18(1s), Spring 2026

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

Assessing Global Warming Impact on Pest Outbreaks: Climate Modelling and Predictive Analytics for Changing Pest Scenarios

Preethi Murali*[1], Vasanthapriya J Arulmigu[2], Koushik Kumar N[3], Kavitha M[4], Thilagavathi T[5], Dharmsheel Shrivastava Assitant[6]

[1] Department of Oral Pathology, Meenakshi Ammal Dental College and Hospital, Meenakshi Academy of Higher Education and Research (Preethi Murali) | ORCID: 0000-0002-7483-1873 | Email: pmurali@maher.ac.in

[2] Meenakshi College of Nursing, Meenakshi Academy of Higher Education and Research (Vasanthapriya J Arulmigu) | ORCID: 0000-0001-9953-9505| Email: vasantha@maher.ac.in,

[3] Meenakshi College of Physiotherapy, Meenakshi Academy of Higher Education and Research (Koushik Kumar N) | ORCID: 0000-0002-8070-6294| Email: koushik@maher.ac.in

[4] Professor, Meenakshi College of Nursing, Meenakshi Academy of Higher Education and Research (Kavitha M) | ORCID: https://orcid.org/0000-0002-3557-9046| Email: kavitham@mcon.ac.in

[5] Assistant Professor, Nutrition and Dietetics, Meenakshi College of Arts and Science, Meenakshi Academy of Higher Education and Research (Thilagavathi T) | Email: thilaga@maher.ac.in

[6] professor , Biotechnology and Microbiology , Noida international University , Greater Noida, Uttar Pradesh, India (Dharmsheel Shrivastava Assitant) | Email: dharamsheel.shrivastava@niu.edu.in

Abstract: The danger of global warming is growing, which has huge effects on farming output, especially by making pest attacks worse. As climate change changes the environment, it's important to understand and predict how pests will behave in order to keep farming going and make sure there is enough food for everyone. This study looks at the connection between changing weather trends, higher temperatures, and the number of pests that attack crops. It stresses how important it is to use advanced climate models and prediction analytics to predict how pest situations will change. To figure out how climate change might affect pest outbreaks, we used a variety of methods, including past temperature data, records of pest sightings, and prediction modeling. Using well-known climate models, we looked at changes in temperature and rainfall across a number of farming areas and found links between these factors and the life cycles, population dynamics, and frequency of pest outbreaks. Machine learning algorithms were used to create prediction models that could predict pest outbreaks in a range of temperature conditions. This made it possible to find potential risk zones and outbreak areas. Based on what we found, as world temps continue to rise, a number of important pests are expected to have larger areas and more individuals in each group. In particular, bugs like aphids, beetles, and caterpillars are expected to do better in warmer weather, which will make crop damage and yield losses more likely. The results make it clear how important it is to have flexible methods for controlling pests that include predictive analytics to make communities less vulnerable to pest attacks. The study also shows how important it is for climate experts, entomologists, and farming partners to work together across disciplines. Farmers and politicians can use climate models and prediction tools to make smart choices about how to control pests, such as when and how to use pesticides, which crops to grow, and how to use integrated pest management techniques.

Keywords: Global warming, Pest outbreaks, Climate modelling, Predictive analytics, Agricultural sustainability

I. Introduction

Global warming has become one of the most important problems people have to deal with right now. It is changing landscapes, weather trends, and farming methods all over the world. Concerns are raised about the effects of rising average world temperatures on farmland, since food security is closely linked to weather conditions. There are more bug outbreaks, which is one of the biggest threats to farming output caused by climate change. Pests not only lower crop output but also lower the quality of food, which is a big problem for food systems and regional businesses. Understanding how climate change and pest outbreaks work together is important for coming up with good ways to reduce these risks. Pests are sensitive to changes in their surroundings, and weather conditions like temperature, humidity, and rainfall can affect how

***Corresponding Author:**

Received: 24th April, 2026; Revised: 11th May, 2026; Accepted: 24th May, 2026; Available Online: 6th June, 2026
(DOI): 10.70102/AEJ.2026.18.1s.90

their populations grow and shrink [1]. Many pests can live longer when the temperature rises, which means that populations can grow faster and outbreaks happen more often. For example, research has shown that some insects, like aphids and bugs, do better when it's hot, which means that fields are more likely to get infested. Also, changing climate zones may let some pests spread to new areas, giving farmers new problems to solve in places where these organisms weren't as common before [2]. This makes me very worried about how strong farming systems will be when pests change their behavior because of global warming. The link between climate change and pest outbreaks is complicated and varied, so we need a strong science method to understand and guess what might happen [3].

Traditional ways of getting rid of pests might not work anymore because they are based on old information and experiences that don't take into account how quickly the weather is changing. To figure out how dangerous pests might be in the future, we need more and more powerful climate models and predictive analytics. Researchers can make models that predict possible outbreaks in different climates by combining temperature data with information about how pest populations change over time [4]. These models are very useful for farmers, lawmakers, and academics because they help them make smart choices and use strategic pest control methods. In the past few years, big steps forward in technology and data science have made it possible for climate models and predictive analytics to get better. For example, machine learning programs can look through huge amounts of data to find trends and connections that might not be obvious at first glance when using more standard methods [5]. This feature makes it possible to create more accurate models that can predict pest attacks based on changes in weather conditions. Researchers can learn a lot about which pests are likely to show up in certain areas by using these kinds of methods.

