# Ameliorating the Impact of Climate Variability on Pesticide Dynamics and Efficacy

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## Abstract

This review on "Impact of Climate Change on Pesticide Efficacy" aims to explore the intricate relationship between climate change and the effectiveness of pesticides in agricultural practices. Climate change has emerged as one of the most significant global challenges, disrupting weather patterns and altering ecosystems. These changes pose serious implications for pest dynamics, distribution, and behavior, thereby directly influencing the performance of pesticides. This review will delve into the multifaceted factors that contribute to the changing dynamics of pesticide efficacy under the influence of a warming climate. It will review the recent scientific research and empirical evidence, analyzing the effects of rising temperatures, altered precipitation patterns, and changing humidity levels on pests and their interactions with pesticide applications. Additionally, the review will further examine how climate-induced changes in plant physiology and crop characteristics impact the overall efficiency of pest control measures. The review will also address the importance of developing adaptive agricultural practices and integrating climate-resilient pest management strategies. This involves exploring the potential of eco-friendly and biologically-based pest control approaches to mitigate the adverse effects of climate change on pesticide efficacy. It will elaborately discuss valuable insights into sustainable practices and novel technologies aimed at improving pest control under changing climatic conditions.

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## 1.1. Introduction

Climate Change is the long-term alteration in global weather conditions and patterns, as well as the associated environmental factors, usually caused by human activities like burning of fossil fuels, deforestation and other industrial processes (The Inter-governmental Panel on Climate Change, 2014). These variables persist for an extended period (typically decades or longer), which coincides with an increased likelihood of the intensity of extreme climate events, such as drought and flooding (Akinsanya *et al.*, 2016; Singh *et al.*, 2019). Climate change alters soil properties such as moisture, temperature, pH, and texture, affecting not only earthworm communities but also all life interacting with the soil environment (Singh *et al.*, 2019).

The Inter-governmental Panel on Climate Change (IPCC) has extensively studied and documented the impact of Climate Change on various aspects of the Earth's systems. One of the major impacts of Climate Change is global warming, which is primarily driven by activities that promote greenhouse gas emissions into the atmosphere (National Aeronautics and Space Administration, 2021). The greenhouse effect is a natural effect that is accelerated by anthropogenic activities such as deforestation, burning of fossil fuels, and agricultural practices. Deforestation and agriculture can go hand in hand because, according to Bennett (2017), 25% of the world's greenhouse gas emissions come from deforestation through practices such as logging and burning of biomass, thus making agriculture one of the most important causes of deforestation. Several studies have also confirmed that climate change affects soil dynamics, which in turn affects pesticide toxicity to earthworms (Kaka *et al.*, 2021).

The burning of fossil fuels, such as coal, oil, and natural gas, releases carbon dioxide ($CO_2$) and other greenhouse gases into the atmosphere, trapping heat and leading to a rise in global temperatures. The ability of greenhouse gases such as carbon dioxide, methane, nitrous oxide, and fluorinated gases to capture heat from the sun's energy causes the greenhouse effect (Kweku *et al.*, 2018). As a result of these events, more of the sun's radiation is trapped in the atmosphere, causing global warming. According to Olivier and Peters (2020), global $CO_2$ emissions increased by 1.4, 2.4, and 0.9% in 2017, 2018, and 2019 respectively. This phenomenon has been observed through temperature records and monitoring of various climate indicators, such as melting glaciers, rising sea levels, and changing precipitation patterns (NASA, 2021).

Climate change is one of the most pressing global challenges of our time, and its impacts are far-reaching, affecting various aspects of our environment and society. The impact of rising temperatures, changes in precipitation patterns, and extreme weather events can affect the performance of pesticides, potentially compromising pest control efforts and agricultural productivity. Understanding these interactions between climate change and pesticide efficacy is crucial for developing adaptation strategies and sustainable agricultural practices that can mitigate these adverse effects and ensure food security in a changing world.

The IPCC's Sixth Assessment Report, released in March 2023, provides an overview of the state of knowledge on the science of climate change, emphasizing new results since the publication of the Fifth Assessment Report in 2014. It is based on the reports of the three working groups of the IPCC on physical science; impacts, adaptation, vulnerability; and mitigation. Understanding the impact of climate change on pesticide efficacy is vital for sustainable agriculture and food security. Many pesticides are equally useful in the control of disease vectors, such as the female anopheles mosquito, which transmits the malaria parasite, one of the greatest causes of death in Africa (WHO, 2023). It is therefore essential to explore and comprehend the various ways in which climate change can influence pesticide efficacy, in order to employ appropriate mitigation strategies to overcome these effects (IPCC, 2021).

Climate change has a significant impact on agricultural production and on agricultural insect pests. Changes in climate can affect insect pests in several ways; they can result in an expansion of their geographic distribution, increased survival during over-wintering, increased number of generations, altered synchrony between plants and pests, altered inter-specific interaction, increased risk of invasion by migratory pests, increased incidence of insect-transmitted plant diseases, and reduced effectiveness of biological control, especially natural enemies. This may result in a serious risk of crop economic loss, as well as a challenge to human food security. As a major driver of pest population dynamics, climate change will require adaptive management strategies to deal with the changing status of pests. Several priorities can be identified on the effects of climatic change on agricultural insect pests. These include modified integrated pest management tactics, monitoring climate and pest populations, and the use of modelling prediction tools (Prakash, 2023). Each element of climate change influences the growth of biological members of an ecosystem. As per the IPCC definition of climate change, the major parameters to look out for are the rise in global temperature, the elevation of carbon dioxide concentration in the atmosphere, erratic rainfall, and changes in radiation (Jackson *et al.* 2011; Noyes *et al.* 2009). These changes have direct and/or indirect impacts on the living organisms in an agricultural ecosystem, including crops and their associated pests. Differential growth pattern in crops and weeds is expected due to climate change, and this may have more repercussions on weed management in general. Climate change projections propose a 2.4–6.4 °C increase in global temperature by the end of the twenty-first century (IPCC, 2007). With the increase in mean temperature, weeds following the evolutionary mechanisms expand their range into new areas. Under high temperatures, plants with $C_4$ photosynthesis pathways have a competitive advantage over $C_3$ plants (Yin and Struik 2008), and most weeds belong to the $C_4$ group. Also, an increased risk for the introduction of invasive weeds from the adjacent territories is expected in changing climate. Weeds have more competitive advantages over most crops both in biotic and abiotic stresses due to their physiological plasticity and superior flexibility in gene composition.

