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ARTICLE

Climate Change's Impact on Honeybee Distribution and Population, Habitats, Bioproducts, and Pest Threats as Protective of SDGs

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ABSTRACT

Bees are essential to human life and ecosystems, significantly contributing to medicine, economics, and environmental equilibrium. Bees serve an essential function as pollinators, facilitating the cultivation of various fruits and vegetables. Bees contribute approximately 117 billion US dollars annually to the economy through their role in crop pollination. They have a direct impact on 35% of agricultural crops and 84% of cultivated plants. Bee products, including honey, propolis, and royal jelly, have been utilized in various traditional medicine practices across numerous countries. These substances have been utilized for their anti-inflammatory, antioxidant, and antibacterial properties. In addition to their economic, ecological, and medical significance, they serve as bioindicators for assessing the health of ecological systems by monitoring distribution and population dynamics. This offers important insights into the current situation, especially regarding the substantial impacts of climate change on the environment. This article seeks to synthesize data from various studies to examine the impact of climate change on bee populations and their habitats. This study illustrates the significant effects of future climate models for 2050 and 2070 on bee distribution, resulting in the decline of specific species populations.

Keywords: Bee Distribution; Bee Population; Climate Change; Ecology; Biodiversity

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1. Introduction

Bees hold significant value in medical, economic, and environmental contexts. Bees are essential for pollination, working alongside other insects like butterflies to transfer pollen, which is vital for the production of fruits and seeds, including apples and pears [1, 2]. The estimated annual contribution is 117 billion US dollars [3], with approximately 35% of agricultural crops directly dependent on pollination processes carried out by pollinators [4]. Furthermore, these insects contribute to the reproductive processes of approximately 84% of cultivated plants, thereby facilitating their survival and promoting biodiversity. Bees are essential to economics, both directly through the sale of products like honey, propolis, wax, and royal jelly, and indirectly by pollinating various crops, which greatly enhances agricultural profits [5, 6]. Bees and their products have been integral to traditional medicine practices since ancient civilizations, including that of Egypt. The discovery of honey in pharaohs' tombs indicates its significance as a medicinal substance and a vital energy source in Greek, Chinese, Korean, and Russian cultures.

The beehive comprises three distinct types of bees, each fulfilling specific roles. The queen bee, as the central figure of the beehive, is provided with sustenance and protection by the other bees. All hives center on the queen, as she serves as the home for all other bees, rather than the beehive itself. The primary function of the queen is to lay eggs and produce pheromones that regulate colony behavior. Worker bees are non-reproductive females and constitute the predominant population of the colony [7]. They perform various functions, including caring for the young larvae. Their role includes providing nourishment and care for the queen. The hive is constructed and maintained by them, and they also process food by converting nectar into honey. The hive is also safeguarded from external threats. The final category of bee is referred to as the drone. Male bees are tasked with reproduction, communication, and coordination within the colony. The primary mechanisms for this phenomenon are pheromones and dancing [8]. The life cycle of each member is associated with their specific role. Queen bees generally live for 2 to 5 years, whereas worker bees have a lifespan of 6 to 8 weeks during the summer and can live up to 5 months in the winter. Drones have a lifespan that extends only until mating occurs, while unmated drones survive for approximately 8 weeks after being expelled from the hive, a strategy employed to conserve resources during winter [9].

Numerous cultures and religions attribute significance to bees and their byproducts. The Islamic religion emphasizes the importance of bee honey because of its notable role in apitherapy, a field of alternative medicine focused on harnessing the healing properties of bee products. This approach focuses on the utilization of bees, bee venom, and bee products—such as honey, propolis, pollen, and beeswax—in the treatment of various diseases and enhancement of immunity, which will be elaborated upon subsequently. Despite various objections to apitherapy stemming from insufficient scientific evidence and reproducibility of results, experiments and research have been undertaken regarding the application of bees and their products in medicine. Bee venom may induce allergic reactions, which can be fatal if not appropriately managed. Bees may function as effective bioindicators for environmental health, as a decrease in bee populations can indicate habitat loss resulting from various factors, such as climate change or pesticide misuse. The heavy metal bioaccumulation in beehives serves as an indicator of terrestrial environmental contamination, represented by the honeybee contamination index [10].

