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Navigating Climate Change and Its Impacts on Parasitoids, Predators and Pollinators

Sushil Kumar

ASPEE College of Horticulture and Forestry, Navsari Agricultural University, Navsari, Gujarat (396 450), India

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Corresponding Author
Sushil Kumar
: saxenasushil2003@gmail.com

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Abstract

This review considers the numerous consequences in which climate change affects insect pest population, natural enemy and crop production. Direct effects of climate induced changes on insect physiology and behaviour; and biological interactions that may influence the interactions between pests and their natural enemies. These temperature fluctuations will be expected to change diurnal activity patterns and modify interspecific interactions and hence reduce the efficacy of natural enemies. Direct impacts are as a change in temperature, precipitation and carbon dioxide (CO_2) concentrations; indirect effects of changes in herbivore and competitor distributions; and changes to higher trophic level interactions, such as predation, parasitism and competition. Even climate change effects on natural enemies become more complicated with changes in the plant physiology by CO_2, temperature and moisture. Then, extreme weather events aggravate these complexities as they further make unpredictable interactions between crops, pests, diseases and natural enemies. Such unpredictability is a problem for current crop protection strategies and agricultural yield. This review is intended to highlight the need for adaptive pest control solutions for limiting the damages related with climate change, towards a sustainable agricultural production.

Keywords: Agricultural ecosystems, Climate change, Parasitoid, Plant-Insect interactions, Pollinators, Predators

Introduction

In recent years, the agriculture and horticulture sectors have encountered numerous challenges in meeting the escalating demand for food and nutritional security for a rapidly growing population. The ever-increasing food demands are forcing the scientists and the farmers to generate larger quantities of food from the diminishing arable land lands. Biotic and abiotic factors, environmental deterioration and greenhouse gas emissions have also contributed to making the situation worse (Abewoy, 2018).

Vegetable and fruit crops, such as cucumbers, tomatoes and strawberries, with high water content, were remarkable highly vulnerable to adverse climatic conditions, including heat-waves, drought and flooding. For instance, cucumbers are very sensitive to drought stress and it could adversely affect fruit quality and yield. Blossom drop and poor fruit setting are often observed in tomatoes when they are exposed to elevated temperatures and strawberries are highly susceptible to flooding, that can cause root rot and compromised crop productivity. These examples highlight the critical need for adaptive cultivation practices to lessen the impact of climatic stressors on these significant crops. Various researches have shown the multifaceted effects of climate change on crop growth, plant physiology and overall productivity (Fuhrer, 2003). Under specific conditions, plant productivity enhances positively with the elevated CO_2 concentrations in the atmosphere (Long *et al.*, 2004). Yet, high temperatures and water scarcity limit this positive response frequently. Research indicates that these multiple stressors reduce the productivity levels of fundamental grain crops together with other staple crops (Challinor *et al.*, 2005; Anwar *et al.*, 2007; Torriani *et al.*, 2007).

Furthermore, global warming has posed significant threats

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to integrated pest management practices. Climatic change conditions will probably reduce the performance of host plant resistance alongside genetically modified crops along with natural enemies, biopesticides and synthetic chemical pesticides. Studies indicate that climate change impacts along with elevating CO_2 levels will deeply influence the crucial relationships between horticultural plants with their diagnostic agents, such as pollinators and insect pests as well as pathogens and weeds (IPCC, 2007). Recent observations have already documented shifts in these interactions in certain regions. For instance, increased temperatures in parts of Southern Europe have led to earlier flowering in horticultural crops, resulting in temporal mismatches with pollinator activity, thereby affecting pollination efficiency. Similarly, warmer conditions in East Asia have been linked to the migration of pest populations, such as aphids and whiteflies, into previously cooler regions, heightening crop vulnerability. These examples underscore the need for region-specific researches to better understand and control the evolving dynamics of horticultural ecosystems under varying climatic conditions.

The influence of climate change on insect pest populations is intricate and can manifest both directly and indirectly. Direct effects involve changes in insect physiology and behavior, while indirect effects manifest through alterations in biotic interactions, including bottom-up and top-down trophic dynamics. Change in climatic conditions may also modify the transport and introduction pathways of invasive species. For instance, wind plays a crucial effect in the distribution and colonization of many insect species and projected increases in storm severity are likely to facilitate the spread and long-distance dispersal of invasive insect pests (Gutierrez and Ponti, 2014).