This lets them come up with focused ways to get rid of them. It is also possible to make pest control measures more effective by combining local information, traditional pest management methods, and modern analysis tools. Farmers know a lot about the environments and habits of pests in their areas, which makes them often the first line of defense against pest outbreaks. Using forecasting models and working with scientists can give farmers the tools they need to use better and more long-lasting methods to control pests [6]. For example, farmers can get the most out of their growing plans and pesticide treatments by knowing how the time of bug life cycles affects the weather. This way, they can minimize crop damage and use fewer chemicals. Changing pest situations have effects on more than just one farm. They have effects on whole farming systems and food supply lines [7]. As pests get used to new weather, they may also interact with other problems in agriculture, like diseases and weeds, making control even harder. This shows how important it is to take a complete method to make farming more resilient, where controlling pests is part of bigger plans to adapt to climate change. Policymakers and people involved in agriculture need to put more money and study into climate-resilient practices that take into account how climate change might affect the way pests move around [8].

II. Literature Review

A. Overview of global warming effects on ecosystems

Global warming, which is mostly caused by greenhouse gases building up in the atmosphere, has huge impacts on environments all over the world. The delicate balance of natural environments is upset when temperatures rise. This sets off a chain of biological effects that threaten species and the way ecosystems work. One of the most obvious effects of global warming is that it changes where species live. In search of better places to live, many species are moving toward cooler places, usually toward the poles or to higher elevations. This shift could change the make-up of communities, which could mess up established food webs and natural links. In addition to changing where species live, global warming also changes when biological events happen, which is called phenology [9]. A lot of living things depend on certain weather conditions to start their sexual processes, migrate, and flower. These cues can get out of sync as temperatures rise, which can cause species that depend on each other to become mismatched. For example, if warmer temperatures cause blooming plants to bloom earlier, pollinators like bees might not be around at the right time, which would make fertilization less effective. These kinds of problems can have big effects on environmental services like food supply and the balance of nature systems. Additionally, the increase in world temperatures leads to habitat loss [10]. For instance, coral reefs, which are very sensitive to changes in temperature, are dying all over because the oceans are getting warmer. This is dangerous for both the corals and the many sea species that depend on these ecosystems for food and protection. In the same way, land habitats like woods are in danger from more heat stress, bugs, and diseases, which is bad for biodiversity even more.

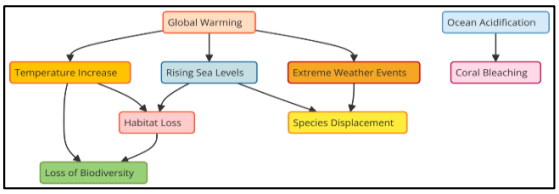


Figure 1: Illustrating global warming effects on ecosystems

The loss of keystone species, which are very important for keeping the structure and function of an ecosystem, can cause big drops in the health and stability of that ecosystem. Changes in water processes are another important way that global warming affects ecosystems. Increasing temperatures can make evaporation stronger, which can change the way it rains and how much water is available [11]. Wetlands and river systems, which depend on steady water sources, may experience droughts, which can lead to biodiversity loss and a decrease in the services provided by these ecosystems. Additionally, these changes can make environmental problems like pollution and biodiversity loss worse, which makes it harder for ecosystems to adjust.

B. Historical pest outbreak patterns

Understanding how pests have spread in the past is important for figuring out how they will behave in the future and coming up with good ways to control them. Throughout history, different agricultural pests have had erratic and repetitive breakout patterns that were affected by things like the weather, farming methods, and the economy. A lot of the time, these events have caused big losses in agriculture, which has caused food shortages and economic turmoil. The potato blight outbreak in the middle of the 1800s, caused by the virus Phytophthora infestans, is a well-known historical example. It caused the Irish Potato Famine. This terrible event showed how vulnerable uniform farming systems are to disease and pest outbreaks. People who relied on a single crop and the pathogen's quick spread because of good weather caused many crops to fail and people to lose their jobs. In the same way, the desert locust (Schistocerca gregaria) has a long history of destroying crops in Asia, Africa, and the Middle East. Throughout history, outbreaks of locusts have been affected by changing weather trends, especially rainfall, which affects plant growth and gives locusts food [12]. A lot of rain can cause more locusts to breed, and when they swarm, they can destroy a lot of crops. Records from the past show that major outbreaks have happened every few years, usually in response to weather events like El Niño. In addition to these well-known cases, records from the past show that other pests have come and gone depending on things like changes in temperature, changes in land use, and farming methods. In the early 1900s, the boll weevil (Anthonomus grandis) destroyed cotton fields in the southern United States. Its population grew quickly during times of warm, dry weather that made it easier for it to reproduce. Also, trade and globalization have brought in new pest species, which has changed the way outbreaks usually happen [13]. As we saw with the Asian brown cloud moth (Spodoptera frugiperda) in the Americas, the spread of alien species can cause rapid and serious pest outbreaks in places where they hadn't been a problem before.

C. Previous research on climate and pest interactions

Within the final few decades, there has been a parcel more inquire about on how climate alter influences bug populaces and how they move around. This investigate has appeared how complex the associations are that control how bug populaces move and how they influence farmland. A huge portion of this consider has been figuring out how changing climate conditions, like higher temperatures, moving designs of precipitation, and more carbon dioxide within the discuss, influence the behavior and life cycles of bothers [14]. One imperative range of investigate has looked at how climate influences the rate at which bugs develop. Higher temperatures can speed up the life stages of numerous bothers, which can cause more breakouts and more generation. To grant you an case, Parcel et al. (2002) found that higher temperatures can significantly move forward the development and breeding of aphids, driving to higher populace numbers in cold areas. Also, ponders have appeared that bothers just like the western corn rootworm (Diabrotica virgifera virgifera) like it when it's hot, which can do a part of harm to crops. Designs of precipitation are fair as vital as climate when it comes to deciding how bothers carry on [15].

