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SPECIAL SECTION: CLIMATE CHANGE VIRTUAL ISSUE

Climate change and managing insect pests and beneficials in agricultural systems

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Abstract

Climate change is expected to alter pressure from insect pests and the effectiveness of insect pollinators across diverse agricultural systems globally. In response to warming, insects are undergoing or are projected to undergo shifts in their geographic ranges, voltinism, abundance, and phenology. Effects on the focal insect species can be affected directly or indirectly, through their interactions with other species at higher and lower trophic levels. These climate-driven effects are complex and as a result variable, sometimes increasing pest pressure or reducing pollination and sometimes with opposite effects depending on climatic baseline conditions and the interplay of contributing drivers. This uncertainty prevents effective responses. Furthermore, in addition to effects of climate change on insect pests and pollinators, projected and ongoing climate change is incentivizing changes in cropping systems such as altered tillage and increasing diversification and intensification with the potential to alter pests and pollinators as great as climate itself. Preparing for this uncertainty must be included in a framework for "Climate-smart Integrated Pest and Pollinator Management," as a component of agricultural production under climate change.

1 | INTRODUCTION

Climate change is altering natural and managed systems worldwide. Documented and projected effects of climate change on ecosystems are expected to accelerate, with implications for global biodiversity and the provisioning of ecosystem services that are critical for human well-being (Intergovernmental Panel on Climate Change [IPCC], 2022).

Abbreviations: CSIPM, climate-smart integrated pest management; CSIPPM, climate-smart integrated pest and pollinator management; IPBES, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; IPCC, Intergovernmental Panel on Climate Change; IPPM, integrated pest and pollinator management; LTAR, Long-Term Agricultural Research Network of the USDA Agricultural Research Service; NRCS, Natural Resource Conservation Service of the USDA.

The implications for production agriculture are significant, multifaceted, and complex. This complexity includes biological constraints, including weeds, plant pathogens, and insect pests (Savary et al., 2019), as well as the beneficial organisms that support healthy agroecosystems. Pests are suppressed by insect natural enemies (Snyder, 2019), and more than 35% of crops accounting for up to 10% of agricultural productivity depend on pollinators (Klein et al., 2007). The effects of climate change on these pestiferous and beneficial insect species in agriculture have generated a growing primary and secondary literature (Bjorkman & Niemela, 2015; Eigenbrode et al., 2022; IPPC Secretariat, 2021; Juroszek & von Tiedemann, 2013; Skendžić et al., 2021). The literature is marked by the variability of the direction and types of effects within and among species, leaving the future of pest and pollinator management uncertain. Relatively unexamined are the additional effects on insect pests and pollinators that will accompany changes in cropping systems as farmers adapt to climate change or respond to policy incentives to do so. This study summarizes these direct and indirect effects of climate change and the implications for pest and pollinator management.

1.1 | Climate change, insects, and insect pests

There are growing concerns about documented declines of insect populations due to human activities, including climate change, expressed in the scientific and popular literature (Forister et al., 2019; Harvey et al., 2022; Raven & Wagner, 2021; Sanchez-Bayo & Wyckhuys, 2019; Wagner, 2020; Wagner et al., 2021). Although trends vary among taxa and regions, there are gaps in data, and the mechanisms are complex and poorly understood, the evidence for insect declines merits concern and action (Forister et al., 2019; Halsch et al., 2021; Saunders et al., 2020). Simultaneously, and seemingly paradoxically, there are warnings about the potential for increases in injury to crops by insect pests with climate change (IPPC Secretariat, 2021). The disparity stems from the different drivers in play. Biodiversity decline is driven in part by habitat loss and fragmentation, which hardly applies to agroecosystems, which are increasing in area and coalescing at the landscape level. Insect species exhibiting declines vary markedly in baseline abundances, life histories, habitat requirements, taxonomy, and niche breadths. Pest species, in contrast, are rare taxonomically, comprising about 3% of insect species, with a handful qualifying as major pests worldwide (García-Lara & Serna Saldivar, 2016). Most are pests because of their ability to colonize and reproduce rapidly on their hosts in simplified agroecosystems and landscapes. Using temperature-driven models of insect performance, Deutsch et al. (2018) projected increasing pest injury to major staple crops worldwide as climates warm. Consistent with this projection, many agricultural pests are indeed increasing in abundance and severity (Skendžić et al., 2021). Since insect pests already account for between 10% and 28% of agricultural yield losses (Savary et al., 2019), increases in pest abundance or injury with climate change could exacerbate climate change-driven reductions in crop performance and yield. On the other hand, empirical evidence for pest severity with warming is mixed with some important agricultural pest species increasing and others decreasing in severity with warming with effects including changes in phenology, range, and trophic interactions (Bjorkman & Niemela, 2015; Kiritani, 2013). Furthermore, other drivers, including changes in precipitation, the frequency of extreme weather events, and increasing concentrations of anthropogenic atmospheric CO_2 alsoare affecting pests.

