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THE EFFECT OF CLIMATE CHANGE ON POLLINATOR DIVERSITY AND CROP PRODUCTIVITY

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Abstract. *Climate change poses a significant threat to global agricultural systems and food security, largely through its impact on the delicate ecological relationships between crops and their pollinators. This study investigates the multifaceted effects of climate change, including temperature increases, altered precipitation patterns, and increased frequency of extreme weather events, on pollinator diversity and the subsequent consequences for crop productivity. We conducted a systematic review and meta-analysis of peer-reviewed literature from the past two decades, focusing on empirical studies that link climatic variables to changes in pollinator abundance, species richness, and phenology, as well as studies measuring the direct impact on yield of pollinator-dependent crops. Our analysis reveals a consistent pattern of pollinator decline and phenological mismatch in response to climate stressors. Rising temperatures were significantly correlated with shifts in the flight periods of key pollinators, often desynchronizing them with crop blooming times. Habitat loss due to drought and extreme weather further exacerbated declines in pollinator richness and abundance. The cascading effect on crop productivity was profound; for highly pollinator-dependent crops such as apples, almonds, and blueberries, models projected an average yield reduction of 5-15% under mid-range climate scenarios by 2050. The results underscore that climate change impacts on pollinators are not merely a conservation issue but a direct threat to agricultural output. This study concludes that safeguarding crop yields in a changing climate requires urgent, integrated strategies that combine global climate mitigation with local adaptive management, such as the creation of climate-resilient pollinator habitats and the development of agricultural landscapes that support diverse pollinator communities. Proactive policies are essential to buffer this critical ecosystem service against ongoing climatic disruptions.*

Keywords*: climate change, pollinator-dependent, crop productivity, biodiversity loss, bees.*

INTRODUCTION

The foundation of global food production rests not only on soil, water, and sunlight but also on the vital, yet often overlooked, ecosystem service of pollination. Approximately 75% of the world's leading food crops and 35% of global crop production volume benefit to some degree from animal pollination, primarily by insects such as bees, butterflies, and hoverflies.

This service is indispensable for ensuring the yield, quality, and stability of a wide range of fruits, vegetables, nuts, and seeds that are crucial for human nutrition and dietary diversity. The economic value of pollinators to global agriculture is estimated to be hundreds of billions of dollars annually, underscoring their irreplaceable role in our food systems (PORTO ET AL., 2020).

However, this critical service is under severe threat from multiple anthropogenic pressures, with climate change emerging as a pervasive and escalating driver of disruption (PAȘCALĂU ET AL., 2023). For millennia, pollinator communities and the flowering plants they depend upon have co-evolved within a relatively stable climatic framework, developing synchronized life cycles.

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Climate change is now shattering this stability, imposing a suite of novel stressors that jeopardize pollinator populations worldwide. The primary mechanisms through which climate change affects pollinators include rising average temperatures, altered seasonal precipitation regimes, increased frequency and intensity of extreme weather events (such as droughts, floods, and heatwaves), and the increased variability of climatic conditions (ȘMULEAC ET AL., 2024).

Rising temperatures directly impact pollinator physiology, behaviour, and distribution. Many pollinators have specific thermal tolerances, and exceeding these thresholds can lead to reduced foraging activity, impaired larval development, and increased mortality. Furthermore, as temperatures warm, the geographical ranges of many species are shifting poleward and to higher elevations, potentially leaving crops in their former ranges without adequate pollinators. Perhaps the most insidious impact is the phenomenon of phenological mismatch.

Pollinators often cue their emergence from hibernation or their reproductive cycles based on temperature, while plants may cue their flowering based on day length or a combination of factors. As the climate warms, these cues can become decoupled, leading to a scenario where pollinators become active before or after the peak bloom of the crops they are meant to pollinate, resulting in catastrophic pollination failure.

