Invited article

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# EFFECT OF CLIMATE CHANGE ON ARTHROPOD AND IMPACT ON CROP PRODUCTION

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## INTRODUCTION

Effect of climate change is not confined to arthropod pests and their outbreaks; beneficial arthropods are also affected. Therefore, an attempt has been made to include effect of global warming on four beneficial arthropods viz., insects, mites, ticks and, spiders. Global warming is a great concern throughout the world. The ill effects of global warming like change in climate, temperature, rainfall, humidity, level of carbon dioxide have been found to have both positive and negative effects on insects, which in turn reduces the effectiveness of crop protection measures. Effect on human animal health is no exception. This creates the need for global warming to be taken as an important criterion in Entomology. Being poikilothermic in nature insects are greatly affected by changing temperature.

The major cause of climate change is the increase in the concentration of greenhouse gases (GHG) viz., carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($NO_2$) as a result of human activities from pre-industrial era. These gases keep the earth warm and cause global warming or greenhouse effect. Global warming is caused by natural factors as well as human activities. There are number of natural factors responsible for climate change. Some of the most prominent are volcanoes, ocean currents, forest fire etc. Among human activities, emissions of greenhouse gases, industrialization, deforestation, fuel burning, etc. are the most important factors contributing to global warming. It is not new that global warming can affect agriculture through their direct and indirect effects on crops, soils, pests, livestock and fish. Changes in climatic factors affect crops in various ways through ineffective pollination, salinity, drought, crop sterility, submergence, flash floods, plant mortality through inappropriate temperature level, hot air flush, cyclone, hailstorm etc. Climate change affects the biology of insects, spiders and mites.

Global climate changes have significant impacts on agriculture and also on agricultural insect pests. Agricultural crops and their corresponding pests are

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directly and indirectly affected by climate change. Direct impacts are on pests' reproduction, development, survival and dispersal, whereas indirectly the climate change affects the relationships between pests, their environment and other insect species such as natural enemies, competitors, vectors and mutualisms. Insects are poikilothermic organisms; the temperature of their body depends on the temperature of the environment. Thus, temperature is probably the most important environmental factor affecting insect behavior, distribution, development and reproduction.

Therefore, farmers can expect to face new and intense pest problems in the coming years due to the changing climate. The spread of crop pests across physical and political boundaries threatens food security which is a global problem common to all countries and regions. Effects of different climatic factor on several aspects of insects, their natural enemies, insecticides, biopesticides and overall impact on crop production and food security are described here starting with effects on some beneficial and commonly known arthropods.

## Apiculture

Climate change is ratcheting up pressure on honey bees and also on other arthropod species. It is disrupting seasonal connection between bees and flowers. As spring arrives earlier in the year flowers bloom earlier in the year, but bees may not be present to feed on them. Even if flowers bloom at their usual times and locations, they may produce less nutritious pollens and nectar under extreme weather conditions (Durant 2022).

Generally, queen mate at temperature below 25° C. Extreme high temperatures have detrimental effect on mating flights. A brood region requires a temperature between 30°C & 36°C to produce broods. Bees maintain a relative humidity lower than 50% inhibits hatching of eggs, and a RH of 90-95% is optimum for egg hatching. RH less than 40% can dry eggs resulting in reduction of population, because honey bee larvae are fed royal jelly excreted by nurse bees and total composition of that jelly is 67 % water (Hossam *et al*. 2017).

## Sericulture

Silkworms are very delicate and highly sensitive to global warming and also vulnerable to survive under extreme fluctuation in temperature, rainfall and humidity. Optimum temperature for normal growth of silkworm is between 20°C and 28°C and desirable temperature for maximum productivity ranges from 23°C to 28°C. Temperature above 30°C directly affects the health of silkworms. If $C0_2$ in the air exceeds by 2 degrees celcious above usual concentration, the growth of silkworm will be retarded (Parrey 2018).

With increase in temperature, mulberry plants will be susceptible to rust disease. Muga silk, Eri silk and Tasar silk worms are domesticated but reared under outdoor conditions and those will be vulnerable to increased temperature, because change in temperature will affect cocoon weight, shell weight, filament length, silk yield, denier and sericin percentage. The decoding of mitochondrial DNA sequence would help in designing new experiment for improving climate resilient strains as being done in Assam, India (Bora and Saikia 2022).

**Beetles**

Dung beetles are saving the World from Global Warming. Cattle contribute to global warming by burping and farting large amounts of greenhouse gases. Some of the same gases are also emitted from cow manure on pastures. But now researchers from the University of Helsinki have found that beetles living in cow manure may reduce emissions of the key greenhouse gas methane. Cattle farming for meat and milk are major sources of methane, a gas with a potent warming effect. Much of this methane comes from the guts of ruminating cattle, but some escapes from dung pats on pastures. Cow dung offers a prime food for a large number of organisms. In fact, there are probably as many beetle species living in dung as there are bird species on this planet. These beetles exert much of their impact by simply digging around the dung. Methane is primarily born under anaerobic conditions, and the tunneling by beetles seems to aerate the pats (Penttila 2013).

Dung beetles battle global warming (Holland 2013) The dung beetle might just be a weapon in the battle against global warming. But the dung beetle, with its sordid habit of laying eggs in and eating cow dung might just be a weapon in the battle against global warming. The 1.3 billion large ruminants-dairy cows and beef cattle, buffalo, sheep, goats that burp, fart, and poop around the world emit about a third of global emissions of methane, a gas that makes up half of the farming's contribution and is even more potent than the much-maligned CO2. Dung beetles, by the way, dig burrows into pasture feces and feed on the droppings of cows and other ruminants. They also deposit their eggs in the excrement, and their hatchlings feed on the same stuff.

The scientists have found that cow patties with beetles, specifically *Aphodius* species, rummaging around in them released nearly 40% less methane over a summer period than beetle-free cowpats did. Sadly, like many animals these days, dung beetles are on the decline. More than half of the dung beetle species are threatened or near endangered. The reasons include the lack of diversity in both dung and pasture that goes with fewer but more intensively managed farms, and the reduced quality of the dung-which nowadays contains more chemicals, such as anti-parasite drugs given to farm animals. The best way to help beetles thrive and "do their thing on the gas fluxes" is to let cattle graze on variable types of outdoor pasture.