Core Ideas

- Climate change is affecting insect pests, their natural enemies, and pollinating species important for agriculture.
- Ongoing and projected changes in these insects are variable among species, systems, and regions, hampering attempts to develop robust generalizations and projections.
- Furthermore, and rarely considered, adoption of "climate-smart" agricultural practices will introduce additional effects on these insects potentially as important as effects of climate change alone.
- Climate-smart Integrated Pest and Pollinator Management is outlined as a framework for responding to these complex drivers of change.

Reviews of the effects of climate change on insect pests have appeared over several decades. Juroszek and Tiedemann (2013) list 45 such reviews from 1988 to 2011. Since 2013, there have been at least five other widely cited ones (Andrew et al., 2013; Bajwa et al., 2020; Bebber, 2015; Han et al., 2019; Lehmann et al., 2020; Ockendon et al., 2014; Pecl et al., 2017; Raven & Wagner, 2021; Scheffers et al., 2016; Thackeray et al., 2016; Wang et al., 2022; Zytynska, 2021), but all of these vary in emphasis on specific climate drivers or focus on pests of specific crops.

Effects of climate change on insect pests and beneficials should include insect pollinators on which the productivity of many agricultural systems depends. The estimated value of pollination for agriculture is at least $235 billion worldwide (Gallai et al., 2009; IPBES, 2017) and at least $30 billion in the United States (Losey & Vaughan, 2006). The principal pollinating insect is the honey bee, *Apis mellifera* (Hymenoptera: Apidae). Other managed species (e.g., bumble bees, blue orchard bees, and leaf cutting bees) or native bees are also critical for some crops (Morse & Calderone, 2000). These species are experiencing environmental stressors such as nutritional shortages, pesticides, pathogens, parasites, agricultural intensification, and the effects of climate change (Goulson et al., 2015; Oldroyd, 2007). Despite their importance, pollinator management is often a secondary consideration after pest management in agriculture (Deguine et al., 2021). Pest management and pollinator management must be better integrated (Egan et al., 2020).

1.2 | This review in overview

This study is intended to make three contributions to understanding and responding to the effects of climate change