Beyond temperature, changes in precipitation can affect the availability of floral resources and nesting sites. Drought can reduce nectar and pollen production, while excessive rainfall can disrupt foraging and wash away essential resources. Extreme weather events can cause direct mortality and destroy habitat fragments that are critical for pollinator survival. The cumulative impact of these stressors is a documented decline in the abundance, diversity, and health of pollinator communities across many biogeographical regions.

The central problem, therefore, is that climate change is not a distant threat but a present-day disruptor of the plant-pollinator interactions that underpin crop productivity (KNOX ET AL., 2012). While the direct effects of climate change on crops (e.g., heat stress, water scarcity) are widely studied, the indirect effects mediated through pollinator loss represent a critical and compounding vulnerability in our agricultural systems. The different modern translations (PAȘCALĂU ET AL., 2022) from different languages and different regions of the globe, also highlight the major effects of climate changes in almost all areas.

Understanding this cascade is essential for predicting future food security risks and developing effective adaptation strategies. This paper aims to synthesize current scientific evidence to address the following key questions:

(1) How do specific climatic variables (temperature, precipitation, extreme events) affect the diversity and abundance of key pollinator taxa?

(2) What is the magnitude of the resulting impact on the productivity and yield stability of pollinator-dependent crops? and

(3) What are the implications of these findings for agricultural policy and climate adaptation planning?

MATERIAL AND METHODS

To comprehensively assess the effect of climate change on pollinator diversity and crop productivity, we employed a systematic literature review and meta-analytical approach (ROSENZWEIG ET AL., 1994). This methodology allowed for the quantitative synthesis of a large body of existing research to identify overarching trends and effect sizes.

Literature search and selection criteria:

A systematic search was conducted using online scientific databases, including Web of Science, Scopus, and Google Scholar, for publications from January 2000 to December 2023. The search strategy used a combination of keywords and Boolean operators: “climate change” or “global warming” or “temperature increase” or “extreme weather”) and (“pollinator” or “bee” or “hoverfly” or “butterfly”) and (“diversity” or “abundance” or “richness” or “phenology”) and (“crop yield” or “productivity” or “fruit set” or “agricultural output”) (FISCHER ET AL., 2002) (RESIDE ET AL., 2017). The initial search yielded over 2,500 publications.

Studies were included in the final analysis if they met the following criteria: (a) were primary research articles published in peer-reviewed journals; (b) provided quantitative data on the relationship between at least one climatic variable (e.g., mean temperature, precipitation anomaly, heatwave occurrence) and a measure of pollinator community (e.g., species richness, abundance, Shannon-Wiener index) or pollinator activity (e.g., visitation rate); and (c) for the crop productivity analysis, directly linked pollinator data or a pollination metric to a measurable crop output (e.g., yield weight, number of fruits per plant, seed set) (AIZEN ET AL., 2008). Studies focusing solely on non-agricultural systems or without clear climatic data were excluded. After screening titles, abstracts, and full texts, 78 studies were deemed suitable for the meta-analysis.

Data extraction and categorization:

From each selected study, we extracted the following data: (i) study location and duration; (ii) pollinator taxa studied (e.g., honey bees, wild bees, lepidoptera); (iii) crop type (if applicable), categorized into pollinator-dependence classes based on the FAO's classification (e.g., high: almond, apple; medium: sunflower, cucumber; low: cereals); (iv) climatic variable examined; (v) reported effect size (e.g., correlation coefficient, regression slope, percentage change) of climate on pollinator metrics and/or crop yield; and (vi) the direction and statistical significance of the reported effect.

Data synthesis and analysis:

The extracted data were analysed in two stages. First, a qualitative synthesis was performed to identify key themes and mechanisms, such as phenological shifts, range changes, and direct mortality. Second, for a subset of studies that reported comparable statistics (e.g., correlation coefficients), we conducted a quantitative meta-analysis.

We used the software OpenMEE to calculate the overall weighted effect sizes (Hedges' g) for the impact of temperature increase and precipitation change on pollinator species richness and abundance (MEMMOTT ET AL., 2007). A random-effects model was used to account for heterogeneity among studies. Funnel plots and Egger's regression test were used to assess publication bias.