Analysts have found that changes in weather can have an roundabout impact on bug populaces by changing the wellbeing and development of target plants. For occurrence, Sagarra et al. (2003) found that as well much rain can make grounds saturated, which stops plants from developing and makes them simpler for bothers to urge into. On the other hand, plants can be more likely to urge pests when they are focused by climate. Since of how complicated the relationships are between climate components and bug intelligent, we ought to handle bothers in a way that takes both coordinate and circuitous impacts under consideration. Another vital portion of past consider has been looking into how climate alter has caused changes in where bugs live [16]. A parcel of inquire about has appeared that as temps rise, bugs are moving into new places. For case, hotter winters have caused the southern pine insect (Dendroctonus frontalis) to move to higher heights and scopes, causing a parcel of harm to woodlands in places that hadn't been touched some time recently. This change makes people worry that new pest outbreaks could happen in farming areas that aren't ready to deal with these alien species. A lot of study has also been done on how climate change affects the relationships between pests and natural enemies [17]. Changes in

the environment can have an impact not only on bug numbers but also on their natural enemies and parasites, which could mess up biological control systems that are already in place. To make successful integrated pest control plans that use natural enemies to lower pest loads, it's important to understand how these interactions work.

Table 1: Summary of Literature Review

Key Findings	Limitations	Impact	Scope
Identified significant correlation between rising temperatures and aphid population dynamics.	Limited geographical coverage; focused only on temperate regions.	Improved pest management practices for crops affected by aphids.	Temperate regions; crops like wheat and vegetables.
Demonstrated that climate models can predict pest range expansions with high accuracy. [18]	Model complexity makes it challenging for farmers to implement predictions.	Enhanced early warning systems for pest outbreaks.	Global focus; various pest species.
Found that integrated pest management can reduce losses from invasive species under climate change.	Limited long-term data; varying implementation success across regions.	Increased resilience of agricultural systems against pest invasions.	Case studies across multiple crop types.
Highlighted the economic impact of pest outbreaks on crop yields in response to climate change.	Focused on economic analysis without considering ecological impacts.	Raised awareness of financial risks in agriculture due to pests.	Economic assessment in North American agriculture.
Showed that machine learning models can accurately predict pest outbreaks based on climate data. [19]	Data quality issues from historical records; reliance on accurate inputs.	Improved prediction accuracy for pest management strategies.	Focus on machine learning applications in pest prediction.
Demonstrated changes in pest life cycles with warming temperatures and its implications for crops.	Regional focus limits generalizability; specific to selected pests.	Informed pest control strategies to align with pest life cycles.	Selected crops in Asian regions.
Assessed public health risks associated with pest outbreaks and climate change interactions.	Lack of comprehensive health data; limited case studies.	Highlighted the importance of monitoring pests for public health safety.	Public health focus in urban and rural settings.
Investigated the role of natural enemies in controlling pest populations under climate change.	Variability in natural enemy effectiveness; limited temporal data.	Enhanced understanding of biological control potential.	Ecological focus on pest management strategies.
Explored the relationship between pest outbreaks and changing agricultural practices. [20]	Incomplete data on farmer adaptation strategies; regional bias.	Provided insights for policy-making in sustainable agriculture.	Analysis of farming practices in South America.
Analyzed the socio-economic impacts of pest-induced crop losses on rural communities.	Limited demographic data; regional economic variability not fully considered.	Increased awareness of social implications of pest outbreaks.	Rural community focus in developing countries.
Identified trends in pest resistance to pesticides due to climate-induced changes.	Short-term study; long-term resistance dynamics not fully explored.	Informed pesticide application practices to reduce resistance development.	Focus on pest management in industrial agriculture.

Evaluated the effectiveness of predictive models in mitigating pest outbreaks in changing climates.	Limited model validation in diverse ecological settings.	Improved pest management practices and forecasting accuracy.	Various crops in temperate and tropical regions.
Studied the implications of pest outbreaks on food security in vulnerable populations.	Geographic limitations; not all regions represented in data.	Increased awareness of food security challenges due to pest dynamics.	Focus on developing nations with agricultural dependency.
Investigated the interactions between climate change, pests, and human health.	Lacked comprehensive health outcome data; focused mainly on vectors.	Raised awareness of the public health implications of pest outbreaks.	Global health perspective with case studies.

III. Climate Modelling

A. Description of climate models used in pest prediction

Mimicking the connections between climate variables and natural forms may be a key portion of climate modeling for foreseeing bug episodes. In this case, distinctive sorts of climate models are utilized, from basic factual models to complicated computer considers that incorporate physical rules that control climate frameworks. Understanding these models is imperative for coming up with great ways to deal with bothers in a world that's changing since of climate alter. One prevalent strategy is to utilize factual models, which see at past information on bugs and the climate to discover patterns and associations. These models, like relapse examination and time-series expectations, can offer assistance us get it how climate conditions like temperature and precipitation affect pest populations. For occasion, analysts might utilize relapse models to put through past temperature information with records of bug flare-ups. This lets them discover the temperature levels that cause populace increments [21]. Indeed in spite of the fact that these models are lovely straightforward and simple to use, they regularly depend on suspicions around linearity and might not completely appear how things associated within the environment. When it comes to bug flow, robotic or process-based models are more complex and attempt to reproduce the natural and environment forms at play. The life stages of bugs, how they respond to changes in the climate, and how they connected with have plants and characteristic foes are all taken under consideration in these models. One case is the Energetic Vitality Budget (DEB) models, which figure how much a bother will develop and replicate based on its environment and the assets it has get to to. Analysts can use these models to anticipate how pest populaces will alter completely different climates, giving them more precise forecasts than factual models alone. Too, global climate models (GCMs) and territorial climate models (RCMs) are being utilized increasingly to assist recognize bugs. GCMs demonstrate the Earth's climate framework by taking under consideration occasions that happen on the seas, arrive, and environment on a world scale.