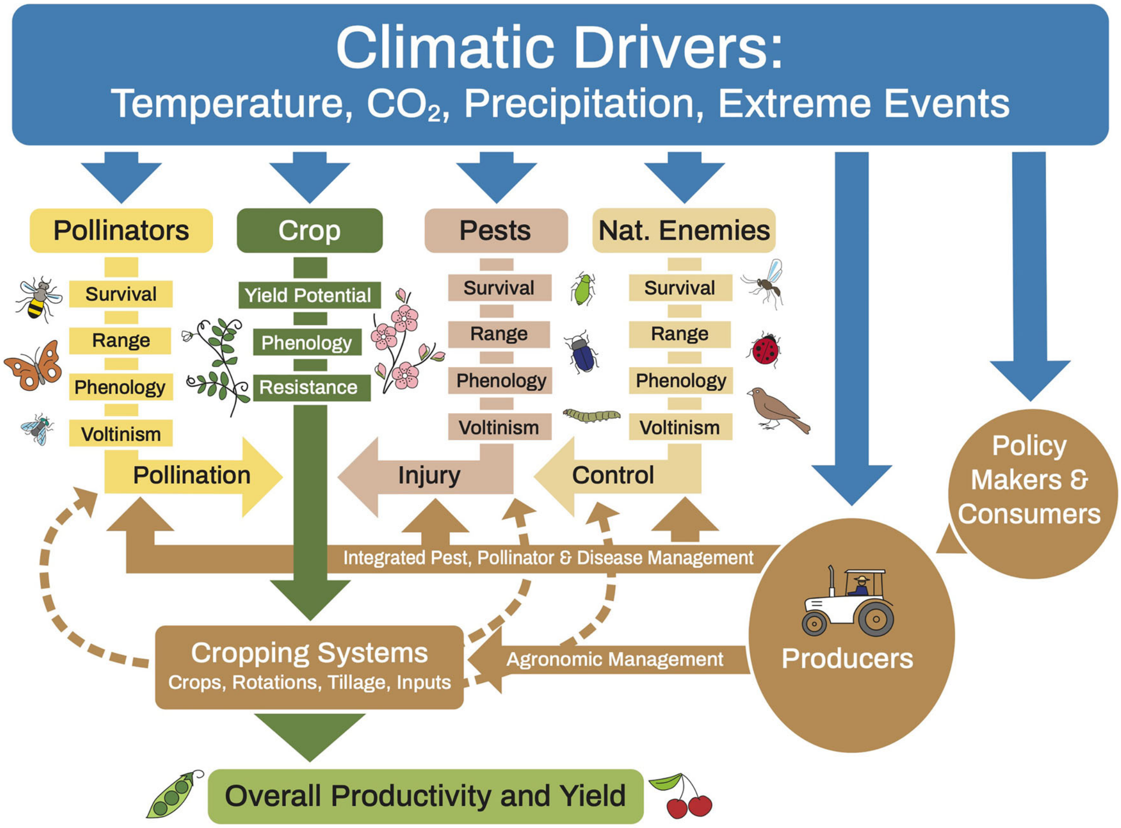

FIGURE 1 A conceptual scheme illustrating the pathways through which climate change can affect pests and beneficial arthropods in production agriculture. Climate change drivers and their routes are shown in blue. For pollinators, pests, and natural enemies (yellow, pink, and tan, respectively), climate drivers can affect aspects of their biology and ecology with repercussions for their interactions and effects on crop yield potential. Human dimensions (brown) include management of pests, pollinators, weeds, and diseases and other decisions about production that are controlled by producers. Climate drivers can influence these practices, whether directly through producers or through policies implemented to promote "climate-smart" agriculture.

on insect pests and beneficials. First, it draws on previous reviews and literature on the effects of climate drivers and climate change on agricultural insect pest biology, ecology, and severity. Second, it takes a similar approach to exploring the effects of climate change on insect pollinators in agriculture. Third, it incorporates the potential effects of climate change on farming practices and cropping systems initiated to respond to climate change, whether to reduce emissions, impart resilience to climate change, or take advantage of opportunities associated with warming climates (FAO, 2013; Steenwerth et al., 2014). These cropping system changes will have effects on pests and pollinators that, at least in the near term, are as great as the effects of climate alone and have not been incorporated into thinking about climate change effects on insects in agriculture. We submit that this comprehensive scope (Figure 1) is necessary for effectively anticipating the effects of climate change on insects in agriculture and their management. Fourth, the study concludes by outlining a framework for Climate Smart Integrated Pest and Pollinator Management (CSIPPM) and suggestions for working under this framework. This study takes a global perspective but draws substantively on literature from the United States and Europe.

2 | CLIMATE CHANGE DRIVERS AND INSECT PESTS

2.1 | Direct effects of warming on pests

Warming is the most consistent, well-documented, and readily modeled aspect of climate change. Warming can alter insect physiology, phenology, dispersal, reproduction, development, and survival of insect herbivores, including pests (Bale et al., 2002). Models based on projected warming trends frequently predict increasing pest abundance and outbreaks with warming (Deutsch et al., 2018; Yamamura et al., 2006), and this is corroborated by some long-term data sets. Combinations of modeling and laboratory or field microcosm experimental studies have also tended to confirm a trend toward pest increases with warming (Hemming et al., 2022; Wang et al., 2021). On the other hand, warming does not consistently increase observed pest abundance (Lehmann et al., 2020). Thermal optima of insects can be exceeded by warming in lower latitudes, reducing pest pressure, while in higher latitudes, warming can move closer to pest thermal optima, increasing pest pressure (Deutsch et al., 2018).