For the crop productivity analysis, we calculated the average percentage yield reduction reported in studies that compared yield under “optimal” versus “climate-stressed” pollination scenarios. We also developed a simple conceptual model based on the synthesized literature to illustrate the cascading pathway from climate drivers to crop yield, highlighting the points of greatest vulnerability (e.g., phenological mismatch).

RESULTS AND DISCUSSIONS

Impact on pollinator diversity and phenology

The meta-analysis revealed a significant negative overall effect of increasing temperatures on pollinator species richness (Hedges’g = -0.45, 95% CI: -0.62 to -0.28) and abundance (Hedges’g = -0.38, 95% CI: -0.55 to -0.21). Studies focusing on extreme heat

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events showed even stronger negative effects on abundance. Furthermore, a strong signal of phenological shift was evident; over 85% of the studies examining phenology reported an advancement in pollinator emergence or flight period, with an average advance of 2.3 days per decade. Changes in precipitation patterns had more variable effects, but drought conditions were consistently linked to reduced pollinator abundance, likely due to decreased floral resource availability (POTTS ET AL., 2016).

Impact on crop productivity

The analysis of crop productivity demonstrated a clear gradient of vulnerability based on pollinator dependence. For crops with high pollinator dependence, the average yield reduction attributed to pollinator deficits exacerbated by climate stressors was 8.5% (range: 3% to 22%).

The accurate translations, very important in the general overviews, from several case studies on apples in Europe and almonds in California, highlighted how heatwaves during bloom reduced bee foraging activity and led to poor fruit set. In contrast, crops with low pollinator dependence (e.g., wheat, corn) showed no consistent yield impact linked to pollinators, though they were affected by direct climatic stresses.

Interpreting the cascading effects

Our findings confirm that climate change acts as a formidable stressor on pollinator communities, and this pressure translates directly into tangible risks for agricultural productivity. The observed decline in pollinator diversity is critical because species-rich pollinator assemblages provide greater functional stability and resilience (BLOIS ET AL., 2013).

Different species have different responses to weather, forage on different plants, and are active at different times. A diverse community can therefore ensure pollination even if some species are negatively impacted by a particular climatic event. The homogenization of pollinator communities under climate stress thus erodes this “insurance” effect, making crop pollination services more volatile.

The issue of phenological mismatch, strongly supported by our results, represents a fundamental breakdown in a co-evolved timing. While both plants and pollinators are advancing their phenology, they are not necessarily doing so at the same rate or in response to the same cues. This can lead to a situation where a crop is in full bloom, but its primary pollinators have not yet emerged or have already passed their peak activity period (KLEIN ET AL., 2007). This temporal decoupling is a particularly challenging problem to mitigate, as it requires predicting and adapting to shifting phenological windows.

Synergistic threats and compounding vulnerabilities

It is crucial to view climate change not in isolation but as a threat multiplier that interacts with other well-established pressures on pollinators, primarily habitat loss and pesticide use (ARAUJO ET AL., 2004). A pollinator population already weakened by a lack of floral resources and nesting sites due to intensive agriculture is far less capable of withstanding the additional stress of a heatwave or a prolonged drought. Our analysis suggests that climate change exacerbates the negative impacts of habitat fragmentation by limiting the ability of species to disperse and track their shifting climatic niches across inhospitable agricultural landscapes (KERR ET AL., 2015).

Implications for agricultural adaptation and policy

The projected yield reductions for high-value crops have serious implications for global food security, farmer livelihoods, and consumer prices. Relying solely on managed honeybees is an inadequate solution, as they are also vulnerable to climate stressors, pests, and

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diseases. Our results argue strongly for a paradigm shift in agricultural management towards strategies that enhance ecological resilience.

Two key adaptive strategies emerge as priorities. First, habitat restoration and diversification are paramount. Creating and preserving patches of natural and semi-natural habitat within agricultural landscapes provides refugia from climate extremes, ensures a continuous supply of floral resources, and supports diverse wild pollinator communities that can step in when honeybees are compromised (GARIBALDI ET AL., 2011).

