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Effects of climate change scenario on insect-pests

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Abstract
Insects, as ectothermic organisms with short life cycles and highly variable population sizes, are expected to respond swiftly to climate change. Despite having thrived and diversified for over 450 million years through Earth's fluctuating climates, insects are now confronted with unprecedented threats driven by rapid changes in temperature and precipitation compounded by decades of human induced environmental pressures. Climate change is also intensifying the damage insects inflict on crops, leading to greater yield losses and posing significant challenges for pest management. Natural enemies are also equally affected by these environmental changes. This comprehensive scientific review warns that without targeted efforts to protect insects from climate related impacts, our ability to achieve a sustainable future will be severely compromised. The threat is particularly acute in tropical regions, where deforestation, agriculture, and climate change intersect to endanger insect populations most.

Keywords: Ectothermic, natural enemies, precipitation and temperature

1. Introduction
Over the last hundred years, global surface temperatures have increased by approximately 0.8 °C and are projected to rise further-potentially reaching between 1.1 °C and 5.4 °C by the next century (Sharma *et al.*, 2010) [52]. Simultaneously, atmospheric CO_2 levels have climbed from 280 ppm to 370 ppm, with expectations of doubling by 2100. These climatic transformations-characterized by elevated temperatures, erratic precipitation, and extended droughts-pose significant threats to agriculture.
Climatic variables influence crop physiology through complex mechanisms, altering photosynthesis at both tissue and organ levels. These changes also have profound effects on insect populations. Insects are impacted directly-through shifts in metabolism and behavior (Samways, 2005; Parmesan, 2007; Merrill *et al*., 2008) [50, 45, 37] and indirectly via alterations in host plant availability, competition, and predation dynamics (Harrington *et al.*, 2001; Bale *et al.*, 2002) [26, 5]. Broader ecological outcomes include changes in species phenology, distribution, and community dynamics, which may ultimately lead to species extinctions (Walther *et al*., 2002) [58]. Additionally, the growing frequency of extreme weather events- such as heatwaves, droughts, floods, cyclones, and hailstorms-poses a direct risk to agricultural productivity (Aggarwal, 2003; Aggarwal *et al*., 2022) [2, 1]. While issues related to food distribution and accessibility are critical, they are outside the scope of this analysis. This review centers on the direct and indirect repercussions of climate change on crop yields and agricultural ecosystems.

Primary agricultural impacts

1. Rising Temperatures
Increasing temperatures disrupt crop development, particularly during critical growth stages. Heat stress reduces yields, compromises grain quality, and in severe cases, results in complete crop failure. For instance, in wheat, elevated heat shortens grain-filling periods and reduces kernel size, negatively affecting overall productivity. Global crop yields may decrease by roughly 10% by mid-century, posing serious food security challenges (Ahmed *et al.*, 2017) [3].

2. Altered Rainfall Patterns
Variations in the timing and intensity of rainfall alter water availability. Irregular precipitation contributes to both droughts and flooding each harmful to crops. Water-scarce regions, in particular, find it increasingly difficult to sustain water-demanding crops such as maize and rice.

3. Increased Extreme Weather Events
Climate change is intensifying natural disasters like hurricanes and storms. These events devastate crops, disrupt transportation and supply chains, accelerate soil erosion, and extend recovery periods. A stark example is Hurricane Maria, which severely impacted Puerto Rico’s agriculture especially its banana and coffee industries.

4. Soil Degradation
Rising temperatures accelerate organic matter decomposition, reducing the soil's capacity to store carbon. This degradation weakens soil structure and hampers its ability to retain water and nutrients. Erratic rainfall compounds erosion, stripping away fertile layers and reducing the land's agricultural potential.

5. Disturbance of Soil Microbes
Soil microbial communities are essential for nutrient cycling and plant vitality are highly sensitive to changes in temperature and moisture. Climate induced shifts may destabilize these microbial populations, undermining plant-microbe interactions and impairing nutrient uptake.

6. Water Scarcity and Mismanagement
Climate change intensifies both droughts and heavy rainfall, worsening freshwater scarcity. Prolonged drought reduces soil moisture, while intense rainfall results in runoff and nutrient leaching. As irrigation demand grows alongside rising temperatures, competition for limited freshwater resources intensifies, especially in already water-stressed regions.