In this analysis, we will delve into the benefits of honeybees, providing comprehensive insights into honey, propolis, and royal jelly. Honey is a viscous, sweet liquid produced by bees through the processing of nectar collected from plants. Nectar is a viscous, sweet liquid secreted by a gland known as a nectary. Honey primarily consists of carbohydrates, including sucrose and fructose, along with some proteins [11]. Honey is utilized in various applications, including wound management, as it has been employed since ancient civilizations and continues to be used in alternative medicine for treating open wounds, insect bites, and sores. Scientific records indicate that honey surpasses modern wound management techniques by promoting wound healing and possessing anti-inflammatory and antibacterial properties that address and prevent contamination or inflammation in the human body [12]. Honey is utilized in pediatric care due to its demonstrated efficacy in treating dermatitis. The combination of honey, olive oil, and beeswax significantly enhances and expedites the healing of skin conditions such as psoriasis and atopic eczema. Honey is utilized in the treatment of diabetic foot ulcers, as it effectively eliminates bacteria that impede the wound healing process[13].

Moreover, honey enhances gastrointestinal health by aiding in the absorption of sugars and starches, while its elevated prebiotic content promotes the proliferation of beneficial gut bacteria. Honey is utilized to enhance oral health owing to its antimicrobial and anti-inflammatory properties, which assist in the treatment of certain oral diseases. In addition, research indicates that substituting sugar in electrolyte oral rehydration solutions with honey enhances recovery, as the elevated sugar content in honey promotes the absorption of water and electrolytes in the body. The high fructose to glucose ratio (1:1) exerts a beneficial impact on liver and pancreatic diseases by aiding in the neutralization of toxins[14].

On the other hand, it is advantageous for individuals with fatty liver disease, as it enhances blood sugar regulation. Regular consumption of honey enhances cardiac health by providing cardioprotective and therapeutic effects against epinephrine-induced cardiac disorders and vasomotor dysfunctions. Cancer treatment plans incorporating honey as a supplement demonstrated increased efficacy, particularly in the management of breast cancer, liver cancer, and colorectal cancer[15].

Propolis is a resinous substance produced by bees, composed of beeswax, saliva, and exudates from tree buds or sap flows[16]. Bees utilize it to construct the hive and seal cracks, while also employing it to smooth the internal surfaces of the beehive and regulate temperature. It functions as an antibacterial and antiviral agent, allowing honey to remain viable for decades; it comprises resin, wax, and essential oils. Propolis, similar to honey, exhibits significant health-related applications and biological activity, including its use in treating gastrointestinal infections that may arise from exposure to contaminated surfaces. Propolis exhibits various biological efficacies, including anticancer, antioxidant, and anti-inflammatory properties. Research has shown the antiviral properties of propolis. It is utilized for the treatment of viral infections. Propolis may enhance gynecological care due to its antibacterial and antiviral properties. A 5% aqueous propolis solution has been reported to enhance vaginal well-being. Propolis may inhibit bacterial growth due to its antibacterial properties[17].

The antitumor properties of propolis may enhance tumor treatment, particularly in breast cancer, suggesting its potential as a significant agent in the management of this disease. Propolis in cream form provides dermatological care through its antiallergy, anti-inflammatory, and antimicrobial properties[15].