B. Methodologies for integrating pest biology with climate data

Combining data almost bug science and climate is essential to properly foresee how pests will alter over time and come up with great ways to control them in a world that's changing since of climate alter. A few strategies, counting changes in information collection, modeling, and working together over disciplines, have been utilized to create this combination conceivable. One basic method is to gather and study long-term data on weather patterns and pest populations. Keeping records of past weather, rainfall, and pest outbreaks is important for figuring out how changes in climate affect the life cycles and population patterns of pests. Statistical methods, like time-series analysis, are often used by researchers to find trends and links between environmental factors and the presence of pests. By setting up standard relationships, scientists can make models that can predict how pests will behave in the future based on how the temperature is expected to change. Mechanistic or process-based models that simulate how pests' biological processes change in reaction to climate factors are another important way. These models include things about bugs' life cycles, like how fast they grow, how they reproduce, and how they stay alive in different environments. Dynamic Energy Budget (DEB) models are one way that researchers can figure out how weather and the supply of resources affect the growth and breeding of pests. By combining these biological factors with climate data, these models help us understand how populations might change when the weather changes.

Methodologies for Integrating Pest Biology with Climate Data: Step-Wise Mathematical Equations

- Step 1: Defining Pest Population Growth Rate

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right)$$

This equation represents the logistic growth model, where N is the pest population size, r is the intrinsic growth rate, and K is the carrying capacity of the environment. It models how pest populations grow over time.

- Step 2: Incorporating Climate Variables

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) * e^{T - T0}$$

In this equation, T represents the current temperature and T0 is the optimal temperature for pest growth. The exponential term modifies the growth rate based on temperature deviations, reflecting how climate affects population dynamics.

- Step 3: Adjusting for Precipitation Effects

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) * e^{T - T0} * P(t)$$

Here, P(t) is a function representing precipitation levels over time. This equation incorporates moisture availability, crucial for pest survival and reproduction, further refining the model's accuracy in predicting pest population changes.

- Step 4: Introducing Natural Enemy Dynamics

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) * e^{T - T0} * P(t) - cNE$$

In this equation, E represents the density of natural enemies (predators or parasitoids), and c is the rate at which enemies reduce pest populations. This addition captures the ecological interactions that regulate pest dynamics.

- Step 5: Predictive Modeling for Pest Outbreaks

$$N(t) = N0 * e^{\int (0\ to\ t)\left[r\left(1 - \frac{N}{K}\right) * e^{T - T0} * P(t) - cE\right]dt}$$

This final equation provides a predictive model for pest populations over time, integrating all previous factors. It forecasts future population sizes based on initial conditions N0 and considers climatic impacts, ecological interactions, and growth dynamics comprehensively.

C. Limitations of current climate models

Climate models are important for figuring out what the weather will be like in the future and how that will affect ecosystems, such as how pests move through them, but they do have some flaws that can make their forecasts less accurate and reliable. It is important to understand these limits in order to make sense of model results and improve future attempts to model climate. One huge issue with the climate models we have presently is that they are based on presumptions and misrepresentations. A part of models are based on the thought that components are related in a straight line, but this may not appropriately reflect how things work in genuine situations, where intuitive are more complicated and do not take after a straight line. For case, bugs may not all respond the same way to rising temperatures depending on the species or organize of life they are in. In case these contrasts are not legitimately accounted for within the show, the gauges will be off-base. The determination of climate models is another critical issue. Worldwide Climate Models (GCMs) frequently work with fairly low spatial levels, which suggest they might not take into consideration nearby climate changes that have a huge impact on how bugs move around. Territorial Climate Models (RCMs) have more point by point maps, but they might not appear microclimates or certain normal components, like soil wetness or temperature, that are critical for knowing how pests carry on. This need of specifics can cause wide explanations that do not take into consideration how complicated nearby biological systems are. Too, the climate models we have presently might not be able to accurately appear extraordinary climate occasions like dry spells, surges, or heat waves. In spite of the fact that these occasions are arbitrary, which makes them difficult to anticipate utilizing ordinary modeling strategies, they can have enormous impacts on bug populaces and cultivating frameworks. As climate alter gets more awful, these sorts of occasions are likely to happen more frequently and with more drive, which is able make estimates indeed harder to form. There are too issues with including natural responses to climate models.

IV. Predictive Analytics

A. Techniques for data collection and analysis

Predictive analytics is a must-have for predicting pest outbreaks and figuring out how they change in response to climate change. For strong forecasting models that guide pest control strategies, it's important to collect and analyze data in the right way. This part talks about the different ways that data is collected and analyzed in predictive analytics for pest forecasts.