### Spiders

These are mostly known as beneficial animals. A study reveals that at increased temperatures and population densities, arctic wolf spiders change their eating habits, starting an ecosystem-wide cascade that could change how quickly melting permafrost decomposes. Scientists have known for almost a decade that climate change would impact spider populations. A 2009 study showed that a warmer Arctic with earlier springs and longer summers could make wolf spiders both larger and (because larger spiders can produce more offspring) more abundant (Machemer 2018)

Spiders become aggressive under unfavorable environment, and males mature earlier in the year than they would normally do. But the disaster is that these males wander around for female, which are not yet ready for mating, rather these are seeking food for sexual maturity. The males do not find female partner and thus Rome males die before meeting and mating with Juliet. Even small temperature increase and more frequent heat waves can wipe out entire population and drastically change ecosystem. Such bad effect on biological control agent might put even more pressure on crops (Henriques 2019).

### Cockroaches

Cockroaches have an awesome array of adaptation to life on dry land and are adaptable and can cope up in a wide range of environmental conditions. Cockroaches have fine-tuned physiology for survival since 250 million years ago. They will do well in the face of climate change. These evolved in humid conditions of rain forest. Their trick of survival under dry environment is their habit of holding breath for half an hour (40 minute by speckled cockroach, *Nauophoeta cinerara*) or shorter to prevent water loss through spiracles at the time of respiration. They hold their breath underground where $CO_2$ can be poisonous (Barley 2009).

In summer, warm weather encourages breeding, which means that there are more cockroaches looking or food in homes. Since these depend on temperate environments for survival, they make their nests in walls of houses, apartment, restaurants, supermarket, kitchen, bathroom, wardrobes, refrigerators and cracks and crevices nearby. Their saliva, droppings, shed skin and body parts are known to cause asthma, salmonella infection etc. It is well known that cattle, sheep and even elephants generate Green House Gas methane. On an average a cow releases between 70 and 120 kg of methane gas per year. Methane is 25 times more potent than carbon dioxide. Interestingly, insect flatulence may account for one-fifth of all the methane emissions on this planet. Centipedes, termites and beetles are all major producers of methane (Jackie 2016).

### Termites

There are around 3000 species of termites across the world, including the ones that consume plant material and even soil. However, the most famous are the wood-eating termites having the ability to decompose deadwood parts of trees that contain carbon making them important part of the planet's ecosystem. As the earth gets warmer, termites will rapidly spread across the world and those will move towards north and south from existing tropical zones. As the environment gets hotter and warmer by less than 2°C the areas with highest termite activity will expand around 2 million square kilometers. Their ideal temperature is 75°F and deadly temperature is from 120 to 140°F. While these small insects are decomposing deadwood, they release carbon into the atmosphere. Termites are responsible for releasing 1-3% global methane. Termites in a region with temperatures of 30°C ate wood seven times faster than in a place with temperature of 20°C. All colonies of termites have fertile males called kings and one or more fertile females called queens. Termite queens have the longest known lifespan of any insect, with some queens reportedly living up to 30 to 50 years (Hindu 2023). Insecticides have not been the sustainable mechanism of controlling termites. Alternative mechanism needs to be developed.

### Bedbugs

Bedbugs will face a situation suitable for human beings. These are very highly reproductive. Preferred temperature is 32°C. Temperature above 32°C is deleterious. Sublethal heat stress may weaken bedbug infestations to potentially cease control. Among survivors, egg production, egg hatching, molting success and offspring proliferation were decreased significantly in the subsequent 7-week recovery period at 22°C (Rukke *et al.* 2018)

### Ticks

There is very scanty conclusive information on resilience of ticks or tick-borne diseases to changing climates and there is even a paucity of information on how ticks might be able to adapt to certain parameters of climate such as temperature changes. Ticks are better adapted in warmer climate than in cooler climate. However, *Ixodes ricinus* speed up oviposition rates, egg development rates, interstadial development rates like insects. Other ticks also have almost similar life pattern and transmission of diseases. They cannot survive long in temperature below -15°C but when temperature reach above 30°C (even if humidity is high i.e., >80%) they experience greater mortality. Tick abundance *per se* can be relevant to pathogen distribution rates. With higher tick densities, there is an increased likelihood of tick-biting (and, therefore, acquiring infection form) a host while it is infectious (Gilbert 2021).

### Head Louse

Climate change will lead to higher number of head lice infestations. Currently head lice affect 6-12 million individuals in the United States every year. As the lice get stronger and more resistant their number is expected to tremendously increase! (Jennie 2016).

### House flies

The incidence of food borne illness could jump in a warming world, due to an increase in house fly activities. House flies are more active when weather is warm meaning there are more chances to land on picnic dips, open restaurant, food shops etc. With warmer temperature Campylobacter (a bacterium which may cause abortion in animals and food poisoning in humans) will be able to replicate more rapidly. At 30°C entire fly breeding cycle can take as little as 10 days! (Intagliata 2019).