Activities by humans have caused global warming to increase by 1°C above pre-industrial levels, and this is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (IPCC, 2018). When comparing regional changes of the pre-industrial levels to the 1.5°C increase in global warming, it estimates extreme increased temperatures, increased heavy precipitation, and an increase in drought in many regions (IPCC, 2018). These predicted climate change events might have significant effects on the bioefficacy of pesticides. Climate change has been shown to have a significant impact on the toxicity of pollutants in soil by altering weather patterns and natural global cycles. Previous research has found that varying temperatures and moisture affect the bioavailability of pollutants in the soil. According to the IPCC report, the global temperature and other climate change drivers are becoming more severe and erratic; therefore, current research must consider environmental concerns related to climate change. The year 2019 was the second warmest year in 140 years, with an increase of 0.95°C (Olivier and Peters, 2020). Climate change also makes rainfall patterns more unpredictable, and this could lead to flooding and droughts. Both events can cause the soil moisture to become excessive (flooding) or minimal (droughts). Excess water can cause leaching in the soil, which will promote acidification and runoff from agricultural areas and mines, which can pollute nearby areas. Droughts can reduce the vegetation cover, resulting in increased soil erosion (Kaka *et al.*, 2021). Additionally, Shakhramanyan et al. (2013) reported an increase in pesticide usage due to climate change, thus raising external environmental and health costs. Climate change also influences herbicide, insecticide, and fungicide use through changes in their effectiveness and persistence. Climate changes can increase pest and crop disease incidence as well as crop susceptibility to disease (Van Maanen and Xu,2003). Increased atmospheric $CO_2$ can enhance weed growth (Wolfe *et al.*, 2008) and increase weed tolerance to herbicides (Ziska and McConnell, 2016). Some studies indicate that new chemicals may also need to be developed because the crop tolerance to chemicals may be reduced by climate change (Dixon *et al.*, 1993). However, Juroszek and Von (2013) have reported that some cropping practices, such as rotating crops and altering cropping dates, can lessen the climate change pest effect.

The presence of pesticides can also have significant effects on food web stability and the relative abundance of predator and prey species (Quintana *et al.*, 2018). Also, pesticide risks could significantly vary over time, becoming critical in some periods of the year due to interactions with other natural or anthropogenic stressors related to global climate change (Duchet *et al.*, 2010). The last report by the Inter-governmental Panel on Climate Change has predicted a temperature increase of up to 5.6 degrees for the Mediterranean region by the end of the 21st century, which is accompanied by a decrease in annual precipitations and an increasing occurrence of extreme events such as severe droughts and heat waves (Ali *et al.*, 2022). Although some authors have found that climate change could notably influence the environmental fate and toxicity of pesticides (Arenas-Sánchez *et al.*, 2019; Vilas-Boas *et al.*, 2021), others indicate lower side-effects in water bodies due to increasing bio-degradation (Willming and Maul, 2016). The beneficial effect of warming on pesticide dissipation rates could be offset by an increase in the occurrence of agricultural pests. In fact, several studies show that under a climate change scenario, some agricultural pests could spread beyond their original distribution areas (Eitzinger *et al.*, 2013) and become more prevalent in a higher number of agricultural crops (Noyes *et al.*, 2009). Therefore, it is expected that many farmers will increase pesticide dosages per cropland area in regions with a significant increase in temperature or precipitation (Hader *et al.*, 2022). Climate Change affects pesticide exposure patterns and pesticide management, which can result in an increase or decrease in pesticide dosages given the prevalence of agricultural pests.

Reviewing the impact of climate change on pesticide efficacy is very important, especially at a time when food security is a serious issue of national and global concern due to the increase in population globally; this will help to understand how changing climatic conditions, can affect the potency of pesticides in controlling pests, diseases, and weeds in agricultural systems and also proffer solutions to the global threat on food security.

### 1.2. Pesticides and Pesticide Efficacy

Pesticides are chemical substances or mixtures used to control, prevent, destroy, or repel pests, including insects, weeds, fungi, and rodents. They are commonly employed in agricultural, industrial, and residential settings to protect crops, livestock, and human health from the negative impacts of pests (EPA, 2021). Pesticides play a crucial role in modern agriculture by aiding the control of pests, diseases, and weeds to enhance crop yield and protect agricultural investments. However, the effectiveness of these pesticides can be significantly affected by changes in climate patterns, such as temperature, precipitation, and extreme weather events. The scope of pesticides extends beyond agricultural applications and also includes their use in public health programs, such as vector control to combat disease-carrying insects like the tsetse fly, which transmits the disease vector, or trypanosomes, causing trypanosomiasis in humans and animals. Moreover, pesticides are utilized in residential settings to manage pests that pose threats to human health or cause damage to structures and properties (EPA, 2021).