Royal jelly is a white, viscous substance characterized by a gelatinous consistency. It is composed of water, proteins, and carbohydrates[18]. Worker bees secrete this substance, which is consumed by the queen bee, hence the designation "royal jelly." The bee larvae consume it for 2–3 days post-hatching, as it is their sole source of nourishment during this early stage. It is essential in queen bee development due to the presence of royalactin, which induces the morphological changes required for the queen's maturation. This jelly is considered the primary factor contributing to the extended lifespan of queen bees compared to worker bees. It is advantageous to humans and can be applied in reproductive health. A clinical study conducted by researchers demonstrated the potential of royal jelly to alleviate premenstrual syndrome, a condition characterized by pain and cramps occurring up to two weeks before the onset of the menstrual cycle, effectively a menstrual cycle without the actual menstruation. A study indicated that royal jelly may significantly improve the quality of life for postmenopausal women[19].

The treatment of anemia uses Oxymetholone, an androgenic and anabolic steroid that facilitates weight gain and promotes muscle growth. However, it also induces an Oxymetholone-related reproductive toxin (OXM) that adversely affects male reproductive health. This poison lowers the levels of luteinizing hormone (LH) and follicle-stimulating hormone (FSH). This leads to less testosterone being made, tubules getting smaller because they don't get enough hormonal stimulation, problems with spermatogenesis, and the loss of Sertoli cells and reactive oxygen species (ROS). In addition, the four effects of the drug result in fertility issues and testicular atrophy. A study suggests that royal jelly may provide protection against OXM. Studies conducted on rabbits indicate that royal jelly may improve semen quality and output, potentially enhancing fertility[20].

In addition, studies have shown that royal jelly has beneficial effects on aging-related diseases such as Alzheimer's[21]. Royal jelly has shown potential to improve the mental and physical health of the elderly, as well as to provide neuroprotective benefits. Royal jelly, akin to honey, has shown potential in promoting wound healing through the migration of human fibroblasts, resulting in elevated sphingolipid levels and a reduction in collagen. Royal jelly offers protection against ultraviolet-induced aging and inhibits infections through its antimicrobial properties [15].

Climate change is expected to lead to habitat loss, diminishing the availability of suitable locations for bee colonies and their food resources. Alterations in precipitation patterns and drought conditions resulting from climate change hinder bees' ability to traverse long distances for food on specific days. Climate change indirectly impacts bees by altering the distribution of pests that pose significant risks, as these pests can transmit lethal diseases. Significant responsibility is attributed to the greenhouse gases released by industrial activities. This is the primary factor responsible for the significant disturbances attributed to climate change, and it is expected to continue to do so. This article addresses three key questions, independent of climate change's impact on bees:

Q1: What impact does climate change have on the distribution of bees?

Q2: How does climate change indirectly impact bee populations by influencing their habitat?

Q3: What is the impact of climate change on pests that pose a threat to bees?

Climate change impacts the environment and the health of ecosystems. Increases in global temperatures have resulted in a higher frequency and intensity of weather events, including droughts, heatwaves, and alterations in precipitation patterns [21, 22]. Changes in biodiversity are ongoing and will persist in the future. Various models simulating climate scenarios for 2050 and 2070 predict continued shifts in species distribution and alterations in ecosystems. Increasing temperatures are expected to modify the distribution patterns of bee species and their associated flowering plants. Delayed flowering, as noted in our recent studies, results in a reduced nutritional season for bees, consequently impacting the overall quality of the hive.

2. Materials and Methods

The analysis of this study was conducted to investigate the impact of climate change on bees, utilizing data from various studies and experiments. Various types of bees were discussed, such as *Apis mellifera simensis* and several species of bumblebees. Additionally, we identified several pests that threaten bee populations, including the Greater Wax Moth (*Galleria mellonella*). Environmental data were analyzed, encompassing slope, soil conditions, temperature, and land cover, sourced from the Shuttle Radar Topography Mission (SRTM) and ISRIC World Soil Information [23]. Future climate scenarios were sourced from international organizations, including Worldclim [24]. Various studies employed genetic analysis to demonstrate species diversity, utilized software packages to model the present and future distributions of bees and pests, and gathered and archived field data through wireless devices.