Warming can also increase the number of insect generations annually based on models (Stoeckli et al., 2012; Tobin et al., 2008; Ziter et al., 2012) and observations. For example, a 25-year warming trend has increased the abundance of first-generation and duration of second-generation *Helicoverpa armigera* (Lepidoptera: Noctuidae) in China (Huang & Hao, 2020); the annual number of generations (voltinism) of *Lobesia botrana* (Lepidoptera: Tortricidae), a pest of grape vines in Spain, increased from 1984 to 2006 (Martín-Vertedor et al., 2010); and voltinism of butterfly and moth species (including forest pests) increased in Europe from 1980 to 2008 (Altermatt, 2010).

Some pests extend their ranges northward with warming (Bebber, 2015; Lehmann et al., 2014). Northward range expansion can potentially be accompanied by contractions in the southern extent of a pest's range (Halsch et al., 2021; Martínez-López et al., 2021). This shift, rather than a simple northward extension of the range, has been observed for some forest pests (Fält-Nardmann et al., 2018; Lesk et al., 2017) but evidently not for agricultural pests, although models suggest that possibility.

Phenology of insect pests can be altered by warming, with implications for their abundance and potential injury to crops. Over nearly 50 years of suction-trap records in the United Kingdom, all 55 aphid species monitored, including most key pests of grains and other crops, had earlier first flights with warming (Bell et al., 2015). Based on that record, the frequency of extreme early flights for the aphid *Myzus persicae* (Hemiptera: Aphidae) is projected to increase in the United Kingdom, which potentially translates into greater direct injury and virus transmission by this polyphagous pest (Hemming et al., 2022). Earlier eclosion of cotton bollworm *H. armigera* with warming has increased yield loss to this pest in wheat because of the vulnerability of the younger crop to attack (Ouyang et al., 2016).

2.2 | Indirect effects of warming through species interactions

Warming can affect pest insects through its effects on their natural enemies, directly affecting their physiology or behavior, disrupting their phenological overlap with pests, altering their geographic ranges differently than those of their hosts, or modifying interactions involving alternative prey in agroecosystems (Eigenbrode et al., 2015; Furlong & Zalucki, 2017; Harrington et al., 1999; Thomson et al., 2010). For example, thermal optima for some lepidopteran pests are higher than those of their parasitoids such that increasing temperatures could interfere with their efficacy for control (Butler & Trumble, 2010; Shirai, 2000). Some lady beetles (Coleoptera: Coccinellidae) have extended their ranges, possibly in response to climate change, changes in prey distributions, or both (Sloggett, 2021). If prey and predator range shifts differ, the species could become spatially misaligned, resulting in prey escaping control by these natural enemies. As a result of these complexities, the effects of warming on biological control are varied. Among 12 crop pests between 2002 and 2014, warming increased the negative effects of natural enemies (predators and parasitoids) on the herbivore populations in six instances, decreased it in five instances, and had no detectable effect in seven instances (Hentley & Wade, 2017). Of the 31 globally important pests reviewed for documented effects of warming by Lehmann et al. (2020), three increased in severity because of reductions in biological control from natural enemies.

Trophic interactions mediated by climate can also be bottom-up, involving effects on crop development and physiology. Crops often differ in susceptibility to pests depending upon their stage of development, but age-related effects differ among species. Younger plants typically are more susceptible to pathogens, including insect-borne plant viruses (Panter & Jones, 2002) and some pests. But the reverse can occur, for example, in soybean in which younger plants are more tolerant to injury; climate-driven earlier emergence of Japanese beetles (*Popillia japonica*) (Coleoptera: Chrysomelidae) relative to the soy crop maturity potentially reduces the injury caused by this pest (DeLucia et al., 2012). Susceptibility can also be greatest at an intermediate stage of the crop. For example, cereal leaf beetle (*Oulema melanopus*) (Coleoptera: Chrysomelidae) injury is greatest during the crop's grain filling stage (Ihrig et al., 2001). If crop planting dates and maturation and insect phenology are differently altered by climate change, injury from pests can be affected through what can be termed "trophic dislocations." Based on models, climate change-induced "trophic dislocations" between pests and crops are projected to increase through the 21st century leading to greater pest pressure over much of the American Midwest (Taylor et al., 2018).