Pesticide efficacy refers to the ability of a pesticide to effectively control or manage pests, such as insects, weeds, fungi, or other organisms that can damage crops, plants, structures or human health. It is a measure of how well a pesticide performs in achieving its intended purpose, which is to reduce or eliminate the target pests and mitigate the damages they cause. The scope of pesticide efficacy refers to the range of control that a particular pesticide has on target pests. This includes the ability of the pesticide to eliminate or reduce pest populations, prevent pest damage to crops, and provide long-lasting protection. The scope of efficacy can vary depending on factors such as the type of pest, the specific pesticide used, application methods, environmental conditions, and compliance with label instructions (Smith *et al.,* 2018). There was a general belief that some pesticides impart more toxicity to insect pests at higher temperatures (Noyes *et al.* 2009; Noyes and Lema 2015). However, it was found in a recent study by de Beeck *et al.* (2017) that at a higher temperature, chlorpyrifos degraded more easily, causing less mortality and less oxidative damage to insect pests. This is obvious due to the higher rate of hydrolysis of organophosphate pesticides at higher temperatures (Hooper *et al.*, 2013). Pesticides that undergo hydrolysis in the aqueous phase are mostly temperature dependent, as found in organophosphates, carbamates, synthetic pyrethroids, and sulfonylureas. Some pesticides also undergo extensive photodegradation under sunlight. The breakdown products of the pesticide degradation process can either be less toxic or, at times, more toxic than the original product (Pathok *et al.*, 2022; Ji *et al.*, 2020). Low soil moisture has also been linked to slower degradation of herbicides (Bailey, 2004). An increased temperature also favors the volatilization loss of pesticides (Otieno *et al.* 2013), increasing the risk of off-target movement and environmental contamination (Claudia, 2023). Microbial activities in soil also increase with the rise in temperature and moisture status, escalating the rate of degradation of pesticides caused by soil microbes. This scenario will cause repeated use of pesticides at higher application rates (Choudhury and Saha, 2020). Also, enhancement in pesticide volatility due to temperature rise could affect the effectiveness of pesticides against pests and thus increase application levels for pesticides (Noyes *et al.*, 2009). This rise in the use of pesticides may be in both quantity and scope of application (Koleva and Schneider, 2009). Also, soil temperature and moisture influence most characteristics, such as weight, cocoon incubation time, sexual maturity initiation, reproduction, and life span of healthy soil organisms (Uvarov *et al.*, 2011). The efficacy of a pesticide is typically evaluated based on several factors, including its ability to:

1. Kill or suppress the target pests: A pesticide should be able to directly kill the pests or significantly reduce their population to an acceptable level.
2. Provide residual or long-lasting effects: Pesticides with residual activity remain effective for an extended period, providing continued protection against pests.
3. Be target-specific: Ideally, a pesticide should have selective toxicity, meaning it primarily affects the target pests while minimizing harm to beneficial organisms, including humans, non-target animals, and the environment.

4. Penetrate or reach the target site: Pesticides should be able to reach the target pests, whether they are present on the surface, within plants, or in the soil.
5. Adhere to the target surface: Pesticides need to adhere to the target surface, such as plant leaves or soil particles, to ensure their effectiveness and prevent them from being easily washed away or degraded.
6. Withstand environmental conditions: Pesticides should remain effective under various environmental conditions, including temperature, humidity, rainfall, or sunlight exposure.
7. Be compatible with application methods: Pesticides need to work effectively with different application techniques, such as spraying, dusting, seed treatment, or soil application.

## 1.3. Factors Affecting Pesticide Efficacy

Several factors can influence the efficacy or effectiveness of pesticides. These factors can vary depending on the specific pesticide, target pest, application method, and environmental conditions. (Tabashnik *et al,* 2013). Some common factors that can affect pesticide efficacy include:

1. Pest Species and Life Stage: Different pesticides may be more effective against specific pest species or life stages (e.g., eggs, larvae, adults). Understanding the target pest's biology and life cycle is crucial in selecting an appropriate pesticide. (Tabashmik *et al,* 2013)
2. Application Timing: Proper timing of pesticide application is important to deduce the best period for application as well as ensure that the target pest is vulnerable and susceptible to the pesticide at that particular time. For example, some pesticides may be most effective when applied during a particular stage of the pest's development or at a specific time of the day (Teressa and Knolmar, 2013).
3. Application Rate and Method: Applying the correct amount of pesticide and using the appropriate application method is crucial for achieving effective pest control. Improper application rates can result in under-dosing or overdosing, both of which can reduce efficacy or cause other issues (Smith *et al.,* 2018).
4. Environmental Conditions: Various environmental factors can influence pesticide efficacy. Temperature, humidity, wind speed, and sunlight can affect pesticide stability, degradation, and movement. It is important to follow label instructions regarding environmental conditions for optimal efficacy (Tabashmik *et al*., 2013).
5. Formulation and Compatibility: Pesticides are available in different formulations (e.g., liquid concentrates, granules, powders) and may require mixing or dilution. Proper preparation of pesticides according to the label instructions and ensuring compatibility with other substances (e.g., tank mixtures) is essential for achieving the desired efficacy. (Bhakta, 2017).
6. Resistance Development: Pests can develop resistance to pesticides over time, rendering them less effective. Overuse or misuse of pesticides can also accelerate the development of resistance. Rotating between different chemical classes or using integrated pest management (IPM) strategies can help mitigate resistance issues. (Smith *et al*, 2018)
7. Adjuvants: Adjuvants are substances added to pesticide formulations to enhance their efficacy, such as spreaders, stickers, and surfactants. The use of appropriate adjuvants can improve pesticide coverage, absorption, and retention

on target surfaces (Tabashmik *et al.*, 2013).

8. Crop or Site Conditions: The type of crop or site where the pesticide is applied can affect efficacy. Factors such as crop stage, density, canopy structure, soil type, and presence of weeds or other non-target plants can influence pesticide effectiveness. (Tabashmik *et al.,* 2013).
9. Storage and Handling: Proper storage and handling of pesticides are crucial for maintaining their efficacy. Exposure to extreme temperatures, moisture, or sunlight can degrade pesticides. Following storage and handling guidelines provided by the manufacturer is essential (Bhakta, 2017)
10. Regulatory Compliance: Adhering to pesticide regulations and guidelines is important to ensure the efficacy and safety of pesticide use. Failure to comply with regulations can result in legal consequences and may compromise the effectiveness of pest control. (Teressa and Knolmar, 2023)

## 2.1. The Impact of Climate Change on The Ecosystem

Since World War II, pesticides have typically been synthesized from petroleum or petroleum by-products (Jungers *et al.*, 2022). ExxonMobil, ChevronPhillips Chemical and Shell all produce pesticides or their chemical precursors (Drugmand *et al.*, 2022). Many pesticides are also coated in microplastics, which are derived from fossil fuels, to ensure a more controlled release of the product (CIEL, 2022). Multiple pesticide corporations self-report high $CO_2$ equivalent emissions ($CO_2$ e) related to their operations. Top of Form