3. Results

3.1. The Impact of Climate Change on Bee Distribution: Migration and Ecological Disruptions

Assessing the global distribution of bees is essential for understanding the effects of climate change on this organism. A collaborative team from various universities conducted research to assess the global distribution and species richness. Initially, all published data were collected, specifically occurrence data, amounting to 5,857,811 records. They subsequently filtered the data to eliminate duplicates, resulting in a total of 20,555 bee species globally. The distribution indicates that high bee intensity is present in the southwestern USA, the Mediterranean Basin, and Australia, while a weaker signal is observed in South Africa; Palestine exhibits the highest richness per unit area. Humid regions generally exhibit higher poverty levels, whereas arid regions tend to demonstrate greater diversity. The latitudinal gradient indicates that peak richness occurs between 30° and 40° latitudes in the northern hemisphere and around –30° in the southern hemisphere. This suggests that distribution is maximized in arid regions rather than tropical areas, challenging the notion that biodiversity is consistently higher in tropical regions. The model utilized for this map incorporated 18 primary variables, including solar radiation and the study area. The model supports the hypothesis that bee richness is elevated in areas characterized by high solar insolation, favorable plant growth parameters, and reduced precipitation. The model supports the idea that bees flourish in arid regions and deserts, with a reduction in wind speed having a beneficial effect on their diversity [25].

A study was conducted by Jaffé et al. to examine the genetic diversity within a specific species [26]. Genetic samples of M. subnitida were collected from its distribution range [27]. Samples were collected from 2013 to 2014, with one sample taken from each colony, resulting in a total of 160 samples. An analysis was conducted to test for outliers, and genetic clustering was performed using two software packages. Genetic diversity metrics were calculated using measures including heterozygosity, expected zygosity, nucleotide diversity, and inbreeding coefficient. Furthermore, the effective population size (Ne) was estimated through linkage disequilibrium methods. Statistical modeling was done to improve parameter estimation for the nested mixed linear predictor model and to find the best model using the Akaike Information Criterion. These were the two models that were used. The influence of environmental variables on genetic diversity was evaluated through an analysis of isolation by landscape resistance. Sensitivity analysis was conducted to verify the robustness of the model.

The research identified distinct genetic clusters shaped by historical and environmental influences. Analysis of the diversity matrices reveals that certain clusters exhibit greater heterozygosity than others, indicating distinct population dynamics and health within each cluster. Geographic distance, forest cover, and climate variables significantly influence genetic diversity. Certain clusters acquired genetic traits in response to environmental changes for survival purposes. This study highlighted that certain bee populations mitigated the effects of climate change by migrating to higher elevations, with observed alterations in their genetic traits. Additional environmental changes would result in a significant decline in the population of elevated habitat bees, as they would be unable to locate alternative suitable habitats [26].

3.2. Indirect Effects of Climate Change on Bee Populations: Habitat Disruptions and Ecological Shifts

Climate change significantly influences various species of bees, similar to many insect species. Climate change can directly influence the life cycle or strategies of bees, or it may indirectly affect them by altering their predators or the distribution of floral resources. Seasonal variations, particularly weather conditions, significantly influence the life cycle of bees. Worker bees may live up to four months beyond their average lifespan when experiencing milder winters in regions typically classified as warm during this season.

In certain regions, bees may migrate to warmer locations during winter. For instance, the giant honeybee (*Apis dorsata*) constructs a hive that can extend up to 2 meters in length and migrates up to 200 km in response to seasonal changes to avoid extreme weather conditions that pose risks of starvation and predation. It was observed that they return to the same hive after intervals of up to 2 years. Climate change may intensify summer and autumn dryness, resulting in increased perceptions. The two factors may directly influence the flowers from which bees gather nectar. The flowers may either become excessively dry, which impedes the production of pollen and nectar, or an increase in precipitation could entirely eliminate the nectar and pollen. Bees generally avoid flowers that have been thoroughly washed by recent rainfall. Consequently, bees face two options to address climate change: they may develop a migration strategy to mitigate the effects of potential extreme weather, or they may modify their behaviors and entire life cycle [28].