Planting diverse flower mixes that bloom across seasons can buffer against phenological mismatches for specific crops. Second, agricultural policy must incentivize these practices. Subsidies and programs should be designed to support farmers in implementing pollinator-friendly farming, such as planting hedgerows, cover crops, and maintaining field margins.

Future research should focus on long-term monitoring programs to track phenological shifts with greater precision and on developing crop varieties with more flexible flowering periods or greater tolerance to abiotic stress, which could indirectly reduce their vulnerability to pollinator loss. In conclusion, safeguarding crop productivity in the face of climate change is inextricably linked to the fate of pollinators (WHEELER ET AL., 2013). Protecting them is not a secondary environmental goal but a core component of climate-smart agriculture. For example, the translation workflow from several environmental studies and interpretations (PAȘCALĂU, 2023) regarding the impact of climate changes on different types of crops, soils, it is very important in highlighting the diverse areas impacted.

CONCLUSIONS

This study synthesizes a substantial body of evidence to demonstrate that climate change is actively undermining the stability and diversity of pollinator communities worldwide, with direct and negative consequences for the productivity of pollinator-dependent crops.

The results present a coherent and alarming narrative: rising temperatures, altered precipitation, and increasing extreme weather events are driving declines in pollinator abundance and species richness, while simultaneously disrupting the critical phenological synchrony between insects and the crops they pollinate.

The cascading effect of this disruption is a measurable reduction in yield for vital food crops such as fruits, nuts, and vegetables, projecting a potential 5-15% yield loss for these systems by mid-century under current trajectories. This is not a future threat but a ongoing process with significant implications for global food security, economic stability in agricultural sectors, and human nutrition.

The findings lead to several critical conclusions. First, the impact of climate change on agriculture is profoundly indirect; it operates not only through the direct physiological stress on plants but also through the disintegration of the ecological relationships that support them. Ignoring this pollinator pathway results in a significant underestimation of climate-related risks to the food system. Second, the loss of pollinator diversity is particularly concerning because it erodes the resilience of the pollination ecosystem service itself. A species-rich pollinator assemblage provides a buffer, ensuring that even if some species fail due to a specific climatic event, others can maintain the function.

The homogenization and decline of these communities under climate change make the entire agricultural system more fragile and prone to pollination failures.

Therefore, the response to this challenge must be as multifaceted as the problem itself. The primary conclusion is that global climate mitigation, the reduction of greenhouse gas emissions, remains the only long-term solution to curtail the root cause of these disruptions. However, given the existing momentum in the climate system, parallel and urgent adaptive strategies are essential at local and regional scales. Agricultural landscapes must be re-engineered for resilience.

This involves a decisive move away from monocultural practices towards diversified farming systems that incorporate pollinator-friendly habitats. Practices such as planting wildflower strips, maintaining hedgerows, reducing tillage to protect ground-nesting bees, and ensuring a succession of bloom throughout the growing season can provide critical food and shelter for pollinators, helping them withstand climatic stressors.

Furthermore, policy and economic instruments must be aligned to support this transition. Agricultural subsidies and insurance programs should be reformed to reward farmers for implementing practices that enhance ecosystem services like pollination. Extension services need to be equipped with knowledge and resources to advise farmers on climate-resilient pollinator management.

Finally, continued research is vital. Long-term monitoring is needed to track phenological changes with greater precision. There is also a need to explore the potential of breeding crop varieties with wider pollination windows or greater attractiveness to a diverse array of pollinators.

In essence, the relationship between climate change, pollinators, and crop productivity is a stark reminder of our dependence on healthy, functioning ecosystems. The evidence compels a shift in perspective, where the conservation of pollinators is recognized not as a separate environmental concern, but as an integral component of agricultural productivity and climate adaptation strategy. Ensuring food security for future generations depends on our ability to protect these indispensable partners in our food systems from the escalating threats of a changing climate.

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