Insects and other arthropods, being heterothermic organisms, exhibit developmental rates that are closely influenced by environmental temperatures as well as other factors such as moisture and nutritional availability. In the short term, their phenology, population dynamics and abundance are governed by both weather conditions and interactions within their ecological food webs. Climate and interspecies interactions determine their average abundance and geographic distribution. Rising surface temperatures, altered precipitation patterns and increased atmospheric CO_2 levels are expected to directly and indirectly impact plant hosts, leading to substantial alterations in the distribution, abundance and extinction potential of numerous insect species.

Confronting these challenges necessitates a thorough understanding of the intricate relationships between climate variables, plant physiology and pest dynamics. Future research should prioritize identifying region-specific crop vulnerabilities, enhancing the thermal tolerance of crops and natural enemies and developing adaptive pest management strategies. The key areas for this investigation include breeding resilient crop varieties, optimizing planting schedules to maintain phenological synchronization between crops and their pollinators or natural enemies and designing integrated pest management systems that account for climate variability. These strategies are very much important to safeguard the food security and agricultural productivity against growing climate change threats and their development and acceptance. To fight the detrimental effects of climate changes and ensure the global food security, resilient agricultural practices, sustainable pest management strategies and adaptive crop varieties should be developed through a collective approach.

Greenhouse Gases

Three primary greenhouse gases that are accountable for climate change are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The utilization of energy via fossil fuel combustion generates the majority of our emissions. Fossil fuel consumption and deforestation along with land-use changes are the greatest producers of CO_2 emissions (Baumert *et al.*, 2009; Sthapit *et al.*, 2012). Climate Analysis Indicators Tool (2011) indicates that carbon dioxide causes approx. 77% of the global warming throughout a century period, thus becoming it the leading GHG.

The Global Warming Potential (GWP) of other GHGs is expressed in terms of carbon dioxide equivalent (CO_2-eq) that represents the warming effect of one molecule of CO_2 over conventional time period of 20 or 100 years (Choudhary *et al.*, 2015). Methane, with a GWP of about 23 CO_2-eq over 100-year timeframe, is a powerful greenhouse gas that released from livestock digestion, manure management, flooded rice cultivation, landfills, wastewater and other waste sources (Baumert *et al.*, 2009; Sthapit *et al.*, 2012). Emissions derived from livestock together with rice cultivation have increased because of rising agricultural activities, thus showing the urgent necessity for better strategies to reduce methane output and combat climate change. The greenhouse effect of nitrous oxide amounts to about 298 CO_2-eq during a century (Sthapit *et al.*, 2012) and it mainly comes from agricultural soil practices utilizing chemical fertilizers and farmyard manure. The sources that produce nitrous oxide emissions also include waste treatment facilities along with combustion of biomass materials (Baumert *et al.*, 2009).

Collectively, these three greenhouse gases account for around 99% of global warming during a century-long timeframe (Sthapit *et al.*, 2012). The global warming contribution by perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulfur hexafluoride (SF_6) remain limited even though these gases have high CO2-eq values that give their emissions significantly impact on global temperatures. For proper climate change mitigation our efforts need to target both major GHG emissions as well as minor GHGs because they contribute a significant role in global warming.

Influence of Climate Warming on Crop Production

Temperature changes create various forms of impact on agriculture through direct and indirect pathways for crop production. For instance, higher temperatures across Northern India have accelerated phenological events, thus wheat and maize crops receive shorter growth periods, which in turn affect their total yields. The changes in precipitation have caused severe droughts throughout Central Africa which negatively impact the production yields of staple crops, including sorghum and millet. Changes in CO_2 levels have enhanced crop yields occasionally, yet this primarily benefits from elevated water stress and pest infestation risks.

Climate warming conditions have indirectly affected Southeast Asian pest migration patterns because rice fields are now being invaded by pests that are previously restricted to more temperate regions. The series of negative consequences demonstrates that we urgently need adaptive agricultural practices which can handle the various impacts of changing climate conditions.