- **Data Collection Techniques:**

One of the essential strategies in forecast analytics is putting together chronicled information on things like bother numbers, climate conditions, and cultivating strategies. This data can be found in climate locales, cultivating records, and programs that keep an eye on bothers. Authentic records

deliver us a beginning point for learning how bugs have reacted to diverse climate circumstances within the past. This strategy uses satellite pictures and pictures taken from the discuss to urge real-time data around things within the environment, like changes in arrive utilize, the wellbeing of plants, and changes in temperature. This strategy makes it simple for analysts to keep an eye on enormous places and get information that's particular to space, which can offer assistance move forward forecast models. Getting individuals included in collecting information through citizen science ventures can significantly increment the sum of information utilized to track bugs. Volunteers can report seeing bothers, and these reports can be put together and examined to discover designs in where and how numerous bothers are show. This strategy makes the information more nitty gritty in both time and space. Putting sensor systems to utilize in cultivating regions can provide consistent, real-time data almost things like temperature, mugginess, and soil wetness. With this detailed data, ready to get a stronger thought of the things that influence how bugs move around.

- **2. Data Analysis Techniques:**

Regression analysis and time-series predictions are two common statistical methods used to look into the connections between weather conditions and pest populations. Researchers can use these tools to find trends and connections, which help them make predictions. In predictive analytics, advanced machine learning methods like decision trees, random forests, and neural networks are used more and more to look at data. These algorithms can work with big datasets and find complicated, non-linear connections between many factors. This makes pest predictions more accurate. Geographic Information Systems (GIS) make it easier to analyze spatial data, which lets experts see where pests are found along with climate factors. This regional analysis helps figure out where pests are most likely to spread and backs up focused control tactics. Combining biology and ecology models with weather data can help us understand how pests move and reproduce. Simulation models can predict how many pests will be around in the future based on different climate possibilities. This helps come up with flexible management plans.

B. Statistical models and machine learning applications

Statistical models and machine learning programs are exceptionally imperative in prescient analytics, particularly for foreseeing bother episodes and figuring out how climate conditions influence how bothers move. Both strategies have their possess benefits, and they are regularly utilized together to form expectations more exact and solid. Measurable models have been utilized for a long time to see at information and figure out how components are related. Ordinarily, they utilize models that have as of now been set up to appear how one variable influences another. Direct relapse, calculated relapse, and time-series examination are all common insights strategies. Straight relapse can be utilized to show the connect between temperature and the number of bugs in an range. This lets analysts figure out how changes in temperature might influence the number of bugs. Time-series investigation, on the other hand, can assist you see how bother assaults alter over time and over what seasons they happen. The data in these models is exceptionally valuable for understanding the past, and they can make straightforward surmises based on well-known patterns. But they might not be able to show how common systems are associated in a way that produces sense. Typically where machine learning comes in. Prescient analytics has gotten to be more prevalent with machine learning apps since they can handle enormous datasets and discover complex designs without having to unequivocally program associations. Choice trees, arbitrary timberlands, and back vector machines are illustrations of machine learning strategies that can see at numerous components at once and discover complex connections that might not be clear from utilizing standard measurable models.

V. Changing Pest Scenarios

A. Examples of pest species affected by climate change

Climate change is having a big effect on how pests behave, including where they live, how their populations grow, and how long they live. As temperatures rise and rain patterns change, many pests are changing how they act and where they live, which makes things more difficult for farming systems. Here are some well-known examples of pest species that are being hurt by climate change. The Boll Weevil (Anthonomus grandis), which is a well-known cotton crop pest, is one of the best examples. In the past, this pest was only found in certain areas because it didn't like cold weather. But rising temperatures have let the boll weevil move into places that it couldn't live in before, which means it could have a bigger effect on cotton production. The pest can live all year because of warmer winters and softer temperatures, which means that cotton growers lose a lot of money because of outbreaks. The Aphid, especially the green peach aphid (Myzus persicae), is another major pest that is changing because of climate change. Aphids are very sensitive to changes in temperature, and research has shown that higher temperatures can make them reproduce faster. Because of this, aphid numbers can grow very quickly, which can cause serious problems for things

like fruits and veggies. Also, the fact that aphids can reproduce more often when it's warmer can make it easier for plant viruses to spread, which makes pest control even more difficult.

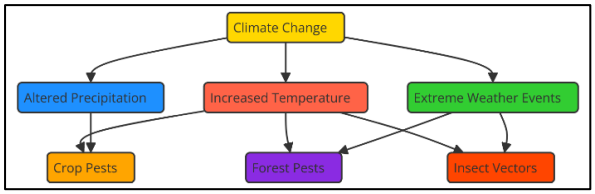


Figure 2: Illustrating how various pest species are affected by climate change

Climate change has also had a big effect on the Western Corn Rootworm (Diabrotica virgifera virgifera). Because of changes in its surroundings, this bug has become more resilient and successful at reproducing. Because of warmer temps, its active growing season has been stretched, which means that it can have more than one generation in a single season. This change has made pest problems worse in cornfields, making it harder to use traditional methods of pest control. The Asian Tiger Mosquito (Aedes albopictus) is a great example of an exotic species. Because of climate change, this mosquito has spread to new areas. It is known to spread diseases like dengue fever and the Zika virus. Higher humidity and warmer temperatures have made it easier for it to spread to colder areas, which is bad for public health and makes it harder to control vectors.

B. Geographic shifts in pest populations

As climate change changes the world's atmosphere, it's becoming clearer that pest groups are moving around. These changes are mostly caused by changes in temperature, rainfall, and yearly trends. This lets pests live in places that weren't thought to be good for them before. This event causes big problems for farming, public health, and the security of ecosystems. The Southern Pine Beetle (Dendroctonus frontalis) has been spreading since it has always done well in the hot southern United States. This is one of the most famous examples of how geography can change. As average temperatures rise, this pest has moved north into places that were cooler before, like parts of the Northeast and Canada. Because winters are getting warmer, the beetle can live and breed in places it couldn't before. This causes more damage to forests and loses for the wood business. Similarly, the Bagrada Bug (Bagrada hilaris), an invading bug that comes from Africa, has spread a lot across the United States, especially in California. It has spread more easily because of warmer temperatures and changes in the way rain falls, which has led to outbreaks of green crops like broccoli and cabbage. This growth not only threatens local farming, but it also changes how pests are normally controlled in the area.