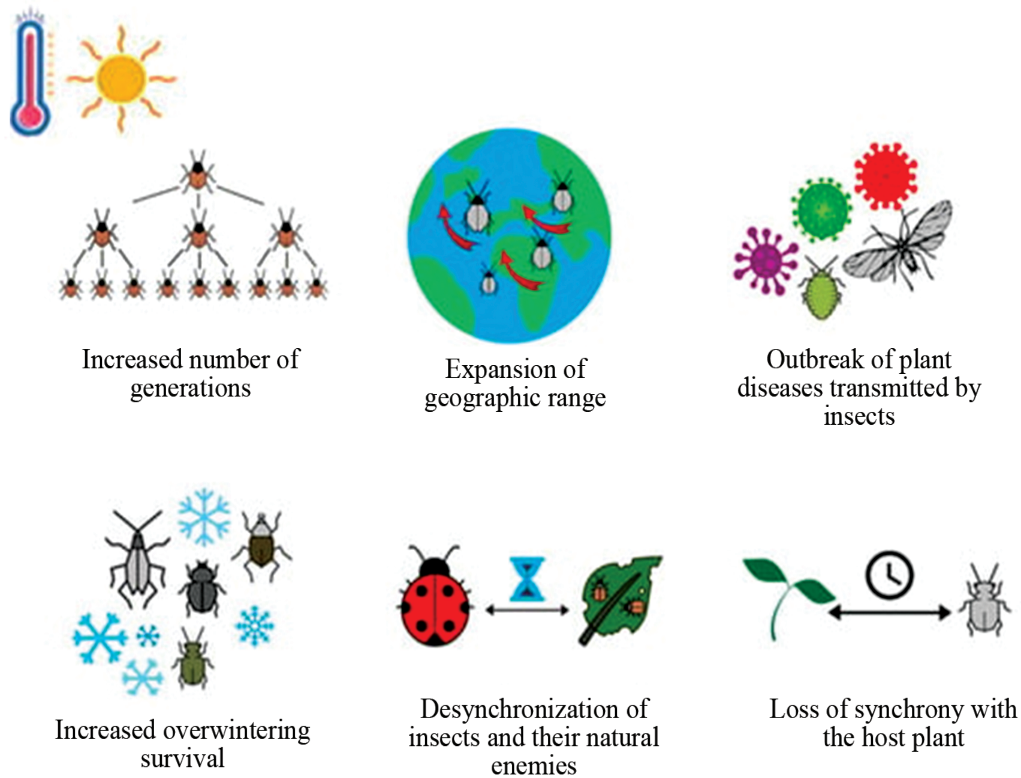
### Mosquitoes

Mosquitoes also breed rapidly under warm climate. Vector-borne infectious disease such as malaria, dengue virus, zika virus, and lyme disease affect nearly half of the world population and can create international health emergencies. The outbreak of zika virus during 2015-2016 transmitted by mosquitoes was widely linked with the prevalence of unusually high temperature. Asian tiger mosquito (*Aedes albopictus*), a known vector of dirofilariasis, is a species native to Asia. Due to increasing temperature the mosquitoes are spreading rapidly across the Europe, where it is now present in 2 states (Leblond 2021).

### Fruit fly

Work in University of Liverpool emphasizes that temperature-driven fertility losses may be a major threat to biodiversity during climate change. They already had reports of fertility losses at high temperatures in everything from pigs to ostritches, fish, flowers, bees and even humans. According to scientists, male fruit flies became sterile at about four degrees below their lethal temperature limits– roughly equivalent to the difference between summer in Northern England and south of France (AFP 2021).

## Response of Insect Pests to Increased Temperature




Insect physiology is very sensitive to changes in temperature and their metabolic rate tends to approximately double with an increase of 10°C. With an increase of 2°C temperature, insects might experience one to five additional life cycles per year. Many researchers have shown that increased temperature tends to accelerate insect consumption, development and movement, which can affect population dynamics by influencing fecundity, survival, generation time, population size and geographic range. Species that cannot adapt and evolve to increased temperature conditions generally have a difficult time maintaining their populations, while other species can thrive and reproduce rapidly.

Temperature plays an important role in metabolism, metamorphosis, mobility and host availability, which determines the possibility of changes in pest population and dynamics. Increase in temperature is associated with increased herbivory rates as well as changes in the growth rate of insect populations. The effects of increased temperatures are greater for above ground insects than for those that spend most of their life cycle in the soil, because soil is a thermally insulating medium that can buffer temperature changes and thus reduce their impact. For example, under warmer conditions, aphids are less susceptible to the aphid alarm pheromone they normally release when threatened by insect predators and parasitoids, which can lead to increased predation.

Whitefly populations are primarily regulated by environmental factors such as temperature, precipitation and humidity in general. High temperature along with high humidity correlates positively with whitefly population build-up. However, global warming may not uniformly increase pest abundance and thus economic crop losses. There is mixed analysis indicating that temperature rise leads to increased pest severity in most of their insect case studies. Another study of about 1100 insect species found that climate change due to global warming will drive about 15–37% of these species to extinction by 2050.

The general consequences of global warming on insect dynamics include: expansion of geographic range, increased survival rates of overwintering populations, increased risk of introduction of invasive insect species, increased incidence of insect-transmitted plant diseases due to range expansion and rapid reproduction of insect vectors, reduced effectiveness of biological control agents such as natural enemies, etc. Global warming has led to earlier infestation by *Helicoverpa zea* in North America and *H. armigera* in North India resulting in increased crop loss. Rising temperatures are likely to result in availability of new niches for insect-pests. Temperature has a strong influence on the viability and incubation period of *H. armigera* eggs.

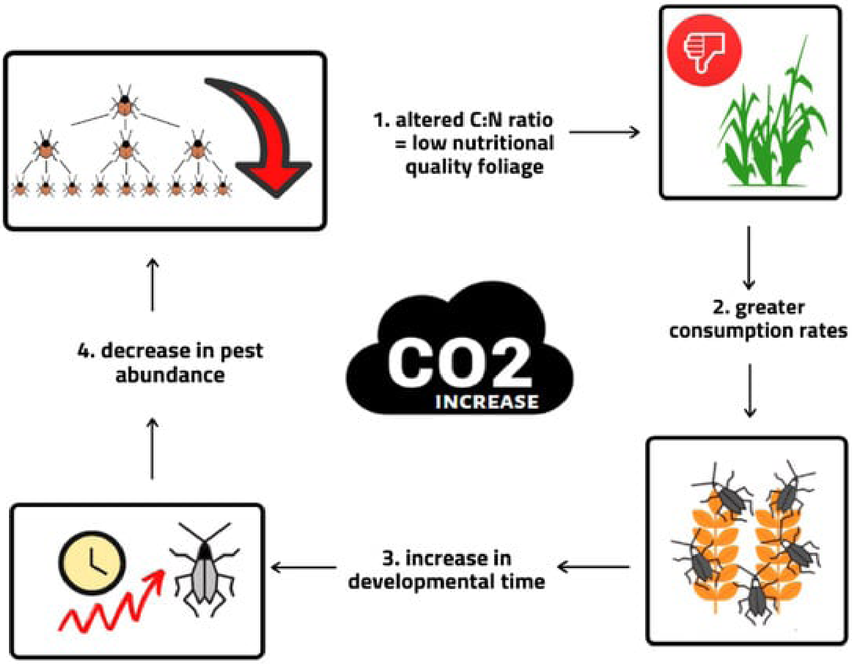
## Increase in Pest Population

With every degree rise in global temperature, the life cycle of insect will be shorter. The quicker the life cycle, the higher will be the population of pests. In temperate regions, most insects have their growth period during the warmer part of the year. The general prediction is that if global temperatures increase, the species will shift their geographical ranges closer to the poles or to higher elevations and increase their population size over time and space.