2.3 | Effects of warming on pest and natural enemy behavior

Pest behavior can mitigate the effects of temperature regimes on their biology. For example, among three species of aphids (Hemiptera: Aphidae), although *Rhopalosiphum padi* has a higher lethal temperature than two other pests, *Sitobion avenae* and *Metopolophium dirhodum*, *R. padi* has better winter survival because of its overwintering behavior (Alford et al., 2014). Warming can also affect biological control because of behavioral effects. Evans et al. (2012) found that a phenological misalignment between the cereal leaf beetle and the introduced specialist parasitoid wasp, *Tetrastichus julis* (Hymenoptera: Eulophidae), occurred during warmer springs in Cache Valley Utah, greatly reducing parasitism. In more typical cool springs (<600 growing degree days by June 1), the overwintering adult beetles seek out warmer microclimates, speeding their development. The parasitoid, *T. julis*, is completing its development in the soil at that time and emerges in time to attack the beetle's early instars. In warm springs, in contrast, the beetles bask less, while the development of parasitoids is accelerated, resulting in phenological misalignment and greatly reduced rates of parasitism (from near 70% to as low as 10%). Warm springs are projected to increase across the range of the cereal leaf beetle in the American Northwest with implications for disrupting biological control of cereal leaf beetle.

2.4 | Effects of warming on insecticides and host plant resistance

Some pesticides can lose efficacy under warmer conditions. For example, the toxicities of two pyrethroids (lambda-cyhalothrin and bifenthrin) and a spinosyn (spinosad) to *Ostrinia nubilalis* (Lepidoptera: Crambidae) decrease with post-exposure temperatures (Musser & Shelton, 2005). Elevated temperature can alter pesticide metabolism and reduce the efficacy of avermectin for control of *Frankliniella occidentalis* (Thysanoptera: Thripidae) (Matzrafi, 2019). There is at least one record of reduced efficacy of an insecticide (triaphos) against a pest *Nilaparvata lugens* (Hemiptera: Delphacidae) under elevated CO_2 (Ge et al., 2013). As an indirect effect of higher pest populations with warming, insecticide use can increase, with negative environmental effects and risks of more rapid development of insecticide resistance (Ma et al., 2021). Host plant resistance to pests can also be altered by higher temperatures. For example, most genes in wheat imparting resistance to Hessian fly (*Mayetiola destructor*) (Diptera: Cecidomyiidae) are sensitive to temperature, and some of them can lose effectiveness at average temperatures above as low as 18˚C, while others remain effective up to 24˚C (Tang et al., 2018).

2.5 | Other climatic drivers

Although warming is the predominant climate factor affecting insect pests, others are also implicated. Under elevated CO_2, plants should fix more carbon, leading to higher carbon:nitrogen (C:N) ratios (Lincoln et al., 1993). Chewing insects feeding on these plants are expected to consume more plant tissue to meet their requirements for dietary N (Lincoln et al., 1993) with greater potential to damage the crop (Dermody et al., 2008; Niziolek et al., 2013). On the other hand, under elevated CO_2, plants may allocate more resources to carbon-based defenses, which, with reduced available N, could lead to insect population declines. A meta-analysis of 75 studies (Stiling & Cornelissen, 2007) confirmed that under elevated CO_2, plants developed with greater C:N ratios and more carbon-based defenses, associated with decreased insect abundance and growth, while herbivore relative consumption rates increased. Stiling and Cornelissen (2007) also detected inconsistencies, with chewing insects affected more strongly than phloem feeders. In controlled studies, elevated CO_2 can have negative, positive, or neutral effects on insect herbivores and effects can be species specific (Coviella & Trumble, 1999; Y.-C. Sun et al., 2011). For example, survival of *Paropsis atomaria* (Coleoptera: Chrysomelidae) increased on *Eucalyptus robusta* but decreased on *Eucalyptus tereticornis* under elevated CO_2 (Gherlenda et al., 2015). The variability in these effects likely reflects an incomplete understanding of plant responses to elevated CO_2, which can include changes in phytohormones, induced responses to herbivory, and allocation to defenses (Landosky & Karowe, 2014; Zavala et al., 2013). Elevated CO_2 can also affect higher trophic levels, increasing, decreasing, or leaving unchanged the effects of natural enemies on pest abundance (Hentley & Wade, 2017; Sun et al., 2011). Direct effects of elevated CO_2 on insect herbivores are minimal (Guerenstein & Hildebrand, 2008) but have been detected in isolated studies. For example, *H. armigera* fed on artificial diet had reduced fecundity and pupal weight at 550 and 750 ppm CO_2 relative to ambient CO_2 (approximately 400 ppm) (Liu et al., 2017).