• *Direct Effects on Plant Health*: The growth and development along with health of plants depend heavily on temperature shifts, precipitation patterns and atmospheric CO_2 levels changes. The fast-forwarding of phenological events occurs when temperatures increase but shifts in precipitation between wet and dry conditions can produce droughts or floods that badly affect crop yields.

• *Indirect Effects on Plant Health*: Chances of crop health and yield are affected by variations in the distribution and abundance of herbivores and competing plant species due to climate. The migration of pests and competitors to new regions may create additional challenges for crop management.

• *Trophic Level Interactions*: Changes in the higher trophic levels (*i.e.*, predation, parasitism and competition) can impact the distribution and abundance of herbivores and competing species and thus indirectly influences plant health.

The changing climate is also pushing the plants and animals together with the agricultural crops to relocate their habitat areas (Pereira *et al.*, 2010). The plants and animals' population will relocate to areas with climate conditions that are more favorable because of the global temperature increases (Sthapit *et al.*, 2012). Therefore, the changing climate conditions are turning formerly productive agricultural regions to unproductive, thus certain planting regions are developing spaces for new agricultural crops.

Climate change impacts pest and disease prevalence, host-pathogen dynamics and the distribution and ecology of insect pests. Changes in climatic conditions influence the timing of pest appearances, migration patterns to new areas and overwintering capacities, thereby presenting significant challenges to vegetable cultivation (Abewoy, 2018). Adapting agricultural practices to these dynamic changes is essential for maintaining crop yield and ensuring global food security.

Impact of Climate Change on Insect Pest Parasitoids and Predators

Climate change is predicted to decrease the value of host plant resistance, biopesticides, natural enemies and synthetic chemical pest control methods. Toxic environmental conditions consisting of higher temperatures, increased ultraviolet (UV) radiation and decreased relative humidity led to this decline (Pareek *et al.*, 2017). Global warming will modify the ecological relationships between pests and their enemy species, leading to population changes of individual pest species.

The modified relationships between pests and their plants caused by climate change may create new vulnerabilities that make resistant crop types vulnerable to infestations. Temperature variations have the potential to modify daily activity behaviors of different insect populations, according to Young (1982); although these changes might affect natural enemy effectiveness through interspecific relationships, as observed by Hill and Dymock (1989) and Pareek *et al.* (2017).

Influence of Climatic Factors on Natural Enemy Populations

Thomson *et al.* (2010) established that the fitness of natural enemies of the ecosystem depends indirectly on plant phenological and physiological factors. Climate changes to atmospheric CO_2, rain and temperature shift the plant phenology cycle and thus affect the development and abundance of herbivores in the region. For instance, earlier flowering times due to rising temperatures in agricultural regions have disrupted the synchrony between herbivores and host plants. In certain temperate zones, altered phenology has led to increased herbivore pressures on crops as the developmental stages of pests no longer align with the natural defenses or management schedules of plants, exacerbating the risk of infestations. This cascade of changes indirectly impacts the accessibility of prey and hosts for natural adversaries. Furthermore, crops grown under elevated CO_2 levels, temperature variations and reduced precipitation provide altered nutritional resources for invertebrate hosts, potentially impacting the fitness of predators and parasitoids (Price, 1987; Pareek *et al.*, 2017).

Climate change also has the potential to influence the temporal synchronization between natural enemies and the periods when crops are vulnerable to herbivore damage. The capability of natural enemies to locate their hosts will be contingent upon their adaptability to ecological fluctuations in relation to their herbivore hosts and their mobility rates. As farmers adopt new management practices to cope with drier and warmer conditions, the dynamics of natural enemies are likely to undergo further changes (Thomson *et al.*, 2010).

Effects on Parasitoid and Predator Efficacy

Minor alterations in thermal conditions can affect the efficacy of parasitoids in managing pest populations (Thomson *et al.*, 2010). Furthermore, the defensive characteristics exhibited by insect pests in response to larval parasitoids may be influenced by fluctuating temperatures (Iltis *et al.*, 2018). In New Zealand's grassland systems, elevated temperatures enhanced biomass production, yet herbivore biomass increased disproportionately, while parasitoids exhibited no significant response to the temperature variations, as illustrated by de Sassi and Tylianakis (2012). Heeb *et al.* (2019) also advocated the similar conclusion.