## Decrease in Pest Population

Not all the insect pest can survive and adapt in the changing climate. Climate change can challenge the availability for their food, mobility; space for oviposition, sex expression etc. as well as climate change implies the change in vegetation richness in the environment. It may imply the decrease in host population, causing insect pest to suffer from lack of hosts for food, oviposition etc.

## Response of Insect Pests to Increased $CO_2$ Concentration




Elevated concentrations of atmospheric $CO_2$ can affect the distribution, abundance and performance of herbivorous insects, consumption rates, growth rates, fecundity, gain in larval weight, and population densities of insect pests. The effects of increasing $CO_2$ levels on insect pests are highly dependent on their host plants. Increased $CO_2$ levels would have a greater impact on C3 crops (wheat, rice, cotton, etc.) than on C4 crops (corn, sorghum, sugarcane etc. Therefore, these differential effects of elevated atmospheric $CO_2$ on C3 and C4 plants may result in asymmetric effects on herbivory and the response of insects feeding on C4 plants may differ from that of C3 plants. C3 plants are likely to be positively affected by elevated $CO_2$ and negatively affected by insect response, whereas C4 plants are less responsive to elevated $CO_2$ and therefore, less likely to be affected by changes in insect feeding behavior.

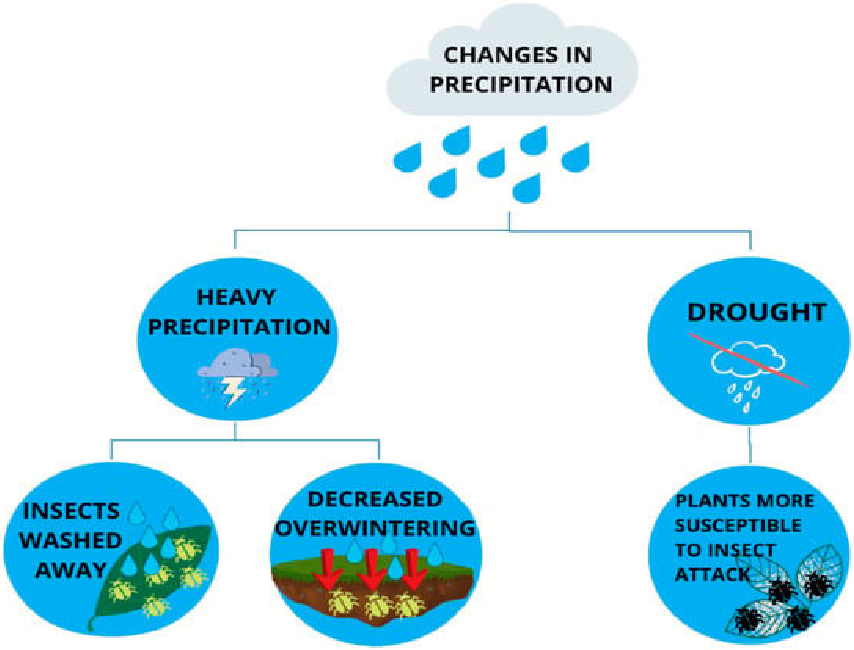
Nitrogen is the key element in the insect's body for its development, and therefore, increased $CO_2$ concentration leads to increased plant consumption rate in some pest groups, because plant tissue will contain reduced level of nitrogen. This can lead to increased levels of plant damage, as pests must consume more plant tissue to obtain an equivalent level of food. Increased consumption rates are a common response in foliage feeders, such as caterpillars, miners, and chewers, to a reduction in nitrogen, as predicted by $CO_2$ fertilization, with compensatory feeding. Soybeans grown at elevated atmospheric $CO_2$ concentrations, and during the early season, soybeans exhibited 57% more damage from insects such as the Japanese beetle (*Popilia japonica* Newman), Potato leafhopper (*Empoasca fabae* Harris), Mexican bean beetle (*Epilachna varivestis* Mulsant), and Western corn rootworm (*Diabrotica virgifera virgifera* Le Conte).

Thrips shows an increase in population size. Phloem-feeding insect pests, including whiteflies and aphids, have combined responses of increased population growth rates and a decrease in population density. Insects were affected due to increased $CO_2$ compared to ambient $CO_2$. Stronger effects of the increase in atmospheric $CO_2$ were also found for chewers in contrast to other feeding guilds, such as sap-sucking herbivores (e.g., aphids, leafhoppers, scale insects).

Plants consist primarily of carbon, and elevated $CO_2$ levels allow them to grow more rapidly because they can assimilate carbon more quickly. Increase in carbon dioxide is often understood as increase in photosynthetic rate and is believed that plant attains better drought tolerance in higher $CO_2$ concentration. This allows the situation where the availability of host is ensured for insects even in harsh conditions. More importantly, major reason for increased level of damage in higher $CO_2$ level is the decreased nutrient level in plants. Plants exposed to higher carbon dioxide implies lower level of nitrogen resulting in poor nutrient content in host plants. A rise in $CO_2$ in atmosphere generally increases the carbon to nitrogen ratio due to accumulation of non- structural carbohydrates of plant tissues thereby reducing the nutritional quality for protein limited insects diluting the nitrogen content by 15-25% in the tissues. So, in order to compensate the nitrogen requirement of insects, the feed intake of insects grows rapidly.

A higher level of sugars like glucose, sucrose, and fructose in soybean foliage grown under higher $CO_2$ is considered to be a preferential factor for Japanese beetle, *P. japonica*. It has also been reported that increased level of $CO_2$has been related with higher fecundity of aphids. Alteration of food quality of chickpea due to elevated $CO_2$ stimulates the growth of pod borer which leads to increased food consumption, gain in larval weight, more fecal matter production, increased pupal weight and total larval duration.

## Response of Insect Pests to Changeable Precipitation




Insect species that overwinter in the soil are directly affected by overlapping rainfall. In short, heavy rainfall can lead to flooding and prolonged stagnation of water. This event threatens insect survival and at least affects their diapauses. In addition, insect eggs and larvae can be washed away by heavy rains and flooding. Small-bodied pests like aphids, mites, jassids, whiteflies etc. can be washed away during heavy rainfall. Variable rainfall can have a major impact on insect populations. Rapid growth of wireworm populations in the upper part of the soil resulted from increased summer rainfall events as opposed to ambient and drought conditions. Herbivorous insects are affected by drought through several mechanisms; (I) dry climates may provide suitable environmental conditions for the development and growth of herbivorous insects; (II) drought-stressed plants attract some insect species. For example, when plants lose moisture through the process of transpiration, water columns in the xylem break apart, producing an ultrasonic acoustic emission that is detected by harmful bark beetles (Scolytidae); (III) plants stressed by drought are more susceptible to insect attack because of a decrease in the production of secondary metabolites that have a defense function.