Multiple climatic drivers acting together can produce complex and nonadditive effects on insect herbivores. A meta-analysis of 42 experimental studies (Zvereva & Kozlov, 2006) found that the negative effects of elevated CO_2 on herbivores were mitigated by elevated temperature, suggesting these drivers could be offsetting under field conditions. Another extensive review found that the variable effects of elevated CO_2 on insect herbivores can be explained by two- and three-way interactions with temperature, soil nitrogen, drought, light, photosystem (C4 vs. C3), and intrinsic plant growth rate (Robinson et al., 2012). Precipitation regimes can mitigate the effect of warming on the timing of aphid flights (Crossley et al., 2022), and winter rain, versus snow, can increase the effects of lethal cold on insects (Bale & Hayward, 2010). Various biotic interactions can additionally modify pest responses to climate drivers. Simultaneously, elevated temperature and elevated CO_2 affect wheat growth and aphid performance differently depending on infection of the wheat with barley yellow dwarf virus (Moreno-Delafuente et al., 2020). Interactions between two aphid species infecting wheat depend on drought stress levels (Foote et al., 2017). Elevated temperature and drought interact to reduce the effectiveness of a parasitoid (*Diaeretiella rapae*) (Hymenoptera: Braconidae) for suppressing populations of its host, the cabbage aphid, *Brevicoryne brassicae* (Hemiptera: Aphidae) (Romo & Tylianakis, 2013).

In summary, although warming temperatures should result in increased insect pest pressure based on their physiology (Deutsch et al., 2018), the direction and level of pest responses to warming and other climatic drivers are variable based on observations, experimental studies, and modeled projections. This stems from the complex effects of warming on pest biology and ecology compounded by diverse effects of other climate change-associated factors. Not only is this variability evident among species, but responses can differ for the same species in different climatic zones (reviewed in Juroszek & von Tiedemann, 2013). Individual studies and reviews have hardly incorporated all these sources of variability or comparable methods of study. Furthermore, only a limited number of pests have been studied extensively. It seems unlikely that additional studies will change the assessment that responses will vary markedly, precluding the identification of meaningful trends. Rather, although changing climates will alter insect pest abundance and pressure, the direction and strength of these changes are uncertain.

3 | CLIMATE CHANGE AND INSECT POLLINATORS

3.1 | Direct effects of climate change on pollinators

As for insect pests, climatic factors directly affect the physiology, morphology, reproduction, development, survival, and dispersion of insect pollinators. For example, temperature can affect the physiology, foraging activity, body size, and life span of pollinators, which could alter their roles in transferring pollen and reducing pollination success in plants (Scaven & Rafferty, 2013). Due to their relatively low critical thermal maxima, solitary species (e.g., sweat bees) and cavity-nesting species (e.g., bumble bees) are more sensitive to climate change than some other taxa (Hamblin et al., 2017). Experimental manipulations have detected negative effects of warming on body mass, fat content, emergence, and survival of wild bees like *Osmia* spp. (Hymenoptera: Megachilidae) (CaraDonna et al., 2018; McCabe et al., 2022). Extreme climatic events can also affect pollinators. For example, heat waves reduce male fertility and attractiveness to females in bumble bees (Martinet et al., 2021).