Precipitation fluctuation accounts for more than 33% of the variable in caterpillar parasitism, regardless of the wide range of host-parasitoid species and habitats across various latitudes (Thomson *et al.*, 2010). This variation is mostly influenced by hymenopteran parasitoids, which exhibit a high degree of host specificity (Hawkins, 1994), in contrast to Tachinids, which possess broader host ranges (Hawkins and Sheehan, 1994).

Phenological changes, like changes in seed germination, dormancy termination, or bud burst, may disrupt the synchronization between herbivores and their host plants. Because of this, the availability of food for natural enemies may typically diminish due to a loss of synchrony, although increases may arise in some scenarios. Herbivore developmental duration, influenced by variations in plant nutrition, can create longer windows of opportunity for predators, making prey more susceptible to predation. For example, the growth cycle of the willow-feeding leaf beetle, *Galerucella lineola* F. (Coleoptera: Chrysomelidae), differs among various hosts. Extended growth period is associated with higher predation rates by heteropteran families such as Pentatomidae and Nabidae, as well as spiders (Haggstrom and Larsson, 1995).

Alterations in host growth also impact parasitoidal action and survival. Extended host development durations can increase susceptibility to parasitism, especially when parasitoids encounter host instars that exhibit heightened vulnerability to parasitism (Sequeira and Mackauer, 1994). Moreover, under drought stress condition, the parasitism of mealybugs in cassava (*Manihot esculenta* Crantz) is minimized, as the immune response of mealybugs improves, leading to higher rates of encapsulation in encyrtid mealybug parasitic organisms (Calatayud *et al.*, 2002).

Increased CO_2 levels may enhance plant vulnerability to herbivory by modifying gene regulation. Herbivory in natural circumstances is influenced by the down-regulation of gene expression for protease-specific deterrents against coleopteran herbivores (Hamilton *et al.*, 2005; Heil, 2008). Changes in the production of volatile organic substances and the excretion of extra-floral nectar stimulated by insect feeding may affect natural predators, as these factors are acknowledged as defensive strategies against herbivores (Heil, 2008).

Current studies indicate that the influence of climate change on natural enemies, influenced by CO_2 levels, temperature and moisture conditions on plants, can be intricate (Thomson *et al.*, 2010). The efficacy of natural enemies may diminish when compelled to prey on inferior hosts and in circumstances where hosts are more challenging to find. On the contrary, it might increase due to easier handling of smaller prey items by predators and longer time windows for parasitism. Models of plant-aphid-parasitoid interactions emphasize the unpredictable outcomes of these combined effects (Hoover and Newman, 2004). Gao *et al.* (2008) observed that elevated CO_2 concentrations may exacerbate the aphid problem, as the prolonged growth period of its primary predator, *Propylaea japonica* (Thunberg) (Coleoptera: Coccinellidae), reduces predation efficiency.

Challenges and Future Considerations

There are many natural enemies that have to survive through thermal extremes but also have to adapt to change by mating and finding host with increasing over broader temperature and humidity ranges. Negative effects of elevated temperatures on the host seeking efficiency and reproductive success of important parasitoid species have been documented. For instance, the host location ability of the egg parasitoid, *Trichogramma carverae* Oatman and Pinto (Hymenoptera: Trichogrammatidae) declines rapidly at temperatures above 35 °C (Thomson *et al.*, 2001). Additionally, significant fertility reductions up to 50% have been documented in *T. carverae* (Scott *et al.*, 1997), *T. pretiosum* Riley and *T. bactrae* (Naranjo, 1993), when exposed to temperatures as high as 30 °C.

Severe weather events can unpredictably affect the relationships between crops, pests, diseases and natural enemies, potentially resulting in the failure of crop protection efforts and diminished yields (Chakraborty and Newton, 2011; Cock *et al.*, 2013; Heeb *et al.*, 2019). Extremely hot and arid conditions in Slovakia diminished the populations of the egg parasitoid, *T. evanescens* Westwood, during May, 1993 (Cagan *et al.*, 1998). High atmospheric temperatures increase insect developmental and oviposition rates and insect outbreaks while decreasing biocontrol effectiveness, insect diversity and parasitism rates (Das *et al.*, 2011). However, in hot summers, ladybird beetles (*Coccinella septempunctata*) have been observed to decrease aphid populations (*Sitobion avenae*) more efficiently than during moderate summers (Karthik *et al.*, 2021).