**Brown Plant Hopper and Hispa:** The abundance of BPH without precipitation is found to be normal. With an increase in 10% precipitation more than normal it is abundant. But with an increase in 10% precipitation and temperature of 1°C successively it has been found to multiply enormously. Global warming has led to the increased risk and abundance of invasive pest such as *Aceria guerreronis*. Incidence of *Helicoverpa armigera* is reported to increase in higher rainfall in November (which is the deviation of normal precipitation pattern). But some species are not affected by change in pattern of rainfall. *Coccoidea lecanopsis formicarum* was seen unaffected by changed rainfall pattern. As well as some species are positively affected by increased rainfall viz. *A. lineatus*. Incidence of *Spodoptera litura* is seen in higher in groundnut, cotton, chillies and coriander in enhanced rainfall.

**Effect of Global Warming on Insect Biology**

The life span of Japanese beetle, *Popillia japonica* a major pest of soybean, is prolonged by 8.25% when fed on foliage developed under elevated $CO_2$. Also, females fed on such foliage laid approximately twice as many eggs as compared to females fed on foliage grown under normal ambient conditions. Life cycle of *Aphis gossypii* Glover ranges from 20-22 days at 10-25°C, but at 30°C it will take only 6-9 days to complete the life cycle. In the cricket, *Gryllus texensis*, 6 days of elevated temperatures resulted in increased egg laying, faster egg development and greater mass gain. Global climate change is projected to increase temperature of the upper soil (0–5 cm) by 1.6– 3.4°C by 2100, which is likely to have several effects on soil insects such as *Sitona* spp. root weevils that are important in lentil in West Asia. Higher temperatures could speed up egg development, resulting in more than one generation per year of the pest.

**Effect of temperature on sex ratio and life tables parameters**

King (1987a) showed the effect of temperature on sex ratio and life tables parameters of the Leek ($L_1$) and tobacco associated (T) Thrips lineages (Thysantoptera: Thripidae). The preoviposition, fecundity, adult longevity and egg hatchability rate were reduced significantly with increasing temperature. In both lineages, the lowest egg hatchability rates were recorded at 30°C and the highest rates were recorded at 15°C. Mean fecundity of the L1 and T lineages were 107.63 and 84.83 at 23°C respectively, and mean fecundity were 19,88 and 70.82 at 15°C respectively. The lowest mean fecundity was recorded at 15°C and 30°C for L1 and T lineages respectively. Mean longevity were 34.22 and 81.82 days at 15°C for L1 and T lineages respectively, whereas, shortest mean longevity (13.63 and 13.91 days) was observed at 30°C for the $L_1$ and T lineages respectively. King (1987b) showed that the sex ratio (female: male) of *Thrips palmi* adult on eggplants was the highest (2: 03) at 31°C and the lowest (1: 22) at 16°C.

Laboratory and field studies on about 100 species in sixteen families indicate that several factors can influence offspring sex ratios in parasitoid wasps. For many species, offspring sex ratio increases with one or more of the following: 1) maternal age at ovipositing or the amount of time since insemination, 2) the age of the male parent or the number of times he has copulated, 3) extreme temperature, 4) decreasing host size, age, or quality, 5) female wasp density, and 6) the number of progenies per host. Other factors which have been shown to affect offspring sex ratios in some species include: 1) number of hours since insemination, 2) genetic factors, 3) maternal size, 4) maternal diet, 5) polyembryony, 6) photoperiod and relative humidity, 7) host sex, and 8) host density. Sex ratio varies on the basis of above situations.

## Changes in Insect Phenology

Change in insect phenology is the most observed indicator of climate change. With increased temperatures, it is expected that insects will pass through their larval stages faster and become adults earlier. Expected responses in insects could include an advance in the timing of larval and adult emergence and an increase in the length of the flight period. Early adult emergence and an early arrival of migratory species have also been reported for aphids. Four Mediterranean insect species viz., butterfly, bee, fly and beetle exhibited changes in their first appearance date over the last 50 years, which was correlated with increases in spring temperature. Research revealed that spring flights of the potato aphid *Myzus persicae* started two weeks earlier for every 1°C rise in combined mean temperature of January and February.

## Effect on Insect Pheromones

Pheromones are utilized by insects for several purposes, including alarm signaling and sexual communication. It was found that when $CO_2$ was elevated, aphids *Chaitophorus stevensis* did not disperse readily. Such response is a big challenge for using pheromone in insect control.

## Expansion of Insect Distribution

In general, the following factors may determine the distribution of insect pests: (I) natural biogeography; (II) crop distribution; (III) agricultural practices (monocultures, irrigation, fertilizers, pesticides); (IV) climate; (V) trade; and (VI) cultural patterns. Climate change will have a major impact on the geographic distribution of insect pests, and low temperatures are often more significant than high temperatures in determining their geographic distribution. Due to the spread of insect pests to new areas, along with the shift in the growing areas of their host plants, farmers will face new challenge with severe pest problems. In such cases, in addition to climatic conditions suitable for the particular crop, other factors such as soil properties and environmental structure are of great importance. The ranges of insect pests are expected to shift to higher altitudes by 2055, with an increase in the number of generations in central Europe.

In Europe, for example, the European corn borer (*Ostrinia nubilalis* Hubner) has shifted more than 1000 km northward. Studies on 35 species of non-migratory European butterflies it was found that the geographic ranges of 63% had shifted 35 to 240 km northward and only 3% southward in the 20th century. Increased fluctuations of warm air masses towards higher latitudes have resulted in the establishment of the diamondback moth (*Plutella xylostella* L.) The pink bollworm (*Pectinophora gossypiella* Saunders), a major cotton pest, is presumed to be expanding its current range from the frost-free zone in southern Arizona and California into the cotton growing areas of Central California.