3.2 | Indirect effects of climate change on pollinators

Indirect effects of climate change on pollinators are at least as important as direct effects on their biology (Gilman et al., 2010; Ockendon et al., 2014). Climate change projections and models suggest suitable habitats will decline for many pollinators (e.g., bees in South America), although habitat generalists (e.g., bees and flies in Europe) may be less affected (Dormann et al., 2008; Giannini et al., 2020; Gonzalez et al., 2021). Warming has caused poleward or altitudinal shifts in the range of some pollinators (Hickling et al., 2006; Inouye, 2020). Changes in floral and pollinator phenology can introduce mismatches (Gérard et al., 2020; Ogilvie et al., 2017), and changes in plant chemistry affect floral rewards or attractiveness for pollinators (Hoover et al., 2012; Tylianakis et al., 2008), with population-level consequences (Iler et al., 2021). Extreme weather events could also negatively affect floral resources (Høye et al., 2013), which can adversely affect honey bee colony growth (Flores et al., 2019). Globally, honey bee declines are attributed to several drivers, including Varroa mites (*Varroa destructor*) (Acari: Mesostogimata), *Nosema* spp. (Microsporidia: Nosematidae), and viruses. Changing climate potentially exacerbates risks from these drivers. For example, warmer autumns and winters allow more late season flights by honey bees, skewing overwintering hive populations to older bees that are more vulnerable and providing more opportunities for hives to acquire pathogens and parasites (Rajagopalan et al., 2022). Pollinators, including honey bees, are being affected by lethal and sublethal effects of pesticides (Tosi et al., 2022). Native bee pollination depends on pollinator diversity as well as abundance (Vasiliev & Greenwood, 2020) and warming can reduce inter- and intra-specific diversity and their resilience toward disturbances (Vasiliev & Greenwood, 2021).

In summary, climate change, with other anthropogenic drivers, is altering the biology, abundance, and diversity of insect pollinators critical for agriculture, just as it is affecting pests and their natural enemies. The additional stress of changing climate can amplify the impacts of other drivers affecting honey bees, other managed bees, and native bees. Managing pollinators in agriculture requires considering and mitigating the effects of these drivers as part of a holistic approach that includes managing pests and beneficial insects.

4 | HUMAN DIMENSIONS: CLIMATE CHANGE, PRODUCERS, AND FARMING SYSTEMS

4.1 | Climate-smart farming

In addition to the effects of climate change on the biology and ecology of pests, their natural enemies, and pollinators, modifications to farming systems designed to mitigate and adapt to climate change can affect these species and their management. Effects of climate change on agricultural productivity (IPCC, 2022) are driving interest in food system transformation (Anderson et al., 2020; Dinesh et al., 2021; Gaupp et al., 2020; Mehrabi, 2020). Climate-resilient or

"Climate-smart" agriculture (FAO, 2013), whether implemented at the field, farm, or landscape scale, is intended to increase agricultural productivity and profitability, build resiliency to climate change, reduce greenhouse gas emissions, and increase carbon sequestration in farmland soils (FAO, 2022; Stringer et al., 2020) through a suite of practices (Box 1).

4.2 | Climate-smart farming and insects

Each of the climate-smart practices described in Box 1 has known and potential effects on insect pests and pollinators.

4.2.1 | Cropping system diversification

Pests and natural enemies: Interest in the effects of cropping system diversification on insect pests and their natural enemies is long-standing (Root, 1973) with hundreds of studies on the effects of crop and weed diversity on insect pests and beneficials, which have been periodically reviewed (Altieri, 1991; Andow, 1991; Letourneau et al., 2011; Tonhasca & Byrne, 1994). Diversification generally is accompanied by reduced pest pressure, although there is substantial variability evident for both intercropping (Huss et al., 2022; Risch, 1983; Theunissen, 1994) and cover cropping (Alarcón-Segura et al., 2022; Bowers et al., 2020; Rowen et al., 2022; Schipanski et al., 2014). Theoretically, reduced pests with diversification can result from increased generalist natural enemies (the Natural Enemies Hypothesis), reduced host finding ability and population growth of pests (the Resource Concentration Hypothesis), or both (Root, 1973). Although there is some support for each of these hypotheses, the mechanisms leading to either reduced or increased pest pressure with diversification are often unknown or result from multiple interacting ecological factors (Bukovinszky et al., 2004; Dassou & Tixier, 2016; Risch, 1983). Diversification can also exacerbate pest problems. For example, cover crops can increase pest pressure either by harboring new pests that must be managed within the cover crop (Carmona et al., 2019; Hammond, 1990) or harboring pests that can also attack a subsequent or adjacent cash crop (Inveninato Carmona et al., 2022). Insect-borne plant pathogens that infect both a cover crop and a main crop can be moved between these crops by the insect vectors increasing risks of infection and injury (Wegulo et al., 2008).