How climate change affects agricultural insect pests
Climate change is creating serious problems for farming not only by hurting crops directly but also by changing how insect pests behave, where they live, and how many of them there are. These pests are affected both directly- through changes in how they grow, survive, and spread and indirectly by changes in their relationships with plants, predators, and other organisms (Prakash *et al*., 2014) [49]. Since, insects are cold-blooded, their bodies depend on outside temperatures to function properly (Kocmánková *et al*., 2010) [32]. So, as temperatures rise, CO_2 levels increase, and soil dries out, we can expect major changes in how pest populations grow-and likely see more crop damage as a result (Fand *et al*., 2012) [20]. Global warming also opens up new areas for pests to live, allowing them to move into places where they previously couldn't survive (FAO, 2020) [21]. All of this threatens global food security and calls for worldwide cooperation to manage the risks.

a. Insects and Warmer Temperatures
Changes in Insect Populations
Temperature has a big impact on insects. As it gets warmer, insects usually grow and reproduce faster. Their metabolism almost doubles with every 10°C increase (Dukes *et al*., 2009) [17], which can lead to more feeding, quicker breeding, and faster spread (Bale *et al*., 2010) [4]. This often results in earlier and more intense pest problems (Yamamura *et al*., 2002) [60], though not all species react the same way. Some pests are already causing more trouble in warmer conditions. Whiteflies, for instance, thrive in heat and humidity (Pathania *et al*., 2020) [47]. Bark beetles are becoming more common because warmer winters help them survive and develop faster (Lantschner *et al*., 2022; Robbins *et al*., 2022) [33,]. Climate change is also disrupting the timing between pests and their natural enemies. For example, the cereal leaf beetle and its predators are now out of sync (Evans *et al*., 2013) [19]. Insects, like aphids and cabbage white butterflies, which can have several generations per year, are especially affected by temperature. Warmer weather shortens the time between generations, leading to more pest outbreaks during the growing season (Bale *et al*., 2002; Pollard & Yates, 2002) [5, 48]. Pests are also beginning to feed on new types of crops and move into new areas (Skendzic *et al*., 2021; Meynard *et al*., 2013) [, 38]. Examples include the corn earworm and cotton bollworm. These pests are now spreading further and surviving winters better, putting key crops like maize at risk worldwide (Diffenbaugh *et al*., 2008; Fand *et al*., 2012; Nayak *et al*., 2020) [15, 20, 40].
Pest populations are growing, moving into new places, and appearing earlier in the year making them harder to control. Aphids, in particular, are reacting quickly to rising temperatures and causing sudden, damaging outbreaks (Shi *et al*., 2014; Wu *et al*., 2020) [53,]. To keep up, farmers and scientists need to better predict how pests will behave as the climate changes and create smarter, more flexible pest control plans. If we want to keep growing enough food in a warmer world, we'll need to deeply understand how pests respond to these environmental shifts.

b. Impacts of Rising CO_2 on Insect Pests and Crops
As atmospheric CO_2 levels continue to rise due to climate change, both crops and the insect pests that feed on them are affected. These changes can alter how pests behave, how their populations grow, and how they interact with plants.

How Higher CO_2 Affects Insects
Insect pests respond to higher CO_2 in two main ways:
- **Direct effects:** These include changes in how insects grow, reproduce and survive.
- **Indirect effects:** These come from changes in the plants that insects eat, especially in how those plants are nutritious.

The impact depends on the relationship between the insect and the plant. Crops that use the C_3 photosynthesis process (like rice, wheat, and cotton) respond more to increased CO_2 than C_4 crops (like maize and sorghum), which means insects feeding on C_3 crops may experience more changes in food quality.

Changes in Plant Chemistry and Insect Diet
Higher CO_2 boosts plant growth and changes the chemical makeup of their leaves. For example, plants grown in more CO_2 often have more sugars but less nitrogen. Since nitrogen is crucial for insect development, this can lead to compensatory feeding where insects eat more to make up for the lower quality of food.
A study on soybeans showed that crops grown under higher CO_2 suffered 57% more insect damage due to pests like beetles and leafhoppers. The increase was likely due to the sweeter leaves encouraging more feeding.

Different Insects, Different Responses
Not all insects respond the same way. Insects that chew (like caterpillars and beetles) often eat more when food quality declines. Sap-sucking insects (like aphids and whiteflies) show mixed results; some reproduce more, others less. Chewing insects were most affected.
A broad study found that higher CO_2 generally leads to:

- 17% more insect feeding
- 22% fewer pest's overall
- 4% longer development times
- 9% slower growth

Can Insects Adapt?

Some pests, like the pine sawfly, can adjust by using nitrogen more efficiently. Others can't, and they suffer reduced growth or reproduction. Some pests, like the Japanese beetle, even live longer and reproduce more when eating CO_2-enriched plants—possibly making them more damaging in the long run.