**Increased Overwintering Survival/Diapause**

Insects may enter diapause, which is an obligate or facultative activity characterized by suppressed development, suspended activity, and increased resistance to adverse environmental extremes such as temperature, photoperiod, humidity, accumulated chilling, food and photoperiod. Aestivation and hibernation are two types of diapause. Aestivation allows insects to survive in environments with higher temperatures, while hibernation keeps them alive at lower temperatures. Some insect species enter diapause during the inactive egg or pupal stages, while others do it as larvae, nymphs, or adults. When diapause occurs in the inactive stages, it is often accompanied by a sharp drop-in metabolic rate that is accompanied by an increase in cold hardiness. During larval diapause, which is likely more common in subterranean herbivores that are protected from low temperatures, feeding may continue and forward development may slow down rather than stop.

General principle is that the duration of diapause is shorter at higher temperatures. Diapause ends when energy reserves reach a critical point. When metabolic rate is high, energy reserves are depleted quickly, and when metabolic rate is low, this set point is reached much later, resulting in a longer diapause. Horticultural pests of plants grown in greenhouses will have more opportunities to survive outdoors as average temperatures increase. In addition, rising temperatures may increase the overwintering survival of insects that were limited by low temperatures at higher elevations, leading to an expansion of their geographic range.

## Increased Number of Generations

As mentioned earlier, temperature is the most important environmental factor for insects, affecting mainly their phenology. The ambient energy hypothesis suggests that growth and reproduction are greater at high temperatures. Therefore, higher temperatures or global warming leads to higher population sizes, which in turn can lead to a higher number of species in dynamic equilibrium. Under a global warming scenario this makes it possible to accelerate reproductive rates within a certain preferred range, leading to an increase in the number of generations of many insect species and to more crop damage. For multivoltine insects, such as aphids and some lepidopteran species, such as the large cabbage white butterfly (*Pieris brassicae* L) will have additional generations within a year. Using several models, it has been extrapolated that a 2°C increase in temperature could result in one to five additional life cycles per year. The most significant examples in this regard are aphids, which can be expected to produce four to five additional generations per year due to their low developmental threshold and short generation time.

## Increased Risk of Invasive Alien Insect Species

Invasive alien species (IAS) are defined as taxa that are introduced either intentionally (e.g., food, crops, ornamentals, pets, livestock) or unintentionally due to human activities outside their natural habitat. Invasive insects are usually agricultural, stored-product, forestry, household or structural pests and can often be vectors of various diseases or parasites. The Convention on Biological Diversity describes invasive alien species as the greatest threat to global biodiversity with high costs to agriculture, forestry and aquatic ecosystems. There is a "rule of 10," according to which approximately 1 in 10 introduced species escape into the environment, 1 in 10 of these introduced species become established in the environment, and 1 in 10 of these established species become economic pests.

To become invasive, alien insects must successfully arrive in a new habitat, survive the given conditions, and thrive. Climate change could positively or negatively influence the components of this invasive pathway. The process of insect invasion involves a chain of events that include transportation, introduction, establishment, and dispersal of invasive alien insects. Dispersal may also occur due to hurricane. For example, the Cactus moth (*Cactoblastis cactorum* Berg), was blown from the Caribbean islands to Mexico during the 2005 hurricane season, where it posed a significant ecological and economic threat to more than 104 prickly pear species (*Opuntia* Mill).

Invasive species usually have a wider range of tolerance or bioclimatic range than native insects, allowing alien insects to find a wider range of suitable habitats.

## Effects on Insecticides

The degradation and biological effectiveness of five insecticides, ES-Fenvalerate (Soumi Gold), pirimicarb (Afox), imidacloprid (Emax), buprofenzin (Ablloud) and methomyl (Methiolate) tested on immature stages of whitefly insect *Bemisia tabaci* indicated the degradation rates of the five tested insecticides which varied according to the chemical structure, time of exposure and wavelength of UV-rays used. Of all the five insecticides, methomyl was the most affected by UV-rays. Losses of ES-Fenvalerate, pirimicarb, imidacloprid, buprofenzin and methomyl were 11.30, 14.80, 29.03, 31.83 and 39%, respectively after one hour to UV-ray exposure. Efficiency against immature stages of whitefly *B. tabaci* was affected when aqueous preparations of the five tested insecticides were stored at 45°C for one and three days, compared to those stored under normal condition of 25°C for the same periods of time. Generally, it could be concluded that buprofenzin and methomyl, were more affected by UV-light, storage and temperature than ES-Fenvalerate, pirimicarb, imidacloprid (Soliman 2012).

The effect of exposure period to heat, UV-rays and sunlight on the degradation of chlorpyrifos and profenofos were studied. It was found that chlorpyrifos insecticide residues were more persistent than profenofos insecticide residues and both showed progressive loss as temperature and prolongation of exposure period increased. This indicates that the interval between successive sprays should be shorter at high temperature and vice versa.

Photodegradation with UV-rays was positively correlated with exposure period and chemical structure of insecticide, profenofos degraded faster than chlorpyrifos in this respect. Sunlight was more effective than UV-rays in accelerating the photodecomposition of chlorpyrifos and profenofos residues. Temperature has roles in metabolism, metamorphosis, mobility, host availability etc. which determines the possibility of change in insect pest population and dynamics (Ali and Ryad 2018).

## Reduced Effectiveness of Biological Control Agents-Natural Enemies

Climate change is likely to have severe impacts on the abundance, distribution, and seasonal timing of pests and their natural enemies, which will alter the degree of success of biological control programs. Aphids are among the insect pests that are controlled by many natural enemy species, such as parasitic wasps, which lay their eggs in the bodies of aphids and predatory species, such as ladybirds. A ladybird can consume 5000 insects in its lifetime (Machemer 2018). All of these species are affected by the effects of global warming and could respond differently to temperature changes. If a natural enemy starts to develop at a slightly lower temperature than the prey (e.g., aphid) and develops faster than the prey when the temperature rises, a too early and warm spring leads to its early emergence and a high probability of death from lack of prey. If this phenomenon is repeated over several years, it may lead to the extinction of the natural enemy.

Aphid populations build up under both elevated temperature and elevated $CO_2$, but the same elevated $CO_2$ level resulted in lower fecundity of the wasps. Asian ladybird (*Harmonia axyridis* Pallas) in food choice experiments indicated that this preferentially preyed on aphids under elevated $CO_2$ concentration compared to ambient $CO_2$ (Skendzic *et al.* 2021).

