volatiles and herbivore-induced plant volatiles (HIPV), which may have an impact on the capacity of natural enemies to locate hosts and the effectiveness of biological control. Additionally, a number of investigations have revealed that parasitoids and their hosts are not in good synchrony. Changing phenology at the trophic level and between them is altering biotic interactions. The reorganization of insect communities is facilitated by these asynchronies. This means that interactions between plants, herbivores, and natural enemies are affected significantly by climate change.	Turlings, 2002); (Zvereva & Kozlov, 2006); (Chen *et al.*, 2007); (Grabenweger *et al.*, 2007); (Zavala *et al.*, 2008); (Puri & Ramamurthy, 2009); (Ramamurthy, 2009); (Dhaliwal *et al.*, 2010); (Thomson *et al.*, 2010); (Bruce & Picket, 2011); (DeLucia *et al.*, 2012); (Damien & Tougeron, 2019); (Abarca & Spahn, 2021); (Chandrakumara *et al.*, 2023)
Coupling and mismatch of signals, and chooser preferences	Insects are temperature sensitive, and this limits the temperature ranges in which they can mate. Temperature has an impact on song in a variety of ways (including frequency, pulse duration, and interpulse length), but the pulse rate is the most crucial. According to Gray *et al.* (2016), female crickets have the strongest preferences for the calling and timing components of courtship songs. Temperature increases may lead to an imbalance in species-specific signal preferences. If female preferences shift to include pulse rate characteristics of closely related species that co-occur regionally, the likelihood of species mismatch increases. Both the environment and preferences can have a role in the mating decisions, which are not always based on preferences.	(Larson *et al.*, 2019); (Ghosh & Debnath, 2023)
Behavioural response	A change in phenology, or the timing of seasonal lifecycle events, is one of the most well-known effects of recent global warming. As a result of many species emerging earlier in the spring and remaining active for longer periods, population dynamics and abundance may be significantly impacted. Insects must quickly modify their phenology to synchronize with these essential resources for survival and fitness because host plant phenology is similarly affected by climate change. Although insects can change their behaviour and activity patterns to avoid these conditions if microclimate temperatures rise too high, this can be difficult depending on the species' level of plasticity in how they react to temperature and photoperiod changes as well as any ecological interactions that might limit their capacity to adapt. According to Williams *et al.* (2015), insects in temperate locations have a difficult time overwintering. Winters are expected to get warmer and more erratic as a result of climate change. Extremely low temperatures, which alter the ion balance in vital tissues and cause membrane depolarization, programmed cell death, and chilling injury, influence the degree of cold stress. Insects have been demonstrated to incur higher energetic and fitness costs when the minimum threshold temperature is exceeded. As a	(Menéndez, 2007); Van Asch *et al.*, 2007); (Stange & Ayres, 2010); (Andrew & Terblanche, 2013); (Van Asch *et al.*, 2013); (Roy *et al.*, 2015); (Sinclair, 2015); (Thackeray *et al.*, 2016); (Overgaard & MacMillan, 2017); (Pareek *et* al., 2017); (Bayley *et al.*, 2018); (Marshall & Sinclair, 2018); (Macgregor *et al.*, 2019); (Radchuk *et al.*, 2019);