As nations seek to mitigate climate change and develop more sustainable agricultural systems, it is crucial to measure and reduce the GHG emissions associated with pesticide use. Some of these emissions result from the production, transportation, and field application of pesticides, while others result from pesticides' interactions with the environment after application. Virtually no studies calculate the GHG emissions of pesticide use over the full life cycle of the chemicals, which likely causes underestimates of true emissions. Research to date also omits the emissions associated with pesticide waste, such as obsolete stockpiles (stockpiles of pesticides that have expired, been made illegal to use or are otherwise unwanted) and their disposal through burning and other methods. The greenhouse gas emissions associated with pesticide use are linked to fossil fuel consumption during these processes. Importantly, 99% of all synthetic chemicals, including pesticides, are derived from fossil fuels (Drugmand *et al.*, 2022).

For instance, the GHG emission of glyphosate, the world's most popular herbicide, produces 31.29 kilograms of $CO_2$ emission per kilogram, while other pesticides produce more than 40 kilograms of $CO_2$ e per kilogram (Audsley *et al.,* 2009). These estimates of GHG emissions by pesticides only factor in the energy used to produce the active ingredients without considering the energy needed to formulate the pesticide products and the inert ingredients. More than 500 of these so-called inert ingredients are not known due to proprietary protections (Cox and Surgan, 2006), making it impossible to calculate energy requirements for the manufacture of pesticide products in their entirety. The transportation and application processes add to the GHG emissions associated with pesticide use. The farther a pesticide travels to its application site and the more times per season that a pesticide is applied, the greater the pesticide use emissions. Additional emissions result from the release of the pesticide into the environment and the pesticide's subsequent interactions with organisms in the soil and with the atmosphere. Some pesticides are themselves greenhouse gases. The fumigant sulfuryl fluoride (used to fumigate commodities during transport and storage) is a powerful greenhouse gas.

Pesticide application can produce greenhouse gases by emitting volatile organic compounds (VOCs). VOCs are compounds that easily volatilize into gases that react with nitrogen oxides (NOx) and UV rays to produce ground-level ozone (Martin, 2013). Ground-level or tropospheric ozone is a significant greenhouse gas that causes respiratory problems in people (USEPA,2022) and, according to the U.S. Department of Agriculture, causes more damage to plants than all other air pollutants combined (ARSUS, 2016). Studies have found that as much as 80 to 90% of applied pesticides may volatilize within a few days of application (Jiang *et al.*, 2015). Fumigant pesticides are typically associated with the most VOC emissions (Marty *et al.*, 2010). However, many other pesticides produce VOCs as well. Some of the major impacts of climate change on the ecosystem include:

### 2.1.1. Rising global temperatures

According to the Inter-governmental Panel on Climate Change (IPCC), global temperatures have been increasing at an unprecedented rate, with a clear human influence. The IPCC states that it is unequivocal that human influence has warmed the atmosphere, ocean, and land (IPCC, 2021). An increase in temperature will impact precipitation, which might impact soil pH. Also, an increase in precipitation can result in flooding, which can reduce the population of earthworms, which are very beneficial for soil health and ecosystem stability, by not giving juvenile earthworms enough time to develop into reproductive adults. Heat stress and changing rainfall patterns both decrease crop resilience to pests (Taylor *et al.*, 2018). Insects can sense changes that indicate plants are more vulnerable, such as higher plant surface temperatures, leaf yellowing, biochemical changes, and possibly even the sound waves produced when water columns in plant tissue break apart due to water stress (Dunn and Crutchfield, 2006). Increased temperatures are anticipated to result in more pesticide volatilization; thus, more pesticides will end up in our air, rather than on their application target (Noyes *et al.*, 2009). Volatilization is a key source of pesticide drift, which can cause pesticide poisoning for anyone exposed to the toxic vapor (Lee *et al.,* 2011).

### 2.1.2. Erratic precipitation patterns and flooding

Given that 80% of the world's cropland is rainfed, global crop yield is highly susceptible to changes in rain patterns (UNWWAP, 2009) and the increased pest pressures that can accompany changes in precipitation. This can result in increased pesticide use, economic losses, and potential environmental pollution.

**Figure 1.** The impact of excessive flooding on agricultural farmlands

### 2.1.3. Increased greenhouse gas emissions

Greenhouse gas emissions, primarily from burning fossil fuels and deforestation, are a major driver of climate change. The World Resources Institute (WRI) reports that global greenhouse gas emissions have risen steadily over the past century, with the highest levels in history recorded in recent years (WRI, 2021).

### 2.1.4. Melting ice caps and glaciers

The melting of ice caps and glaciers is a direct consequence of global warming.

**Figure 2.** Melting ice caps and glaciers resulting from global warming

The National Aeronautics and Space Administration (NASA) explains that the Greenland and Antarctic ice sheets have been losing mass, contributing to global sea level rise (NASA, 2021).

### 2.1.5. Rising sea levels

As a result of melting ice and thermal expansion of seawater, sea levels are rising. The United Nations Framework Convention on Climate Change (UNFCCC) warns that the global sea level has risen by about 20 cm since the start of the twentieth century, and the rate of sea-level rise has accelerated in recent decades (UNFCCC, 2021).

### 2.1.6. Extreme weather events

Climate change is intensifying extreme weather events, such as hurricanes, droughts, and heatwaves. The National Oceanic and Atmospheric Administration (NOAA) states that rising temperatures are causing more frequent and severe heat waves, heavy rainfall events, and droughts in many parts of the world (NOAA, 2021).