The *Apis mellifera* simensis species of honeybee, known as the most economically significant pollinator of agricultural crops globally, was the subject of a study in Northern Ethiopia [29]. The research concentrated on plants like *Hyposdtes forsjaolii*, which supply crucial pollen and nectar for this bee species in the region. Environmental data were collected, encompassing slope, soil conditions, temperature, land cover, and additional factors. The data were primarily sourced from the Shuttle Radar Topography Mission (SRTM) and ISRIC World Soil Information. Agro-ecological zonation systems were employed to classify landscapes in the region, and temperature was modeled in relation to elevation levels. The Principal Component Analysis (PCA) technique was employed to identify the primary environmental conditions, alongside Spearman correlation and Maxent variable selection. Future climate scenarios for the 2030s, 2050s, 2070s, and 2090s indicate that climate changes will create challenging conditions for H. forskaolii, thereby affecting the nutrition of honeybees in the Tigray region. The study's accuracy was confirmed through the assessment of the model's performance using the True Skill Statistic (TSS), which yielded a value of 0.634, indicating a certainty level of 63.4% [30].

Researchers conducted a study at an apiary at the University of Córdoba, Spain, during the pre-flowering, flowering, and post-flowering periods of 2016 and 2017[31]. The hives' weight was monitored remotely through a wireless communication system. This system comprises a wireless node that transmits data to an industrial computer using the IEEE protocol, which manages the wireless network, processes the data, and stores it in a local database. A honey sample was collected from the colony to ascertain its botanical origin via melissopalinological analysis. Statistical analysis was conducted utilizing SPSS software. In 2017, Spain experienced its highest recorded temperature to date. The pre-flowering period experienced increased rainfall and cloud cover, resulting in a decrease in hive weight. Throughout the flowering period, an increase in the hive's weight was observed. Following this period, the hive's weight was monitored to ascertain the appropriate timing for honey extraction and to evaluate the bees' dependence on stored food. In 2016, the hives exhibited an average weight gain of 18.92 kg, attributed to the late and short flowering period. Conversely, in 2017, the average weight gain decreased to 7.67 kg, likely due to increased rainfall during the pre-flowering period[31].

3.3. The Impact of Climate Change on Pests Threatening Bee Populations

Enemies of bees and beehives Natural enemies can be categorized into three primary groups: predators, parasites, and pathogens. Predators are categorized into two groups: the first includes insects, primarily wasps (e.g., hornets), which can kill bees in flight and consume honey and larvae. Certain wasps, such as the Asian giant hornet (*Vespa mandarina*), possess the capability to eliminate an entire hive independently. Ants invade the hive to seek honey and may consume the brood. Praying mantises prey on bees during nectar collection and also target hive beetles (*Aethina tumida*), which infest hives by consuming honey, pollen, and larvae. Additionally, parasites include mites. Mites are small arachnids, specifically eight-legged arthropods, such as honeybee tracheal mites (*Acarapis woodi*), which inhabit the trachea of worker bees. Their population can increase significantly, ultimately leading to the suffocation of the host bee. Tropilaelaps is a parasitic mite that consumes brood and reproduces within it.

The proliferation of these mites has the potential to decimate an entire colony and facilitate the transfer of pathogens. The varroa mite (*Varroa destructor*) is a significant pest that devastates hives of *Apis mellifera* globally. The hives affected by these mites are typically destroyed after approximately three years, and regrettably, this infection is untreatable. It inhibits the immune response, enhances the likelihood of viral infection, and functions as a vector. Protozoan pathogens, specifically *Nosema apis*, target the midgut wall of adult honeybees. This disease may progress asymptomatically, compromising the hive's integrity and potentially resulting in the demise of the entire colony. Nosema ceranae is a microsporidian that poses a threat to bee populations. Bacteria infect the brood, leading to diseases such as American foulbrood. External pollen supply may mitigate the disease. While antibiotics are the only effective treatment, their use results in significant damage and losses, and they pose a considerable drawback due to the residues present in the honey afterwards. Viruses can induce both chronic and acute paralysis, remaining undetectable until they have significantly weakened or decimated the hive[28].