	result of lower survival costs brought on by winter warming, more insects may survive the winter. Insects that are unable to feed during the winter months may also experience energy depletion as a result of elevated mean temperatures. Therefore, depending on each species' adaption strategy and cold hardiness mechanism, different species may function differently in the winter.	(Marshall *et al.*, 2020); (Jastoria *et al.*, 2021); (Skendžić *et al.*, 2021); (Bhat *et al.*, 2022); (Chandrakumara *et al.*, 2023); (Hassan *et al.*, 2023)
Diapause	Insects have evolved a number of survival techniques to combat unfavorable winter weather, such as diapause, a dormant stage during which an insect's physiological and metabolic functions are delayed. The beginning and end of winter diapause are crucial life-history transitions in temperate insects that control the amount of time spent on development and population increase. The timing of diapause in both insect pests and their natural adversaries has demonstrated local adaptation in several studies, suggesting that they may change in response to changing climatic conditions. Studies on genome-wide association indicate a connection between local adaptation in the timing of diapause induction and termination and the circadian clock genes found in insects. Short day durations towards the conclusion of the growth season and the start of the severe winter are typically employed as a cue for inducing diapause. However, the photoperiodic induction's adaptive value depends on past correlations between the photoperiod and a particular value of environmental factors like temperature and rainfall. These connections may be distorted by rapid climatic change, which would result in an inappropriate diapause timing. Additionally, the temperature throughout winter often influences when the diapause ends and when spring phenology begins. Due to the complicated interactions between diapause patterns, spring phenology, and the phenological synchronization to important supplies and enemies, climatic change can have an impact on insect populations' ecological and evolutionary processes.	(Hodek, 1996); (Bradshaw *et al.*, 2001); (Kostal, 2006); (Paolucci *et al.*, 2013); (Posledovich *et al.*, 2015); (Van Dyck *et al.*, 2015); (Forrest, 2016) (Lehmann *et al.*, 2017); (Kharouba *et al.*, 2018; (Pruisscher *et al.*, 2018); (Lindestad *et al.*, 2019); (Kozak *et al.*, 2019); (Kerr *et al.*, 2020); (Marshall *et al.*, 2020); (Chandrakumara *et al.*, 2023)
Efficacy of behavioural method: Pheromone communication	Increased temperatures and shifting CO_2 and O_3 concentrations in the atmosphere are anticipated to have an impact on every aspect of pheromone communication, from production to behavioural response. The most impacted insects are those that rely on long-range chemical signals for communication since these signals may be exposed to oxidative gases during dispersal. Ozone may change unsaturated terpenes, which are components of aggregation, alarm, or sexual pheromones in a variety of insects, including aphids, bark beetles, and fruit flies. Furthermore, because an insect's enzymatic activities are affected by its changing body temperature with the environment, higher temperatures are predicted to have an impact on pheromone biosynthesis both qualitatively and quantitatively. For instance, the temperature of the potato tuber moth *Phthorimaea operculella* Zeller from the family Gelechiidae may alter the ratio of chemicals in the sex pheromone. The production of pheromonal secretions in adult males as well as the proportion of molecules with a high molecular weight in pheromones were both increased by warmer rearing conditions for the larvae of *Philanthus triangulum* Fabricus (European beewolf) from the family Crabronidae. Changes in temperature can also affect the structure of scent plumes and how well insects can find their prey when their pheromones are diffused over a large area. Aphids' capacity to create and/or react to the alarm pheromone can also be affected by elevated CO_2 levels, which has an impact on their defensive actions. According to numerous investigations, climate warming can disrupt insect pheromone communication by raising temperatures and air gas concentrations. All semi chemical-based insect control techniques may be affected by climate change, which may alter how insects respond to pheromones and allelochemicals in terms of behaviour. Evidence suggests	(Ono, 1993); (Neven, 2000); (Francis *et al.*, 2005); (McFrederick *et al.*, 2009); (Roeser-Mueller *et al.*, 2010); (Sun *et al.*, 2010); (Sarles *et al.*, 2015); (Taft *et al.*, 2015); (Boullis & Verheggen, 2016); (Boullis *et al.*, 2016); (Renou & Anton, 2020); (El-Sayed *et al.*, 2021); (Chandrakumara *et al.*, 2023)