Developing climate-resilient pest management strategies will require comprehensive research and technological interventions to predict and mitigate the intricate impacts of climate change on the relationships between insect pests and their natural predators.

Impact of Climate Change on Pollinators and Pollination

Insects are vital providers to various ecological services. Pollination is an essential service, as these organisms act as outstanding pollinators for most of the economically significant crops. Numerous commercially valuable crops require pollinators to fulfill their ecological function, according to studies conducted by Murugan (2006) and Sidhu and Mehta (2008). Research indicates that bees contribute to pollinating 73% of the world's cultivated crops while other pollinators include flies with 19%, bats with 6.5% and wasps with 5% with beetles also pollinating 5%, while birds, butterflies and moths pollinate 4% each (Abrol, 2009). For hundreds of years, pollinators and plants developed this beneficial interaction to get floral elements of nectar and pollen, which forms a vital relationship between natural ecosystems and agricultural lands. Klein *et al.* (2007) stated that entomophilous pollination sustains roughly one-third of the food humans consume worldwide.

Threats to Pollination Services

The Millennium Ecosystem Assessment Report (2005) identifies pollination as a threatened ecosystem service among its 15 major categories because of growing population demands and declining natural resources together with climate change (Costanza *et al.*, 1997). Recently recorded climate changes have caused vital pollinator species, including bees, butterflies and moths to demonstrate substantial reductions in their geographic ranges and population numbers and pollination work.

Climatic Factors and Their Impact

The vital phases of plants from flowering until pollination and fruiting heavily depend on climatic conditions that include temperature fluctuations and water resources (Cleland *et al.*, 2007). Most pollinators have learned to match their natural life patterns with the ecology of plants. The timing connection between plants and pollinators faces danger from climate change because it changes the natural timing of plants and pollinators, thus endangering pollination processes (Kudo *et al.*, 2004; Sachs, 2008). The disturbances affect food security and they impact species diversity and reduce ecosystem resilience to climate change effects.

Implications for Food Security and Biodiversity

The quantity and quality of pollination directly influence agricultural productivity, which stands as a critical factor for achieving food security. Additionally, effective pollination contributes to maintain species diversity and ensure the ecosystem stability. A reduction in pollination services can undermine ecosystem resilience, diminishing its adaptability to shifting climatic circumstances.

Research Gaps and Conservation Strategies

Many scientists overlook pollination as a vital service even though it is less prioritized than services that affect water quality, air quality, climate regulation and food accessibility. Scientists require focused research initiatives to define pollination methods and establish methods to protect them because pollination services currently receive inadequate attention. Addressing these research gaps are very much essential for alleviating the risks correlated with climate change and guaranteeing the sustainability of pollination services.

In conclusion, protecting pollinator populations and their ecological functions necessitates immediate research and policy measures to alleviate the detrimental effects of climate change. Without proactive measures, the decline of pollinators significantly affects the agricultural productivity including the stability of ecosystems worldwide.

Impact of Climate Change on Plant-Pollinator Interactions

Interactions between plants and pollinators are very much essential for the vitality of natural ecosystems and the agricultural yield. A considerable segment of the human diet relies on insect pollination. The stability of these interactions is currently jeopardized by global climatic changes, including elevated temperatures, heightened atmospheric CO_2 concentrations and modified precipitation trends. Confronting these difficulties is crucial for preserving biodiversity and guaranteeing agricultural sustainability.

Impact on Phenology, Morphology and Distribution

Global environmental change components directly modify plant-pollinator relationships by shifting how plants and insects flower in time and space as well as altering their physical characteristics. The timing disparities between flowering and pollinators activity during the season lead to a reduction of pollination efficiency and crop yields (Karthik *et al.*, 2021). Such disruptions significantly affect ecosystems and agricultural systems that rely heavily on synchronized plant-pollinator relationships. Understanding and mitigating these mismatches is essential for preserving ecosystem functions.