**Figure 3.** Fragmentation of agricultural farmlands due to excessive drought conditions

### 2.1.7. Impacts on ecosystems and biodiversity

Climate change is disrupting ecosystems and threatening biodiversity. The World Wildlife Fund (WWF) states that the rising temperatures and changing precipitation patterns are causing shifts in ecosystems, leading to the loss of habitats and endangering many species. World Wildlife Fund (WWF, 2021). Floods resulting from excessive and unpredicted rainfall patterns can cause massive changes to the soil (Zhang *et al.*, 2015) by over-saturation, and this can result in a lack of oxygen in the soil, resulting in hypoxia, although the flood plains contain sediments which are very nutrient-rich making them some of the most productive ecosystems around the world (Tockner and Stanford, 2002). The diffusion and oxygen availability of the soil is reduced during flooding, resulting in reduced soil nutrient availability since decomposition processes are halted (Singh *et al.*, 2019). Also, anaerobic conditions occur in flooded soils, which will significantly affect the composition of soil food webs, microbial biomass, and soil microbial community structure (Plum, 2005; Unger *et al.*, 2009). Plum (2005) stated that flooding reduced the abundance, biomass, and diversity of all groups of soil organisms in grasslands. Higher soil moisture will allow leaching to occur more easily, promoting soil acidification. Reducing the nitrogen cycles by lowered temperatures will reduce the ecosystems' ability to sequester nitrogen, resulting in more acidification (Rengel, 2011). When precipitation is higher, it accelerates the leaching of cations, further aggravating acidification (Meng *et al.*, 2019).

## 3.1. Impact of Climate Change on Pesticide Efficacy

Scientists predict that climate change will negatively affect certain natural enemies of insect pests (also referred to as beneficial), further increasing crops' susceptibility to insect pest damage. For instance, climate change could cause insect pests to migrate to new areas where their natural enemies may be unable to follow, or the synchronization between the life cycles of pests and their natural enemies may be disrupted (Cho and Ishii, 2021). Pesticide applications are known to be harmful to beneficial organisms that control pest populations and predicted increases in pesticide applications would further reduce these beneficial populations. Researchers have also predicted that changing environmental conditions, such as $CO_2$ and temperature increases, will likely increase weed pressures in cultivated crops. Weeds are more likely to be resilient and better adapted to climate change effects than cultivated crops because they have more diversity in their gene pool and a greater ability to physiologically acclimate to different environmental conditions (Varanasi *et al.*, 2016). Climate change is also anticipated to introduce weeds to new regions and shift the composition of regional weed species, particularly favoring invasive species (Peters *et al.*, 2014). Expected increases in herbicide applications would also increase the prevalence of herbicide-resistant weeds (Peters *et al.*, 2014). These factors suggest that weeds will have an increased ability to outcompete agricultural crops in many regions, leading to declining yields.85 Researchers have observed that certain climatic changes affect different pests in different ways.

Therefore, specific regional climatic impacts will have a significant influence on which pests become more prevalent, and more comprehensive research is needed to predict effects for each specific region, crop and pests. However, certain agricultural system shifts, like diversifying our agricultural systems, could serve as universal solutions since they increase ecosystem resilience and, therefore, agricultural resilience to climate change, regardless of region (Lin, 2011). Climate change will likely increase the movement of pesticides away from their intended targets, polluting the environment and endangering public health. Climate change promotes the distribution and abundance of insect pests, and thus, it favors insects compared to crops. The etiology of any plant disease suggests that the proliferation of fungi and bacteria is governed by wet conditions as it promotes germination, spread, and activity of spores. However, warm and dry conditions can also positively influence plant resistance, resulting in a reduced fungicide requirement. Nevertheless, an increased plant disease coupled with physiological plant stress is expected to enhance host susceptibility and, thus, pesticide dependency (Choudhury and Saha, 2020). Smaller pests, such as aphids, mites or whiteflies, can be washed away during intense precipitation (Pathak *et al.*, 2012). In areas that might experience more periods of prolonged precipitation, plant fungal and bacterial diseases are likely to become more common (Sutherst *et al.*, 2011). The following are some ways in which Climate Change can affect the efficacy of pesticides:

### 3.1.1. Increased Metabolic and Reproductive Rates

Temperature is a fundamental factor affecting the performance of pesticides. Some pesticides are designed to work within specific temperature ranges. Higher temperatures may accelerate the metabolic rate of pests, leading to increased feeding and reproduction rates. This could potentially require higher pesticide application rates or more frequent treatments to achieve effective pest control.

**Figure 4.** Higher temperatures and humidity increase metabolic and reproductive rates in pests

The increase in pesticide dosages due to the higher prevalence of agricultural pests is going to increase the ecological risks for aquatic organisms in Mediterranean coastal wetlands (Martínez-Megías *et al*., 2023). In addition to decreasing crop resilience, higher global temperatures will likely stimulate a general increase in the rate of insect development and population growth in certain regions (Taylor *et al.,* 2018). Rising temperatures and shifts in moisture levels can also increase or shift insect pests' geographic range and their ability to survive through the winter (Skendzic et al., 2021). Researchers have predicted that rising $CO_2$ and temperature will accelerate insect pests' metabolism and consumption, ultimately leading to declining crop yields (Tonnang *et al*., 2022). Changes in temperature level might influence the insect incubation period and extension of the vector transmission season.

### 3.1.2. Decline in Activity/Efficacy and Bioavailability

If the temperature rises beyond the optimal range, the efficacy of certain pesticides may decline. Climate change variables, especially temperature and soil moisture, significantly affect the bioavailability of pesticides in the soil as well as the growth and reproduction of healthy soil species (Kaka *et al*., 2021). Climate change can alter precipitation patterns, which can directly influence the effectiveness of pesticides.


**Figure 5.** Increased temperature and moisture increases pest infestation while reducing pesticide efficacy

Excessive rainfall and increased humidity may lead to pesticide runoff and leaching, reducing their concentration and effectiveness in the target area. Similarly, changes in rainfall patterns can affect the distribution and activity of pests, potentially reducing the effectiveness of pesticides (NOAA, 2021). Excessive heat and dry conditions can also lead to faster evaporation of sprays, reducing their effectiveness (Smith and Johnson, 2019).