Cameron and Sadd conducted a study involving 260 wild species of bumblebees, which are native to various biogeographic regions, excluding sub-Saharan Africa, Australia, and New Zealand. The authors analyzed research from the past decade concerning the population decline of this bee species, particularly in Europe and America. While certain species exhibit stability, others demonstrate inconsistent declining trends, including Bombus fervidus, Bombus pensylvanicus, and Bombus dahlbomii[32]. The decline of bumblebee populations can be attributed to several factors, including the application of pesticides, especially neonicotinoids; climate change affecting floral resource availability and suitable habitats; the spread of pathogens such as *Nosema bombi* in North America and *Nosema ceranae*, which poses a risk to the European honey bee (*Apis mellifera*) and has been found in bumblebee hives globally; and the introduction of non-native bumblebees that adversely affect native populations through competition and disease transmission. The authors identified a notable knowledge gap, as the lack of data from specific regions hinders the monitoring of this bee species[32, 33].

A research project investigated the effects of climate change on the distribution of Greater Wax Moth (GWM) pests, specifically *Galleria mellonella*, considering the expected decrease in honeybee populations during an outbreak of these pests. GWM poses a threat to bees by competing for resources and facilitating the transmission of diseases among bee populations. This research utilized species distribution modeling (SDM) via Maxent to predict the future distributions of GWM. Existing data on the occurrence of GWM and bioclimate variables were utilized. The WorldClim organization supplied data regarding prospective climate alterations. The analysis considered various climate factors, including ambient temperature and annual mean temperature. The analysis indicated that the annual mean temperature was the primary factor, responsible for 64.2% of its spatial distribution. This study focused on two main issues: the significant suitability of GWM in regions such as Europe and Asia (specifically China, India, Vietnam, and Thailand), as well as the Americas (notably the U.S., Mexico, and Argentina), where there are numerous active beekeeping operations, some of which are prominent honey exporters. Furthermore, the model forecasts a reduction in potential habitat for indigenous honeybee populations in Africa as a consequence of rising temperatures [34].

4. Conclusions

Bees play a crucial role in medicine, ecology, and ecosystems. In addition to their function in pollinating the majority of crops, bees also play a significant role in the production of valuable substances such as honey, propolis, and royal jelly. This organism functions as a bioindicator for ecosystem health; nonetheless, climate change presents considerable threats to the population and distribution of these vital insects. This research focuses on three main areas: the effects of climate change on bee populations, the current and expected reduction in floral resources, and the projected increase in the incidence of certain diseases and pests. An overview of the challenges faced by bees as a result of climate change was presented. This study highlights the necessity of understanding and addressing the effects of climate change on bees to ensure their survival and the continuation of their benefits. Addressing the challenges presented by climate change is essential for maintaining the health and stability of our ecosystem and economy, as well as ensuring an adequate food supply. Collaboration among scientists, politicians, and the public is crucial for achieving this objective. Moreover, future research should focus on the long-term monitoring and study of bee populations. This approach facilitates a comprehensive understanding of the effects of climate change, rather than limiting the analysis to two- or three-year intervals. It is essential to collect additional data from various countries globally. A study encountered challenges in reaching a global conclusion due to the lack of information from African countries, which hindered the ability to draw definitive results. Increasing awareness of the threats posed by global warming and climate change will lead to further research that either supports or refutes the proposed hypotheses regarding future impacts, thereby enabling predictions and interventions to mitigate undesirable outcomes. New policies will be implemented to mitigate global warming by addressing its root causes.

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The data used for this study is available upon request from authors.

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Conflicts of Interest

All authors disclosed no conflict of interest.

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