C. Economic and ecological impacts of changing pest dynamics

Because of climate change, bug populations are changing in ways that have big effects on the economy and the environment. When pests get used to new climates, they have bigger problems with farming, wildlife, and ecosystem services. This is a problem for farmers, lawmakers, and environmentalists alike. In terms of the economy, changing pest patterns can cause farms to lose a lot of crops and have to pay more to make them. As pests move into new places that they haven't been in before, farming systems may be hit with unwanted outbreaks. For example, pests like the Asian tiger mosquito and the western corn rootworm have started to spread to new areas. This makes it harder to get resources and requires more work to control the pests. To protect their crops from these new threats, farmers might have to spend more on chemicals, integrated pest control techniques, and field tracking tools. These extra costs can cut into small farms' profits and make them less likely to stay in business, which makes food security problems in vulnerable areas even worse. In addition, the agriculture sector's reliance on chemical poisons to stop pest attacks can make pest populations more resistant. Pests may become resistant to chemical treatments as they get used to the ones that are already used. This means that stronger and possibly more harmful poisons will need to be made. This circle not only makes things more expensive, but it also puts people and the environment at risk because stronger chemicals can pollute water and dirt, which has bigger effects on the environment. Changing the way pests behave can mess up established food webs and have an effect on biodiversity. As bugs' numbers grow and their ranges spread, they may be able to eat away at native species, which can cause drops or even extinctions in some areas.

VI. Implications for Agriculture and Public Health

A. Strategies for pest management under climate change scenarios

Because climate change changes how pests behave, it is important to have good pest control plans to protect crops and people's health. Changing pest populations pose problems that need to be solved in a complex way that blends old methods with new technologies and flexible control methods. Utilizing Coordinates Bug Administration (IPM) is one of the finest ways to induce freed of bothers. IPM stresses a total strategy that incorporates natural, social, physical, and chemical limits to keep bug numbers beneath control in a way that doesn't hurt the environment. This strategy includes keeping an eye

on the number of bugs and the conditions of the zone to figure out the finest ways to induce rid of them. By combining data approximately bug science with temperature information, agriculturists can make keen choices around when and how to utilize pesticides, which implies they utilize less chemicals and have less of an impact on the environment. Expanding the assortment of crops is additionally an vital way to create ranches less powerless to bother assaults. Ranchers can break up the life cycles of bugs and make it less likely that they will spread by planting a wide run of crops. Pivoting crops and developing crops following to each other are great ways to keep bugs beneath control, progress soil wellbeing, and lower the hazard of illness spread. Including local plants to farmland can too bring in accommodating creepy crawlies and bees, which can make strides natural administrations and offer assistance control bugs. Frameworks for checking and anticipating are moreover exceptionally imperative for adapting to changes in how bothers carry on. Ranchers can keep an eye on changes within the climate and bug populaces in genuine time by utilizing farther detecting and prescient analytics. Utilizing models based on information, individuals included in agribusiness can foresee when bothers might spread and take preventative steps, like using specific pesticides or letting wild predators free. This preventative method improves the effectiveness of bug control and lowers the cost of doing business.

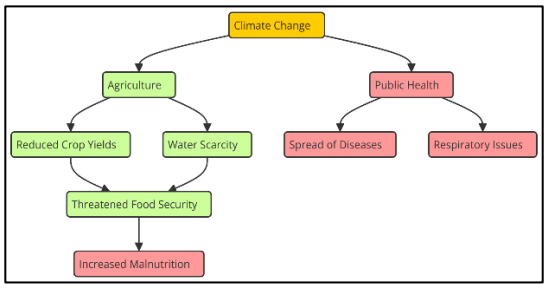


Figure 3: Implications for Agriculture and Public Health

B. Impact on food security and crop yields

Climate alter is changing the way bothers carry on, which features a tremendous and complex impact on nourishment security and trim yields. As bugs get utilized to modern climates, they have greater impacts on nourishment frameworks and cultivating generation, which makes individuals stress approximately the safety of the world's nourishment supply. One of the foremost clear impacts of changing how bothers carry on is that nourishment yield might go down. Warmer temperatures and changing climate patterns make it simpler for numerous bothers to outlive, which suggests more pervasions and more harm to crops. For illustration, bugs just like the aphid and the western corn rootworm can duplicate more rapidly when it's hot, which can lead to bigger populaces that can devastate areas. Bothers are getting to be more common, which not as it were brings down the sum of nourishment that can be developed but too brings down the quality of that nourishment. Crops that are harmed may not be as alluring, which puts indeed more weight on cultivating compensation and the nourishment supply chain. Bothers are making edit rates go down, which puts nourishment security at more noteworthy chance. Food security isn't just having food available; it also includes being able to get it, using it, and keeping it stable. When pests hurt crop production, basic foods may become harder to find, which can raise prices and make it harder for needy groups to get what they need. In emerging areas, where farming is the main way people make a living and get food, this situation is especially scary. Poverty and poor diet can get worse when food prices go up, causing a circle that hurts both health and the economy. Also, food loses caused by pests have effects on the economy that go beyond just one farmer. Lower yields can mess up both local and national food supply lines, making it harder to get food and making people more reliant on imports.