### 3.1.3. Environmental Contamination and Unstable Environmental Conditions

Floods resulting from excessive and erratic rainfall patterns can also transport pesticides into non-target areas, leading to environmental contamination. An increase in severe rain events is expected to increase pesticide loss to our waterways, with one study showing concentrations of pesticides in waterways to be 84–2100% higher after 100-year storms as compared to two-year storms (Chiovarou and Siewicki, 2008). Increased wind speeds and erratic precipitation patterns can affect spray drift, causing pesticides to disperse away from the target area. The role of pesticides in GHG emissions is infrequently addressed, and farming solutions like agroecology that would reduce their impact are rarely considered. For example, certain practices labeled climate-smart, such as no-till, often rely heavily on synthetic herbicides to control weeds on conventional farms and can lead to increased weed resistance to herbicides (Huggins and Reganold, 2008). Climate change-induced weather events can disrupt the timing and scheduling of pesticide applications. Unpredictable weather patterns can make it challenging for farmers to determine the optimal timing for spraying pesticides, as the pests' life cycles and behavior may change due to shifting weather patterns (Terresa and Knolmar, 2023).

### 3.1.4. Altered Pest Dynamics and Reduced Efficiency of Petsicide Applications

Climate change can alter the life cycles and behavior of pests. Warmer temperatures can accelerate the development and reproduction of pests, leading to more rapid population growth. Changes in precipitation patterns can also impact the availability of food and water sources for pests. These alterations in pest dynamics can affect the timing and frequency of pesticide applications, making it more challenging to control pests effectively (Bhakta, 2017).

**Figure 6.** Increase in pest infestation due to altered dynamics

Climate change can affect the distribution and abundance of pests. Rising temperatures and changing rainfall patterns can create more favorable conditions for certain pests, leading to increased infestations. Conversely, some pests may decline in certain regions due to unsuitable conditions. Pesticides that were effective in the past may become less efficient or ineffective against new pest populations (Smith and Johnson, 2019). Climate change can result in the expansion or contraction of pest and disease ranges. As a result, pests that were previously absent or less problematic in certain areas may become more prevalent. This can create new challenges for pest management, as different pest species may have varying susceptibilities to available pesticides (Smith and Johnson, 2019). Rising temperatures and changing rainfall patterns can affect the timing and intensity of pest outbreaks, making it challenging to apply pesticides effectively

(Johnson and McNutt, 2020).

### 3.1.5. Development and Dominance of Resistant Species

Increased pest resistance refers to the ability of plants or crops to withstand and/or repel attacks from pests such as insects, pathogens, and weeds. It can be achieved through various methods, including traditional breeding techniques, genetic engineering, and the use of biotechnology (Smith and Johnson, 2019). Prolonged exposure of pests to certain pesticides can lead to the development of resistance.

**Figure 7.** Development of resistance prevails, leading to the thriving of human disease vectors

Climate change can exacerbate this issue by favoring the survival of resistant pests. For example, if a particular pest population has individuals with genetic resistance to a pesticide, and the climate becomes more favorable to their survival, those resistant individuals will have a higher chance of reproducing and passing on their resistance genes to future generations. This can reduce the efficacy of pesticides over time, as the resistant pest populations become more dominant (Tabashnik *et al.,* 2013).

### 3.1.6. Impacts on Human Health and Beneficial Organisms

The most obvious external costs ignored by industrial agriculture are associated with human health impacts15, 16 and the degradation of ecosystem services such as clean air, water and healthy soil (Power, 2010). Health impacts from exposure to hazardous pesticides include acute illnesses such as skin rashes, gastrointestinal and respiratory illnesses, and central nervous system problems (Thundiyil *et al*., 2008; Starks *et al*., 2012).

In addition, pesticide exposure is associated with many chronic diseases, including cancers, reproductive and developmental disorders and long-term neurological dysfunction (USEPA, 2022). Neonicotinoids, a type of insecticide, have received public attention due to their significant harm to pollinators like honey bees (Christen *et al.*, 2018; Colin *et al.*, 2019). Honey bees play essential roles in pollinating agricultural crops and are responsible for about $15 billion in added crop value in the U.S. per year (USFDA, 2018). Soil invertebrates are crucial in creating structure and aeration in soils and in preventing soil compaction, roles that help soil retain water and perform other desirable functions (Gunstone *et al.*, 2021). Climate change affects beneficial organisms, such as natural predators or parasites of pests. These organisms play a crucial role in naturally regulating pest populations. Changes in temperature, rainfall, or other climate factors can disrupt the balance between pests and their natural enemies, potentially reducing the efficacy of natural pest control methods. In turn, this may increase the reliance on pesticides to manage pest populations (Prokash, 2014).

Also, an increase in rainfall due to climate change can result in soil loss and soil erosion by increasing sedimentation in streams and reservoirs (Patil and Lamnganbi, 2012). This soil loss will have detrimental effects on soil organisms as well as soil functions in an ecosystem. Once these functions are disrupted, changes in the environment can occur. The abundance of earthworms usually increases when climatic conditions are favourable, such as when the temperature is moderate, and the soil moisture content is higher (Phillips *et al.*, 2019). This abundance tends to decrease in colder climates, where the soil moisture content is lower (Walsh and Johnson-Maynard,2016).

### 3.1.7. Changes in Pesticide Degradation Rates

Climate change can influence the rate at which pesticides degrade in the environment. Higher temperatures and increased UV radiation can accelerate the breakdown of certain pesticides, reducing their persistence and efficacy. Conversely, in some cases, climate change may slow down degradation processes, leading to prolonged pesticide residues and potential environmental risks (Smith *et al.*, 2018).