Rethinking the CO_2 Benefit

It was once believed that more CO_2 would simply help crops grow better but in reality, this benefit may be reduced or canceled out by increased pest damage. So instead of boosting agriculture, rising CO_2 might make pest problems worse, especially for crops that are already vulnerable.

c. Impact of Altered Precipitation Patterns on Agricultural Insect Pests

Climate change is significantly altering global precipitation patterns, modifying not just the amount of rainfall but also its distribution, timing, and intensity. These shifts influence hydrological mechanisms such as infiltration, evapotranspiration, and streamflow as well as atmospheric moisture levels and soil water content. Collectively, these changes have far-reaching implications for the life cycles and population dynamics of agricultural insect pests.

Insects like aphids, jassids, whiteflies, mites, and wireworms are particularly responsive to fluctuations in rainfall (Gregoryet *et al*., 2009, Johnson *et al*.,2008, Staley *et al*., 2007) [23, 28, 55]. While intense downpours can physically dislodge or drown smaller pests, irregular precipitation patterns-marked by alternating periods of drought and flooding can disrupt ecological balances, including predator-prey relationships, or weaken plant defenses (Pathak *et al*., 2012) [46]. For instance, Oriental armyworms often thrive after extended droughts followed by sudden heavy rains, benefiting from the diminished presence of their natural predators (Sharma *et al*., 2010) [52].

Water stress in crops further exacerbates vulnerability to pest infestations (Zayan *et al*., 2019) [61]. Drought conditions, for example, are closely linked with increased bark beetle activity, while plants exposed to intermittent water availability may become more conducive to sap sucking pests (Netherer *et al*., 2019 and Netherer., 2015) [42, 41]. Pest species such as *Helicoverpa armigera* show higher population densities during unusually wet periods in certain seasons, indicating a close association with precipitation variability.

Extreme rainfall events can also directly influence pest behavior and spatial distribution. Simulated rainfall experiments using sprinkler systems have demonstrated that aphid populations in wheat fields, among other crops, tend to decline under consistent wet conditions (Daebeler and Hinz, 1977; Chander, 1998) [14, 9]. Root-feeding insects may respond differently, with some thriving in wetter soils and others showing no marked change (Karuppaiah and Sujayanad, 2012) [29]. Additionally, agricultural practices such as host plant pre-cultivation and crop rotation influence pest emergence; for example, outbreaks of *Spodoptera litura* are often linked to a combination of specific weather conditions and cropping systems (Chari *et al.,* 1993) [10]. Phytophagous insects may also develop adaptations to overcome higher carbon to nitrogen ratios, for example the pine sawfly, *Neodiprion lecontei*, showed an increase in the efficiency of nitrogen utilization when reared on plants treated with high CO2 concentration (Williams *et al*., *1994*) [59]. However, other insect species seem unable to compensate the lower nutritional quality of the plants by increasing the efficiency of nutrient utilization (Brooks and Whitekar, 1999) [8]. The experiments of Lindroth *et al.* (1993) [34] on three species of saturnid moths showed that the performance of caterpillars is only marginally affected when the nitrogen content of the leaves is reduced by 23% and the carbon to nitrogen ratio increased by 13-28%.

Geographic redistribution of pests under a changing climate

Shifts in insect pest distributions are increasingly driven by climate-induced changes, particularly in temperature and precipitation. While traditional factors like crop choice, land management, and international trade still play roles in pest dispersion, climatic variables are now critical in shaping future pest ranges. Historically, colder temperatures have served as natural barriers limiting pest spread. However, as global temperatures rise, these constraints are diminishing, allowing pests to colonize higher latitudes and altitudes. Notable examples include the northward expansion of the European corn borer by over 1,000 kilometers and the unexpected presence of the Diamondback moth in Arctic zones (Coulson *et al*., 2002) [13]. The pink bollworm, once restricted to the warmer regions of Arizona and California, has also moved into cooler cotton-producing areas, facilitated by increasingly mild winters (Gutierrez *et al*., 2006) [24]. Lopez-Vaamonde *et al*., 2010 [35] reported that 97 non-native Lepidoptera species in 20 families have become established in Europe, and 88 European Lepidoptera species in 25 families have expanded their range in Europe, with 74% of species becoming established in the last century. Parmesan *et al*. studied 35 species of non-migratory European butterflies and concluded that the geographic ranges of 63% had shifted 35 to 240 km northward and only 3% southward in the 20th century.

The ecological impact of these shifts is complex. In some areas, rising temperatures may reduce the number of pest generations due to seasonal mismatches, while in others, warmer conditions permit more generations per year. Alterations in frost patterns are particularly important, as they can aid the survival of frost-sensitive species and enable earlier infestations aligned with earlier plant growth stages (Fleming *et al*., 1995) [22].