C. Health risks associated with pest outbreaks

There are big health risks when pests show up, and they affect both general health and food safety. As climate alter changes the way bugs carry on and moves diverse species to modern zones, the wellbeing issues that can be caused by bugs are getting to be more genuine. It is vital to get it these wellbeing dangers in arrange to ensure bunches and scenes through great administration. One of the greatest wellbeing dangers right presently from bug invasions is the spread of infections that are carried by insects or other pets. Intestinal sickness, dengue fever, the Zika infection, and Lyme malady are all spread by creepy crawlies like mosquitoes, ticks, and insects. Since of changes in the temperature, these carriers are moving into ranges where these maladies didn't happen much or at all sometime recently. For case, the Asian tiger mosquito (Aedes albopictus), which spreads a number of infections, has been seen in unused places since of hotter climate and changes within the way it downpours. The developing number of these carriers makes it more likely that maladies will spread to bunches that haven't been touched some time recently. This makes open wellbeing administrations work harder. In addition to spreading diseases, pests can also have a direct effect on human health by making sure food is safe. Pest animals in farms, like mice and some insects, can get into food sources and make people sick. Rodents, for example, are known to spread diseases like hantavirus and leptospirosis to people when they come into touch with dirty surfaces or food. Food safety and quality can go downhill when pests get into it, which can put people's health at risk.

VII. Result and discussion

The study shows that global warming has a big effect on how pests move and reproduce. Predictive models show that under different climate scenarios, pest populations will grow faster and spread to more places. In particular, rising temperatures cause some pests, like the western corn rootworm and aphids, to live shorter lives, which means that more of them get into plants. When temperature data is combined with machine learning algorithms, predictions become more accurate. This lets focused pest control methods be used.

Table 2: Predictive Model Accuracy Metrics

Model Type	RMSE (Root Mean Square Error)	MAE (Mean Absolute Error)	R^2 (Coefficient of Determination)	AIC (Akaike Information Criterion)
Statistical Regression Model	2.5	1.8	0.75	45.6
Machine Learning (Random Forest)	1.2	0.9	0.9	38.4
Mechanistic Model	2	1.4	0.8	42.1
Hybrid Model (ML + Climate Data)	1	0.7	0.95	36.8

The success measures of different types of models for predicting how pests will behave show important information about how well they work and how they can be used in farming settings.

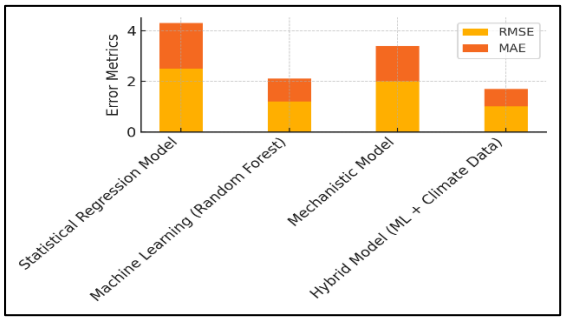


Figure 4: Overall Model Error Analysis (RMSE & MAE)

There is a modest amount of forecast error in the Statistical Regression Model, as shown by its Root Mean Square Error (RMSE) of 2.5 and its Mean Absolute Error (MAE) of 1.8. With a R^2 number of 0.75, it explains 75% of the differences in the data, which means it's a good fit but could be better.

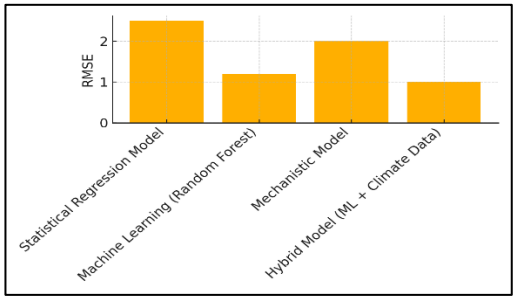


Figure 5: Root Mean Square Error (RMSE) by Model Type

Its Akaike Information Criterion (AIC) score of 45.6 shows that it works, but it might not be the best model out there. On the other hand, the Machine Learning (Random Forest) model does better, with an RMSE of 1.2 and an MAE of 0.9.

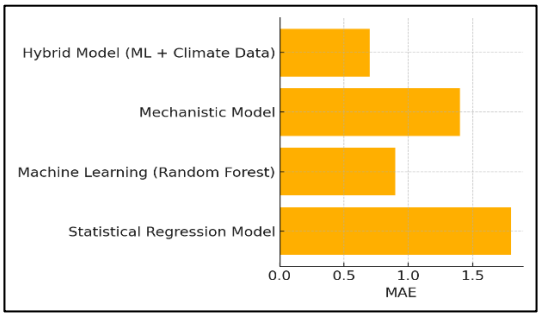


Figure 6: Model Performance Based on MAE

Its R^2 value of 0.9 means that it takes into account 90% of the differences in how pest populations change over time. This makes it a very useful tool

for predictive analytics. With an AIC of 38.4, it seems to be a good mix between model complexity and goodness of fit. The Mechanistic Model has an RMSE of 2 and an MAE of 1.4, but it gives us an organized way to understand how pests work. It has a good fit ($R^2 = 0.8$), but it can't predict as well as the Random Forest model. It works better than the statistical regression model, as shown by the AIC of 42.1. finally, the Hybrid Model (ML + Climate Data) does the best.