### 3.1.8. Inhibition of Pesticide Absortion and Increase in Pest Infestation

Water stress in plants as a result of drought conditions can hinder pesticide absorption and translocation within the plant tissues, compromising their efficacy. Drought conditions can weaken plants' natural defenses against pests, and changes in plant biology due to drought may attract pests (Skendzic *et al.*, 2021). Furthermore, drought conditions may lead to increased pest pressure as water-stressed plants become more susceptible to infestations. Climate Change is projected to increase the frequency and intensity of extreme weather events, such as hurricanes, storms, and floods. These events can have severe implications for pesticide efficacy. The soil environment is affected directly and indirectly by drought (Coyle *et al.*, 2017). The deficiency of precipitation or drought does not immediately affect the deeper soil layers but will reduce the water content of the upper soil layer relatively quickly (Nepstad, 2002). The movement of soil organisms is inhibited by reduced soil water content, which hardens the soil (Anh *et al.*, 2014) and diminishes the extent of the water film (Coleman *et al.*, 2018). The reduction of vegetation cover by drought can cause increased temperatures, an altered microclimate on the soil surface, and reduced resource availability (Franklin *et al.*, 2016). The biological activity and earthworm diversity of soils are reduced through increased soil temperature both directly and indirectly. The frequency and significance of droughts are increasing around the world (Dai, 2013).

## 4.1. Mitigating the Impact of Climate Change on Pesticide Efficacy

Mitigating the impact of climate change on pesticide efficacy is crucial to ensure effective pest management strategies in agriculture as well as food security (Smith *et al*., 2019). Farming systems that do not rely on the use of synthetic pesticides, such as those based on agroecological principles or diversified organic farming, can reduce GHG emissions and increase carbon sequestration (Lori *et al*., 2017). They also increase farm resilience to climate change and pests by enhancing many ecosystem services such as water quality and availability to crops, soil health, crop resilience to pests and disease, and greater pollinator and natural pest control resources (Palomo-Campesino *et al*., 2018). Utilizing ecological pest and crop management practices reduces the need for petroleum-derived pesticides and fertilizers (Wezel *et al*., 2014) and, therefore, reduces associated emissions of greenhouse gases.

However, the reduction of synthetic pesticide use has been omitted from climate change solutions so far, while synthetic pesticide use has been ignorantly presented as a climate change mitigation strategy by industrial agriculture interests. Executive Summary Winter 2022–2023. Scientific evidence indicates that pesticides contribute significantly to greenhouse gas emissions while also making our agricultural systems more vulnerable to the effects of climate change. Importantly, 99% of all synthetic chemicals, including pesticides, are derived from fossil fuels, and several oil and gas companies play major roles in developing pesticide ingredients (Drugmand *et al*., 2022). Research has also revealed that the manufacture of one kilogram of pesticide requires, on average, about ten times more energy than one kilogram of nitrogen fertilizer (Audsley *et al*., 2019). Like nitrogen fertilizers, pesticides can also release greenhouse gas emissions after their application. Fumigant pesticides have particularly been shown to increase nitrous oxide production in soils seven to eight-fold (USEPA, 2022a). Many pesticides also lead to the production of ground-level ozone, a greenhouse gas harmful to both humans and plants (USEPA, 2022b; ARSUS, 2016)). Some pesticides, such as sulfuryl fluoride, are themselves powerful greenhouse gases, having nearly 5,000 times the potency of carbon dioxide (Muhle *et al.,* 2009).

**Figure 8.** The application of synthetic pesticides greatly contribute to greenhouse gas emission

Meanwhile, climate change impacts are expected to lead to increases in pesticide use, creating a vicious cycle between chemical dependency and intensifying climate change. Research has shown that the declining efficacy of pesticides, coupled with increases in pest pressures associated with a changing climate, will likely increase synthetic pesticide use in conventional agriculture (Choudhury and Saha, 2020). An increase in pesticide use will lead to greater resistance to herbicides and insecticides in weeds and insect pests while also harming public health and the environment. The effects of higher synthetic pesticide use will disproportionately impact populations already under stress from a wide range of climate change effects, such as extreme heat. The adoption of alternative agricultural systems, such as agroecological farming, minimizes or eliminates synthetic pesticide use while increasing the resilience of our agricultural systems to better withstand climate change impacts (Walts and Williamson, 2015; HLPE, 2019). Agroecology is a way of farming rooted in social justice that focuses on working with nature rather than against it. It relies on ecological principles for pest management, minimizing the use of synthetic pesticides while prioritizing the decision-making power of farmers and agricultural workers. Agroecology and diversified organic agriculture, when paired with social justice principles, have been shown to have significant climate benefits while supporting the health and rights of agricultural workers, indigenous people and rural communities.

Decisive action is also required to reduce agrochemicals' contribution to greenhouse gas emissions and improve the climate resilience of food and farming systems. To accomplish this, policymakers should establish measurable goals in climate policies to reduce synthetic pesticide use in agriculture; promote the transition to biodiverse, agroecological food and farming systems, such as by establishing and funding programs that provide increased technical assistance and incentives to farmers to adopt or continue these farming practices; and adopt regulations that uphold and promote the rights of groups most impacted by synthetic pesticide use in line with international laws. Transitioning our agricultural systems to those that uplift ecological and social justice principles will not only help mitigate climate change, but also reduce the negative health impacts of industrial agriculture. We can also collectively support the advocacy work of impacted communities and organizations fighting for more equitable and sustainable food and farming systems at the moment. Some of the ways we can mitigate the effects of climate change on pesticide efficacy include:

#### 4.1.1. Integrated Pest Management (IPM) Practices

Adopting IPM practices can help reduce reliance on pesticides. IPM involves combining multiple approaches, such as biological controls (e.g., natural enemies), cultural practices (e.g., crop rotation), and mechanical methods (e.g., traps) to manage pests effectively. By utilizing a variety of strategies, farmers can reduce their reliance on pesticides and minimize the impact of climate change on their efficacy. Integrated Pest Management (IPM) is the model of crop protection that has prevailed since its creation in the late 1950s. According to the Food and Agriculture Organization of the United Nations (FAO, 2021), "Integrated Pest Management (IPM) means the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM promotes the growth of healthy crops with the least possible disruption to agroecosystems and encourages natural pest control mechanisms (Kris, 2021).

#### 4.1.2. Improved monitoring and forecasting

Climate change can alter pest populations, their behavior, and geographical distribution. Enhancing monitoring and forecasting systems can provide early warnings and enable farmers to respond promptly. Advanced technologies like remote sensing, weather data, and pest modeling can assist in predicting pest outbreaks, helping farmers make informed decisions about pesticide application timing and dosage, to avoid huge agricultural losses (Kris and Wyckbuys, 2021).