Diapause disruption and overwintering challenges

Many insect pests rely on diapause—a dormant physiological state—to survive unfavorable conditions, particularly in winter. As ectothermic organisms, insects synchronize diapause initiation and termination with environmental cues such as temperature and photoperiod. However, the increasing unpredictability of seasonal transitions is disrupting these cues (Bale and Hayward, 2010, Hahn and Denlinger, 2007) [4, 25]. Warmer winters accelerate insect metabolic rates, shortening diapause duration and triggering earlier emergence. While this can result in greater pest pressure and additional generations in some areas, it can also increase mortality if insects emerge prematurely and encounter subsequent cold snaps. This mismatch introduces greater instability in agroecosystems (Naeem-Ullah *et al*., 2012, Overgaard *et al*., 2017) [39, 44].

A case in point is the green stinkbug in Japan, which requires adult-stage diapause to survive the winter. When diapause onset is delayed and insects remain in juvenile stages, overwintering success diminishes sharply (Boyes *et al*., 2021) [7]. Conversely, in warmer climates, the extended growing season enables pests to complete development before winter, increasing their chances of survival (Numata *et al*., 2023) [43]. As diapause timing becomes increasingly misaligned with environmental rhythms, pest management becomes more complicated. Disruptions to diapause not only affect survival rates but also elevate metabolic demands, further threatening insect populations and agricultural productivity (Bale *et al*., 2010, Ma *et al*., 2021, Kerr *et al*., 2020, Dyck *et al*., 2015) [4, 36, 30, 57].

Climate change and the role of natural enemies in pest management

Natural enemies such as predators, parasitoids, and pathogens are key allies in controlling plant-feeding insect pests. These species function within a tri-trophic system that includes plants, herbivores, and their natural enemies, forming a delicate balance essential to both agriculture and natural ecosystems.

Disruption of Tri-Trophic Relationships

Climate change significantly influences the biology and behavior of both pests and their natural enemies (Thompson *et al*., 2010). Alterations in temperature, precipitation, and atmospheric CO_2 can disturb the timing and effectiveness of biological control. For example, warming trends may cause predators or parasitoids to develop faster than their prey, leading to mismatches in their life cycles and reduced survival rates due to lack of hosts. In addition, shifting crop zones due to climate stress can relocate herbivores into new regions where their natural enemies may not be present. This disconnect can lead to uncontrolled pest populations unless predators can also expand their ranges.

Varying Responses Among Natural Enemies

The degree to which natural enemies are affected by climate change depends on their ecological strategies. Generalist species, which feed on a range of prey, are generally more adaptable and better suited to cope with environmental shifts. In contrast, specialist species are more vulnerable to disruptions in host availability and timing (Selvaraj *et al*., 2013) [51]. The direct effects of temperature changes and different responses by each component species can disrupt pests and their natural enemy dynamics (Kiritani *et al*., 2006) [31]. Climate factors also indirectly affect predator-prey dynamics through changes in plant health (van Doan *et al*., 2021) [16]. Elevated CO_2, variable rainfall, and temperature extremes can alter plant nutritional quality, which in turn affects herbivore physiology and the fitness of their predators and parasitoids (Jamieson *et al*., 2012) [27].

Evidence from Ecological Studies

Experimental studies show that climate change influences biocontrol outcomes in complex ways:

- In a system involving annual bluegrass, green peach aphids, and the parasitoid *Aphidius matricariae*, both aphid abundance and parasitism increased under higher temperatures, though elevated CO_2 alone had minimal impact (Bezemer *et al*., 1998) [6].
- In another case, elevated CO_2 reduced the reproductive capacity of *Aphidius picipes*, despite an increase in parasitism of the English grain aphid (Chen *et al*., 2007) [12].
- Alfalfa studies revealed that while beet armyworm larvae developed more quickly under low-nutrient conditions induced by climate change, their parasitoid *Cotesia marginiventris* could not survive, leading to its local extinction (Dyer *et al*., 2013) [18].
- Predatory ladybirds (*Harmonia axyridis*) preferred aphids grown in elevated CO_2 environments, though their development and predation efficiency remained stable (Chen *et al*., 2005 and Chen *et al*., 2007) [11, 12].

These outcomes underscore that the impacts of climate change on natural enemies are species-specific and dependent on traits like environmental tolerance and life cycle synchronization.

Moving forward: integrated assessment is key

To effectively manage pest populations in a changing climate, we must evaluate entire food webs rather than individual species. Predictive models and long-term studies that consider plant physiology, herbivore dynamics, and predator-prey relationships under different climate scenarios are critical. A systems-based approach to pest management one that recognizes and integrates the cascading effects of climate change will be essential for building resilient and sustainable agricultural systems in the future.

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