	that temperature change has an impact on the stability of pheromone molecules, decreasing their biological potency in the field. As a result, climate change may pose a general issue for chemical communication among insect species.	
Impact on insect indirectly through host plant interactions	Due to the altered vegetation brought on by climate change, insects will also be indirectly impacted by this phenomenon. In addition to adapting to climate change, vegetation also shapes the microclimate. The life cycle and development of insects are inextricably tied to the phenology of their host plants, which is mostly controlled by the ambient temperature. Therefore, changes in temperature, CO_2, and humidity levels can affect insects by altering the physiology and metabolism of the host plant. Additionally, a rise in the average temperature may have distinct effects on plants and phytophagous insects, which may throw off the timing of crucial activities at various trophic levels in an ecosystem. By improving photosynthetic activity, elevated CO_2 levels are predicted to have an impact on plant physiology and promote plant development. C_3 plants are more likely to be positively impacted by elevated CO_2 levels and negatively impacted by insect feeding, whereas C_4 plants are less responsive to increasing CO_2 and less likely to be impacted by changes in insect feeding behaviour. As CO_2 levels rise, plants tend to store more sugars and starches in their leaves, which may further alter the metabolism and feeding habits of insects. As a result, the carbon: nitrogen ratio of plants alters. Climate change is expected to result in changes in rainfall frequency, duration, and severity. This shift in rainfall will have an impact on soil moisture, which is crucial for many insects that live in the soil. Further to this insect play a key role in the transmission of numerous diseases affecting plants, including bacteria, viruses, and phytoplasmas. These illnesses are thought to cause annual economic losses of more than $30 billion. The epidemiology of plant viruses could significantly shift as a result of climate change. When it comes to agricultural crop species, the majority of viruses are single-stranded DNA viruses and messenger RNA viruses, with the primary host-to-host transmission technique using insect vectors with mouthparts for sucking and piercing. Geographical extension and a rise in the numbers of insect vectors are two effects of climate change that enhance the incidence of insect-transmitted plant diseases worldwide. Hemiptera, an order of sap-feeding insects, are the primary vectors of viral infections and include the families of aphids (Aphididae), leafhoppers (Cicadellidae), and whiteflies (Aleyrodidae). Aphids, which spread more than 275 different virus species, are the largest group of the aforementioned vectors. The Barley Yellow Dwarf Virus (BYDV), a very significant virus, infects members of the poaceae family and is spread by a number of aphid vectors. Based on extensive monitoring, the bird cherry oat aphid (*Rhopalosiphum padi* Linnaeus) belonging to the family Aphididae is the primary vector for BYDV in central Europe, and the minimum temperature for its movement is 8 C. Warmer conditions in autumn and winter in central and northern Europe increase vector persistence and consequently the risk of virus transmission in winter crops like winter wheat and barley, while warm temperatures and low rainfall decrease the availability of hosts, which presents a number of difficulties for viruses and their insect vectors. Aphid survival decreases at temperatures over 36 °C during the hottest summer months, which slows the transmission of BYDV. It is anticipated that newly established insect-transmitted plant diseases may proliferate due to climate change. Therefore, having diagnostic equipment and qualified workers is crucial for finding novel diseases. Through the extension of insect vector ranges and their fast reproduction, climate change may increase the prevalence of plant diseases that are transmitted by insects. Due to the early colonization of virus-carrying	(Lincoln *et al*., 1984); (Cotrufo *et al*., 1998); (Szujecki, 1998); (Robert *et al*., 2000); (Visser & Holleman, 2001); (Bale *et al*., 2002); (Stevens *et al*., 2004); (Curtis & Abby, 2005); (Sharma *et al*., 2005); (Moore & Allard, 2008); (Canto *et al*., 2009); (Ramamurthy, 2009); (Netherer and Schopf, 2010); (Petzoldt & Seaman, 2010); (Sharma *et al*.; 2010); (Roos *et al*., 2011); (Parry *et al*., 2012); (Sharma, 2014); (Sastry & Zitter, 2014); (Trębicki *et al*., 2016); (Fereres et al., 2017); (Pareek *et* al., 2017); (Chen *et al*., 2019); (Marshall *et al*., 2020); (Jastoria *et al*., 2021); (Karthik *et al*., 2021); (Skendžić *et al*., 2021); (Bhat *et al*., 2022); (Chandrakumara *et al*., 2023); (Dwarka *et al*., 2023); (Hassan *et al*., 2023)