The entomopathogenic bacterium *Bacillus thuringiensis* (Bt) has been used in crop protection for the last 70 years; however, many environmental conditions affect its activity. Background *Bacillus thuringiensis* (Bt) is one of the earliest developed entomopathogens and it is widely used as biopesticide. It produces insecticidal proteins (δ-endotoxins) which exhibit toxicity to many insect species belonging to order Lepidoptera, Diptera, and Coleoptera. Recently, several gene coding for the insect toxins of Bt has been genetically incorporated into crop plants. These are referred to as Bt-crops representing (19%) of all GMO crops worldwide.

Shelf life of entomopathogens is often low, and there is a difficulty to achieve a viable product after 1 or 2 years under ambient conditions. As it is known that products based on natural molecules tend to be less stable than synthetic compounds, hence their residual effects are biodegradable. In addition, these products are not stable under natural environmental stresses such as temperature, ultra violet (UV) radiation and sunlight. Radiation from sunlight or UV light is the main limitation that obviously reduced the potency of Bt crystals against different insect pests (Mousta *et al.* 2018).

The influence of environmental conditions on mycosis of grasshopper caused by *Beauveria bassiana* (Balsamo) Vuellemin, was investigated. Despite the deposition of considerable quantities of conidia on to grasshoppers, ($6.7 \times 10^3$) colony forming units {CFU} per nymph, Beauvoir bassinet did not significantly reduce field population, nor did it affect specific grasshopper taxi. Conditions were warm and sunny during the trials. Small numbers of conidia (<2CFU per grasshopper) were recovered from surface sterilized grasshoppers 5-15 d after application indicating that if infection occurred, *Beauvoir bassinet* did not proliferate in the hemocoel.

Higher prevalence and more rapid development of disease were observed in grasshoppers placed in shaded cages (83-89%) than in cages exposed to full sunlight (0-15%) or protected from UV radiation (1-43%); conidial survival was equally enhanced in the shaded and UV protected environments (Inglis *et al.* 1997).

**Reducing Effect on Natural Enemies**

Predators can be sensitive to increase in temperature and precipitation. Parasitism of the caterpillar *Spodoptera littoralis* by the parasitoid *Microplitis rufiventris* is less at 27°C (80.6°F) than at 20°C (68°F). Natural enemies of the spruce budworm, *Choristoneura fumiferana*, are less effective at higher temperatures. Oriental armyworm, *Mythimna separata* population increases during extended periods of drought (which is detrimental to the natural enemies), followed by heavy rainfall because of the adverse effects of drought on the activity and abundance of natural enemies of this pest.

**Effect of Climate Change on Expression of Resistance to Insect Pests**

Host plant resistance to insects is one of the most environmentally friendly components of pest management. However, climate change may alter the interactions between the insect pests and their host plants. Climate change may result in breakdown of resistance to certain insect pests. Sorghum varieties exhibiting resistance to sorghum midge, *Stenodiplosis sorghicola* in India become susceptible to this pest under high humidity and moderate temperatures.

**Effect of Climate Change on Effectiveness of Transgenic Plants**

Interestingly, such changes have important implications for the use of certain transgenic plants that are resistant to insects. It was observed that growing these transgenic plants in elevated carbon dioxide resulted in a nearly 25% reduction of the expression of proteins. This reduction allowed beet armyworms, *Spodoptera exigua* to survive on these plants.

**Effect on Insect Coloration**

Insect coloration is the phenomenon of adoption to maintain the heat. Scientists have noticed that warming climate is changing ladybugs of the coast of Netherlands from black to red. Red reflects more energy hence ladybugs stay cool.

**Increased Incidence of Plant Diseases Transmitted by Insect Vectors**

Insects are important vectors that transmit many plant diseases such as viruses, phytoplasmas and bacteria. Viruses are major causes of many plant diseases in global food production. The estimated economic loss from these diseases exceeds \$30 billion per year. Outside their vector or host insect, viruses are immovable and, therefore, are heavily dependent on their vectors for transmission and spread. Climate change may have a major impact on the epidemiology of plant viruses. Most viruses of agricultural crop species are messenger RNA viruses and single-stranded DNA viruses. Their main host-to-host transmission strategy is the use of insect vectors with mouthparts for piercing and sucking.

The majority of insects that transmit plant viruses are the sap-feeding hemipteran sucking insects as aphids (Aphididae), leafhoppers (Cicadellidae) and whiteflies (Aleyrodidae). Among these, aphids are the largest group of vectors, transmitting more than 275 virus species. The short development time and high reproductive capacity of aphids and whiteflies make them particularly sensitive to responses to climate change. Aphids are expected to have higher survival rates in milder winters, and higher spring/summer temperatures increase their development and reproduction rates. Temperatures above 36°C in warmest summer months result in decreased survival of aphids, reducing the spread of Barley yellow dwarf virus (BYDV). Whiteflies (*Bemisia tabaci* Gennadius) are most important virus vectors. Moderate precipitation and high temperatures are generally favourable for *B. tabaci* and lead to population increases. Environments with dry and hot climates with installed irrigation systems provide favorable conditions for *B. tabaci*. Considering their short generation time, large populations can develop in summer. Drought could decrease its survival rate and disrupt its development.

## Effects on Pollinators

Honey bees, bumble bees, wasps, butterflies, flies etc. are some common pollinators. Changing climate has clearly declined the population abundance, geographic range and pollination activities of important pollinator species like bees, moths and butterflies considerably. Temperature and water availability have been found to affect profoundly the critical events like flowering, pollination and fruiting in the life cycle of plants. The quality and the quantity of pollination have multiple implications for food security, species diversity, ecosystem stability and resilience to climate change.

## Mitigation Strategy

**Adaptation and Mitigation Strategies for Pest Management in a Changing Climate:** Climate change is widely expected to make pest infestations more unpredictable and increase their geographic range. The adaptive capacity of agricultural production systems will depend on several biological, economic and sociological factors. The ability of local communities to adapt their pest management practices will depend on their physical, social and financial resources. With climate change and the acceleration of global trade, uncertainties and frequency of occurrence of existing and new pests will increase. Increasing the ability to adapt rapidly to disturbances and climatic changes will, therefore, become all the more important. Potential adaptation strategies have been identified to reduce the risks of spreading new pests and diseases and to mitigate the negative impacts of existing pests.

The most commonly mentioned strategies are modified integrated pest management (IPM) practices, monitoring climate and insect pest populations and the use of modeling predictions tools.