Influence of Climate Factors on Phytochemicals

The development of essential phytochemicals for attracting pollinators gets influenced by climate conditions. Plants make floral biogenic volatile organic compounds (BVOCs) to entice pollinators and allow mutual interactions between plants and pollinators (Karthik *et al.*, 2021). Petunia hybrid flowers along with other blooms release BVOCs through plasma membrane protein transporters to reach the environment at enhanced temperature conditions (Adebesin *et al.*, 2017).

However, anthropogenic pollutants like ozone and diesel exhaust degrade floral BVOCs after release, increasing pollinator foraging times. Farré-Armengol *et al.* (2016) demonstrated that optimal ozone levels decreased the *Brassica nigra* floral BVOCs in constituent-specific manners, modifying bouquet compound ratios and significantly inhibiting the attraction of *Bombus terrestris*, a generalist bumblebee pollinator. These findings underscore the need for pollution control strategies to protect pollinator health and ensure effective pollination.

Effects of Moist and Humid Atmosphere

Moist and humid conditions can wash away pollen, encourage insect pests and diseases and interfere with pollinator activity. For instance, apple production is severely affected by climate-related factors such as scab disease, premature leaf fall and red spider mite infestations. Excessive water and decreased winter snowfall have reduced chilling hours in key apple-growing regions, posing significant risks to production, especially in India (Singh *et al.*, 2010). Traditional apple cultivation areas in India and Nepal are now shifting to higher elevations due to warmer climates. Mitigating these climate-induced challenges is essential to sustain apple production and other horticultural crops.

Impact on Horticultural Crops

Premature flowering in subtropical areas frequently leads to diminished fruit set due to irregularities induced by low nocturnal temperatures combined with atypical precipitation. Low daytime temperatures reduce pollinator activity, further impacting fruit set. Successful mango production, for instance, necessitates a lack of precipitation during the flowering phase. Moist and humid conditions throughout the flowering season can promote tree development, however hinder flower production and elevate the danger of illnesses (Sthapit *et al.*, 2012). Rising temperatures exacerbate these issues by causing pollen desiccation and reducing pollinator activity, ultimately leading to poor crop yields (Bhruguvanshi, 2009). Comprehensive strategies addressing temperature extremes and moisture levels are vital for the resilience of horticultural crops.

Conclusion

Crop protection in the 21st century presents a substantial issue for humanity, attributable to diminishing agricultural productivity, the exhaustion of natural resources and the severe influence of climate change on insect pest populations, natural predators and pollinators (Karthik *et al.*, 2021). The plant-insect relationship dynamics that affect horticultural ecosystems are endangered by climate change since it disrupts the behavioral patterns and physiological processes of beneficial and destructive insect species.

Physical alterations to climate change environments affect insect physiology and behavior directly, while quantitative shifts in biological interactions together with plant-host relations result in indirect effects. Shifts in plant phenology and physiology have been found to indirectly impact the fitness of natural enemies within ecosystems. These changes may further impact the synchronization between the appearance and abundance of natural enemies and the periods when crops face herbivore pressures. Alterations in insect-host development due to climate-induced stress also affect parasitoid activity and fitness; hosts that experience extended development times may become more susceptible to parasitism, particularly at more vulnerable developmental stages.

The impact of climate change on natural enemies, facilitated through changes in CO_2 concentration, temperature and moisture availability, presents a complex scenario that defies straightforward predictions. Elevated CO_2 levels and temperature extremes not only alter plant nutritional profiles but also influence the synthesis and emission of volatile compounds crucial for attracting pollinators and supporting natural pest control agents. These multifaceted changes underscore the intricate web of interactions within horticultural ecosystems that are vulnerable to climate-induced disruptions.

Moreover, the burgeoning global issue of climate change endangers pollinators on various fronts, undermining their pollination efficacy and the stability of horticultural production systems. The reduction in pollinator numbers caused by climatic extremes, habitat fragmentation and modified flowering seasons presents a significant threat to world food security and biodiversity.

Given these intricate and interconnected difficulties, it is essential to implement adaptive and resilient crop protection techniques. The critical need exists for multiple disciplines that incorporate agricultural strategies for climate change with predator protection and kept pollinator habitats to counteract detrimental climate effects on horticultural systems. A combination of wide-scale research and technological innovation creates sustainable farming solutions which maintain agricultural production in response to rapid climate change.

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