	aphids, the primary vectors for potato viruses in Northern Europe, higher temperatures have been found to enhance the frequency of viral illnesses in potato, particularly in early season. Several insect species cause agricultural losses through disseminating infections. Hemipteran insects play a major role in the spread of disease. Climate change may enhance the prevalence of insect-transmitted plant diseases by expanding the ranges of insect vectors and causing a rapid increase in the number of insect vectors. A rise in population and hazards from insects similar to aphids can be blamed for the spread of associated diseases.	

4.2. Strategies to mitigate the effects of climate change

Pest insects significantly reduce global agriculture output. Global climate change may cause pest populations to become unstable, resulting in outbreaks that cause greater losses in some regions while decreasing pest-related losses in others. There are numerous ways that agro-ecosystems are anticipated to adapt to climate change. The following factors contribute to the decoupling of natural control mechanisms:

- Changes in the geographic distribution of insect pests;
- Temperature thresholds for pest and natural enemy species;
- Selection of novel strains with varied virulence;
- Differential effects on pest-natural enemies;
- Variations in the availability of food leading to pest shifts and
- modifications in the rivalry between crops and weeds.

All of this could lead to the extinction of some pest species and their corresponding niches as well as the potential for secondary pests and survivor species to spread more widely. Climate change-related increases in temperature and precipitation have a significant impact on insect growth, development, reproduction, and survival. Species' sensitivity to temperature will vary depending on their environment, life history, and capacity for adaptation [10] [13] [14] [15] [56] [59] [94] [105] [122] [138] [160] [170] [171] [174].

The geographic spread of insect pests is greatly influenced by climate change, and low temperatures have a greater impact on this distribution than high temperatures. Crop growth simulation models have been widely used in research on global climate change. However, the majority of simulation models don't take losses from weeds, diseases, and pests into consideration. In order to predict future spread and development, which ultimately affects worldwide agricultural production, it is essential to consider how the changing global environment is affecting epidemics of pest and disease. New pests and pest niches are predicted to become available as a result of rising temperatures. Since insects cannot control their body temperatures, the temperature to which they are exposed determines how they develop. Any variation in temperature will have a direct impact on insect development [26] [84] [91] [98] [120] [134] [140] [172] [195] [214].

Changes in phenology, dispersal, and community dynamics are only a few of the ways that insects react to climate change. While some effects of climate change may be beneficial in preserving the health of the crops and forests, many others will be highly detrimental. It is clear from the large range of climatic settings where forest groups exist that forests can endure changing climatic conditions. However, the introduction of pests into new areas without the assistance of natural enemies, the invasion of new host species, or the expansion of host species, may cause pest outbreaks, stunted growth of the forest, and the death of trees techniques [47] [85] [101] [135] [175] [205] [215].

More so than polyphagous insect pests, which exhibit phenotypic and genotypic adaptability and appear in a variety of habitats, specialist insect pests that limit a small niche in harsh circumstances are more likely to suffer negative effects. There will be enormous economic losses as crop insect damage increases. One of the first signs of a biological reaction to climate change may come through long-term monitoring of population levels and pest activity, especially in clearly susceptible areas. A significant body of knowledge is also lacking regarding how long-term variations in CO_2 and temperature, both separately and together, would alter crop interactions in the tropics and subtropics through influencing the behaviour of other agronomic management variables, such as water and nutrients. Therefore, it is crucial that potential climatic changes be taken into account as a key element in research on pest management techniques [47] [85] [101] [135] [175] [205] [215].