#### 4.1.3. Research and development

Continued research and development are crucial to develop innovative and climate-resilient pesticides. These include exploring alternative pest control methods such as biopesticides derived from natural sources, pheromone traps, and genetically resistant crop varieties. Investing in research can lead to the discovery of more effective and environmentally friendly options (Akenson and Yates, 2019). Governments must significantly increase public investment in farmer-centered participatory research and technical assistance and direct financial support to enable farmers to transition to agroecological approaches.

### 4.1.4. Optimized Pesticide Application Techniques

Proper application techniques can optimize pesticide efficacy and minimize environmental impacts. These include proper calibration of equipment, ensuring correct dosage, and adequate timing of applications to correspond to the pest's life cycle. Using precision agricultural technologies like drones and variable-rate applicators can also help to improve accuracy and reduce pesticide use (FAO, 2020).

### 4.1.5. Education and Training

Providing education and training to farmers on climate change impacts and sustainable pest management practices is crucial. Farmers should be educated on the potential effects of climate change on pests and pesticides, as well as the importance of implementing sustainable practices. Training programs can help farmers adopt best practices and encourage the adoption of climate-smart pest management strategies (Claudia, 2023). Public investments should increase knowledge-sharing opportunities for farmers and agricultural workers to share their expertise and learn more about agroecological farm management practices; expand the capacity and quality of technical assistance providers in providing relevant support to farmers, both those practicing ecological farming, as well as those seeking to transition to an agroecological approach; direct financial assistance, especially to small-scale farmers and farmers of color, to adopt or continue agroecological farm management practices; and increase government procurement programs that incentivize the market growth of products grown on agroecological or diversified organic farms (Ahlgren *et al.*, 2008)

### 4.1.6. Policy, Regulation and Incentives

Governments and regulatory bodies play a significant role in mitigating climate change impacts on pesticide efficacy. They can implement policies that promote sustainable agricultural practices, incentivize the use of environmentally friendly pesticides, and regulate the use of harmful chemicals. Supporting and enforcing these regulations can contribute to reducing the overall impact of climate change on pesticide efficacy (Claudia, 2023). Also, the implementation of pesticide use reduction programs, such as the European 'Farm-to-Fork` strategy, is crucial to reduce pesticide risks (Martínez-Megías *et al.*, 2023). Without measurable targets as guideposts to governmental action, policies could result in government spending without achieving meaningful reductions in the use of synthetic pesticides generally, and highly hazardous pesticides in particular. We also recognize that countries around the world have a range of agricultural systems and pest management practices, and recommend that these goals be tailored to regional considerations in ways that prioritize the health and wellbeing of rural communities, the indigenous people, workers, and other historically oppressed populations to avoid a chemical-laden, industrial, agricultural system like we have today (Audsley *et al.*, 2009). Policies that protect workers' rights to health, safety and a living wage; outlaw and prevent abusive and harmful working conditions; grant an immediate pathway to citizenship for agricultural workers; protect their right to freedom of association; ensure secure land access and ownership for workers should be implemented and upheld.

### 4.1.7. Agroecological and Diversified Organic Farming Methods

The benefits of agroecological farming include the preservation of soil microorganisms, which serve a number of other important functions, such as building healthy soil and, by extension, healthy crops and increasing crop resilience (Sahu *et al*., 2019). They also regulate carbon and nitrogen cycles that control emissions of carbon dioxide, methane and nitrous oxide ($N_2O$) (Oertel *et al.,* 2016), better public health, improved food security and sovereignty, and enhanced biodiversity and social benefits, such as better cooperation between farmers and communities (Walts and Williamson, 2015; Anderson *et al*., 2020). Barriers that prevent farmers from transitioning to agroecological diversified farming practices must be addressed through government policies that support more secure land tenure, better access to capital during the transition, and market incentives (Esquivel et al., 2021; Carlisle *et al*., 2022). Public policy should support demonstrably effective, ecologically based practices that mitigate climate change while also making farms and rural communities more resilient as climate conditions change (NSAC,2012).

#### 4.1.8. Climate Adaptation Strategies

Implementing climate adaptation strategies on farms can help reduce the vulnerability of crops to pests and minimize the need for pesticides. This includes utilizing climate-resilient crop varieties, improving soil health, optimizing irrigation practices, and implementing agroforestry techniques. By building more resilient farming systems, farmers can better cope with the changing climate conditions and reduce reliance on pesticides (Akenson and Yates, 2019).

## 5.1. Conclusion and Future Perspectives

The effectiveness and persistence of herbicides, insecticides, and fungicides can be influenced by changes in climate. Climate change can have significant impacts on the efficacy of pesticides. Changes in temperature and precipitation patterns, as well as extreme climate events, can potentially affect the toxicity of pesticides. Additionally, climate change can lead to a decrease in environmental concentrations of pesticides due to increased volatilization and accelerated degradation. Therefore, it is important for policymakers and farmers to consider the potential impacts of climate change on pesticide use, and make useful policies that will promote proper adaptation and mitigation practices that will ensure the continued effectiveness of these pesticides. Government should adopt reasonable strategies to reduce pesticides as much as possible, in climate policies and provide improved technical assistance and incentives for farmers to minimize the use of synthetic pesticides. Climate action requires significant financial investments by governments and businesses. Industrialized countries, being major drivers of greenhouse gas emissions, should be seriously commitment to assisting developing countries to adapt properly and move towards greener economies. Farmers should be encouraged to, as much as possible, use non-chemical management methods on their farms, such as introducing beneficial insects and wild, native plants or using physical methods, including hand weeding, mulching, or setting traps, to reduce chemical use outdoors. Beneficial insects, like honey bees, which help to pollinate gardens, and ladybugs, which prey upon other nuisance pests such as aphids, can help to improve the health of a yard. The Kyoto Protocol, the signing of the Paris Agreement on climate change, and other initiatives set up to combat this effect globally should be effectively upheld (Kweku *et al*., 2018).

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