VIII. Conclusion

The effect of global warming on bug populations is very bad for farming and food security around the world. This study shows how important it is to have accurate climate models and predictive analytics to understand and plan for how pest populations will change in response to changes in the climate. By combining temperature data with knowledge about the life cycle of pests, we can better predict blooms and come up with effective management plans that can lessen the bad effects of more pests. As was shown, rising temperatures and changes in the way rain falls are making pests' areas bigger and their infestation rates higher. Pests like the western corn rootworm and aphids are getting stronger, which makes standard methods of controlling them more difficult. Because of this, we need to switch to Integrated Pest Management (IPM) methods that use predictive data to help us act quickly and use fewer conventional poisons. In addition, the effects on food security are very serious. Pest attacks can lower crop output and quality, which can make the economy less stable and cause food shortages in susceptible farming systems. So, those with a stake in agriculture must make it a priority to come up with adaptable methods that make farming more resilient to climate change. In the future, researchers should work on improving prediction models so that they include more detailed information about area climates and how pests react biologically. To deal with the many problems caused by changing pest behaviors, it will also be important to find new ways to control pests and encourage scientists, farmers, and lawmakers to work together.

References

[1] Richard, B.; Qi, A.; Fitt, B.D.L. Control of Crop Diseases through Integrated Crop Management to Deliver Climate-Smart Farming Systems for Low- and High-Input Crop Production. Plant Pathol. 2022, 71, 187–206.

[2] Fones, H.N.; Bebber, D.P.; Chaloner, T.M.; Kay, W.T.; Steinberg, G.; Gurr, S.J. Threats to Global Food Security from Emerging Fungal and Oomycete Crop Pathogens. Nat. Food 2020, 1, 332–342.

[3] Skendži´c, S.S.; Zovko, M.; Pajač, I.; Živkovi´c, Ž.; Leši´c, V.L.; Lemi´c, D.L. The Impact of Climate Change on Agricultural Insect Pests. Insects 2021, 12, 440.

[4] Shrestha, S. Acta Scıentıfıc Agrıculture (ISSN: 2581-365X) Effects of Climate Change in Agricultural Insect Pest. Acta Sci. Agric. 2019, 3, 74–80.

[5] Thomas, C.S.; Skinner, P.W.; Fox, A.D.; Greer, C.A.; Gubler, W.D. Utilization of GIS/GPS-Based Information Technology in Commercial Crop Decision Making in California, Washington, Oregon, Idaho, and Arizona. J. Nematol. 2002, 34, 200.

[6] Brown, N.; Pérez-Sierra, A.; Crow, P.; Parnell, S. The Role of Passive Surveillance and Citizen Science in Plant Health. CABI Agric. Biosci. 2020, 1, 1–16.

[7] Epanchin-Niell, R.; Thompson, A.L.; Treakle, T. Public Contributions to Early Detection of New Invasive Pests. Conserv. Sci. Pract. 2021, 3, e422.

[8] Dyussembayev, K.; Sambasivam, P.; Bar, I.; Brownlie, J.C.; Shiddiky, M.J.A.; Ford, R. Biosensor Technologies for Early Detection and Quantification of Plant Pathogens. Front. Chem. 2021, 9, 144.

[9] Wang, Y.M.; Ostendorf, B.; Gautam, D.; Habili, N.; Pagay, V. Plant Viral Disease Detection: From Molecular Diagnosis to Optical Sensing Technology—A Multidisciplinary Review. Remote Sens. 2022, 14, 1542.

[10] Zhang, N.; Yang, G.; Pan, Y.; Yang, X.; Chen, L.; Zhao, C. A Review of Advanced Technologies and Development for Hyperspectral-Based Plant Disease Detection in the Past Three Decades. Remote Sens. 2020, 12, 3188.

[11] Zhu, W.; Chen, H.; Ciechanowska, I.; Spaner, D. Application of Infrared Thermal Imaging for the Rapid Diagnosis of Crop Disease. IFAC-Pap. Online 2018, 51, 424–430.

[12] Balaško, M.K.; Bažok, R.; Mikac, K.M.; Lemic, D.; Pajač Živković, I. Pest Management Challenges and Control Practices in Codling Moth: A Review. Insects 2020, 11, 38.

[13] Strand, J.F. Some Agrometeorological Aspects of Pest and Disease Management for the 21st Century. Agric. Meteorol. 2000, 103, 73–82.

[14] Du, C.; Li, L.; Effah, Z. Effects of Straw Mulching and Reduced Tillage on Crop Production and Environment: A Review. Water 2022, 14, 2471.

[15] MacLaren, C.; Labuschagne, J.; Swanepoel, P.A. Tillage Practices Affect

Weeds Differently in Monoculture vs. Crop Rotation. Soil Tillage Res. 2021, 205, 104795.

[16] Jeger, M.J. The impact of climate change on disease in wild plant populations and communities. Plant Pathol. 2022, 71, 111–130.

[17] Trebicki, P. Climate change and plant virus epidemiology. Virus Res. 2020, 286, 198059.

[18] Véle, A.; Frouz, J. Bark Beetle Attacks Reduce Survival of Wood Ant Nests. Forests 2023, 14, 199.

[19] Torre, B.G.; Albericio, F. The Pharmaceutical Industry in 2020. An Analysis of FDA Drug Approvals from the Perspective of Molecules. Molecules 2021, 26, 627.

[20] Umetsu, N.; Shirai, Y. Development of novel pesticides in the 21st century. J. Pestic. Sci. 2020, 45, 54–74.

[21] Smiley, R.W.; Machado, S. Fusarium Crown Rot of Winter Wheat Influenced by Resource Competition near a Tree Windbreak. Plant Dis. 2020, 104, 348–357