**Modified Integrated Pest Management (IPM) Practices:** In the context of sustainable agriculture, the emphasis in plant protection is given on preventive or indirect measures, which must be fully exploited before control or direct measures are applied. Direct pest control tools are to be used as a last resort when economically intolerable losses cannot be prevented by indirect measures.

Effectiveness of pheromones, insecticides, biocontrol agents like parasitoids, bacteria, fungi will be reduced, new biotype will develop. In this context, the focus should be on the development of new pest management strategies and possible new formulations of insecticides, attractants and repellents. There is an urgent need to better understand the effects of global warming on the performance of many synthetic insecticides, their persistence in nature and also the development of resistance to certain insecticides in pest populations. Therefore, it is necessary to consider the use of efficient biological control agents or the introduction of pest-resistant crop varieties obtained through conventional genetic breeding or genetic engineering or mutation research. This requires the development of new agricultural practices, the introduction of new crops species and the application of the principles of integrated pest management to contain the spread.

**Monitoring Abundance and Distribution:** One of the most important prerequisites for determining whether climate change is altering the population dynamics of insect pest species is the access to long-term data. These data will help in understanding how climate change is affecting insects over the years. Effective monitoring and management systems are needed to prevent invasive species from becoming an economic pest in new geographic regions. Therefore, adaptive responses in both pest management and biosecurity will be required.

Currently available pest management strategies such as detection, prediction, physical control, chemical control and biological control could be intensified to control pests in response to climate change. Due to the trans boundary nature of many insect pests, a global management approach is needed for effective monitoring and risk assessment. A global system for sharing information between regions, including important information on insects, invasive alien species, diseases and ecological conditions, including weather data, is also needed.

Therefore, it is important to improve cooperation between countries and regions, including national, regional and global organizations.

**Climate Forecasting and Model Development:** It is impossible to design a priori climate change adaptation strategies for specific national or global climate change scenarios because of the heterogeneity of changes in average temperature and other climate parameters around the world. Adaptation strategies to climate change must be one of the components of an integrated strategy that takes into account, all aspects of agricultural production.

## Effect of Climate Change on Mosquito Population and Changing Pattern of Some Diseases Transmitted by Them

The maturity of mosquitoes from larvae to adult, their endurance, biting frequency and nourishment of pathogen are temperature dependent. Rainfall, being another significant climatic factor, is also decisive for construction and perseverance of mosquito breeding sites. Moreover, environmental changes like deforestation could also amplify local temperatures in the highlands enhancing the capacity of different mosquito species. This experimental data will be supportive in facilitating the understanding of the impact of climate change on three important mosquito vectors *Anopheles, Culex*, and *Aedes* (Chandra and Mukherjee 2022).

## GMO Mosquitoes

GMO mosquitoes are mosquitoes that have been implanted with a gene or bacteria which was not originally present or naturally occurring in the insect. In one case, the implant in question is a self-limiting gene that disrupts the normal processes of mosquitoes' offspring. These offspring will, in turn, not survive to adulthood. These lab-reared *Aedes aegyp*ti mosquitoes would be released into the wild to mate with the wild population-where their offspring's inability to grow to adulthood would lower the population of mosquitoes. These are also often referred to as transgenic mosquitoes. Alternatively, scientists have also created an infertile male mosquito which, when sent into the wild, breeds with females which then lay unfertilized eggs. These mosquitoes also contain a heritable gene which gives them a fluorescent mark, so that researchers can see the difference between the GMO mosquitoes and wild ones.

Another form of GMO mosquitoes has been implanted with bacteria called Wolbachia to fight dengue fever. Wolbachia stops the dengue virus from replicating inside the mosquito, making it impossible for dengue to pass on to humans. Scientists hope that the Wolbachia mosquitoes will then mate with the wild population, creating mosquitoes that are not able to carry and transmit dengue. The Wolbachia bacterium is much too large to fit in the mosquito's proboscis-the probing mouthpart used to drink blood- and, therefore, has no chance of being transmitted into humans.

**Why GMO Mosquitoes?**

The main reason GMO mosquitoes are being developed is to stop the spread of infectious diseases without the use of potentially harmful chemicals. In the 1950's, for example, DDT was used to eradicate the *A. aegypti* mosquito during an outbreak of Malaria. Few mosquitoes were left, but bred so rapidly that they returned to their normal population numbers once again. The chemicals were also known to kill off beneficial insects as well. All these years later, the environment is still recovering from the side effects of using DDT – particularly with bird populations like the Bald Eagle and Peregrine Falcon, which were devastated by the use of this chemical.

**Research Needs on Entomology**

As described above, the conventional research with insecticides, parasites, predator, fungus and Bt gene for controlling insect pest will be gradually obsolete. Therefore, there is dire need for new dimension of research. Some of the approaches are indicated below:

- Look for alert pheromone as existing in aphids.
- Develop technique of reducing fecundity of pest insects.
- Sustainable sterility development technique for pest insects.
- For shrubs and trees, devise technique of injecting insecticides, fungicides and fungal spores to contaminate cell sap to control disease and insects (specially burrowing insects like buprestid and lamellicorn beetles).
- Identify causes of resistance of plants to insects and diseases and incorporate those through collaborative research with plant breeders.
- Research on insect genetics and molecular biology to decode mitochondrial DNA sequence to change the trait of silkworm, honeybees and some prominent predators and parasites.
- Coccinellid beetles are more tolerant to global warming because of their potential of changing color. So, for aphid control, coccinellid beetles have a better potential under global warming.

- Mobility of sperms of male insect will be reduced due to global warming. Research is needed to protect these for beneficial insects.
- Work on fungus eating arthropods called "Springtail" to control fungal disease. But be careful not to use for compost making ecosystem/arrangement.
- While different aspects of pesticides are tested for efficacy before approval for commercial use, consider level of their degradation through sunlight, UV light and different level of temperature, since many pesticides have been proved to be degraded by sunlight and high temperature.

Different universities and institutes in Bangladesh are working on pest management based on the experience and interest of scientists, and available infrastructure and resources. There is no master plan on pest management research strategy. This can be possible if a "Pest Management Institute" is established where a national Master Plan will be formulated and all researchers in the country will formulate research program based on that Master plan. In Germany, there is Institute of Plant Disease (Institut fuer Pflanzenkrankheiten) at the University of Bonn, Germany established 50 years ago.

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