Climate change-related changes in species diversity and abundance may reduce the effectiveness of insect pest management programs, necessitating the development of new monitoring techniques as well as the improvement of current ones in order to identify potential changes in pest distribution, population ecology, damage assessment, yield loss, and impact assessment [54] [55] [175] [215]. For the development of novel IPM alternatives or the dissemination of current ones to new locations where farmers may find them appropriate, potential changes in pest survival strategies may require larger and stronger inter-center partnerships. The incorrect use of synthetic insecticides has led to current sensitivity to environmental contamination, risks to human health, and the comeback of pests [175] [215]. Several items with botanical and biological bases are currently employed as eco-friendly products. However, a lot of these pest management techniques have a high environmental sensitivity. Many of these management measures may become ineffective as temperatures and UV radiation rise and relative humidity falls [128] [215] [223].

Therefore, it is important to create effective pest management measures that will work in the future as a result of global warming. A potentially workable option for integrated pest management is provided by host-plant resistance, natural plant products, bio-pesticides, natural enemies, and agronomic methods. However, due to global warming, the relative effectiveness of many of these management methods is anticipated to vary. Climate change will have a significant impact on biological control, which is regarded as an essential and successful component of IPM programs because it will alter the connection between natural enemies and host pests [215].

The ecosystem is extremely sensitive to almost all insect control techniques, including cultural practices, natural enemies, host plant resistance, biopesticides, and synthetic pesticides. As a result, stronger and more climate-adaptive pest management solutions are required for the control of insect pests. It's crucial to assess how climate change will affect crop production and the creation of climate-smart crops in order to promote sustainable agriculture and reduce the effects of the climate on the sector. Development of soil productivity, techniques for adjusting insecticide/herbicide inputs to weather, and crop and climatic models for land use criteria are also necessary. It is also necessary to investigate cutting-edge cropping systems and practices that would lessen the risk of attack or competition [215].

The movement of insect pests to new areas in the absence of natural enemies is concerning since it will cause pest outbreaks. The major task at hand is to create reliable prediction models that will enable their management. The necessity for developing and implementing modeling approaches to foretell the shifts in the geographic distribution and population dynamics of insect pests, as well as the approaches to be modified to minimize agricultural losses, is believed to be urgent. Lack of water and unpredictable weather patterns may result in lower yields and a reduction in the amount of land that can be used for agriculture, making society more susceptible to the consequences of climate change [215].

Farmers can assess the likelihood of pest outbreaks under various climatic conditions with the use of the crucial decision-support tools provided by weather-based pest warning systems. The warning systems need accurate information on the weather, crops, and/or insects in order to take the appropriate precautions against pest outbreaks and economic losses. If this is the case, we can create plants that are adapted to these severe conditions before they become extreme naturally, eliminating the need for us to wait for evolution to improve crop output and allowing us to have plants with high yields [215].

5. Conclusion

This review placed critical emphasis on impact of climate change on insects. Insects control the populations of other organisms, cycle nutrients, pollinate plants, aids in seed dispersal, maintain soil fertility and structure and provide a significant food supply for other taxa. Insects also serve the role of being important keystones species in the health and services of the ecosystem. Globally, the insect population is declining drastically because of the negative impacts of the changing climate. It is important to adapt new strategies to mitigate the threats of climate change. Extreme weather conditions such as high temperature, an increasing level of carbon dioxide gas (CO_2) in the atmosphere and heavy precipitation all contribute to the shift in the global climate that are affecting the biodiversity of insects, their geographical distribution, their behavioural preferences and the rapid pests' outbreaks due to ineffective pest management interventions that some countries are challenged with and the agriculture sectors are being faced with on an annual. More research should be done in relation to climate change on insects as well as mitigation strategies. Many of the published literatures that were reviewed were external to countries outside the neotropics. There is need for more extensive research in the neotropical realm based on the impact of climate change on insects as there is a limited and paucity of data.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors hereby declare that this manuscript does not have any conflict of interest.

Statement of informed consent

All authors declare that informed consent was obtained from all individual participants included in the study.

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