Pollinators: Diversification that involves adding flowering species supports more pollinator species and sustains their populations by providing additional nectar and pollen sources. Intercropping or multiple cropping in which forbs are planted with cereals (e.g., legumes with wheat) increases pollinator diversity and abundance (Brandmeier et al., 2021; Kirsch et al., 2023; Norris et al., 2018). Flowering cover

Box 1: Climate-smart agricultural practices

Cropping system diversification. Introducing additional plant species into traditional or business-as-usual cropping systems can help to slow erosion, improve soil health, enhance water availability, compete with weeds, improve soil and water quality, fix nitrogen, enhance nutrient cycling efficiency, improve carbon capture, and increase cash crop productivity and yield stability (Altieri et al., 2015; Bowles et al., 2020; Ponisio & Ehrlich, 2016; Raseduzzaman & Jensen, 2017).

Intercropping is co-planting more than one crop in the same field, whether as alternating strips or rows or intermixed, grown simultaneously or in relay, with partial temporal overlap within a season (Bybee-Finley & Ryan, 2018). Although it is an ancient agricultural practice that is still used in small-scale farming, it is increasingly being promoted for both small- and large-scale production systems due to its agronomic benefits and potential to increase productivity (Huss et al., 2022; Lamichhane et al., 2023).

Cover crops are single species or mixtures of species undersown with the main crop, seeded after harvest, or added to rotations to maintain soil cover and living roots within the soil when the main crop is not being grown (Clark, 2019). Cover crops improve soil health and microbial diversity (Ashworth et al., 2020; Ghimire et al., 2019; Kim et al., 2020). The number of acres and number of farms planting cover crops has increased rapidly in the United States (USDA National Agricultural Statistics Service, 2017).

Reduced tillage. Conventional tillage reduces soil carbon and nutrients, releases greenhouse gases into the atmosphere, and accelerates soil erosion (Lal & Kimble, 1997; Conant et al., 2007). Reduced tillage, less disruptive than moldboard plowing and ranging from direct seeding to minimal tillage using chisel plows, mitigates these effects while increasing soil agroecosystem biodiversity, including microbial biomass (Holland, 2004; Mangalassery et al., 2014; Stinner & House, 1990; Yuan et al., 2022). Adoption of reduced tillage continues to accelerate in the United States and elsewhere because of these benefits (Jat et al., 2020; Sun et al., 2020; USDA, 2017; USDA Economic Research Service, 2022).

Precision soil, water, and energy management. Precision or site-specific agricultural technology

(Continues)

Box 1: (Continued)
for water and soil nutrient management are climate-smart practices that help improve energy efficiency, thereby reducing energy inputs and greenhouse gas emissions and impart resilience to water limitations and drought (Alluvione et al., 2011; Bwambale et al., 2022). Adoption rates of these technologies are as great as for any previous technological innovations in agriculture (Lowenberg-DeBoer & Erickson, 2019).
Reduced agrochemical use. While agrochemicals (e.g., synthetic pesticides, fertilizers) in industrialized crop production have greatly improved yields, they are also drivers of declines in biodiversity, soil erosion, pesticide resistance, greenhouse gas emissions, and eutrophication (Devi et al., 2022). These effects can be further intensified due to climate change (Ma et al., 2021). Hence, reduced and judicious use of agrochemicals is included in climate-smart agricultural practices although pesticide use continues to increase worldwide (Fernández, 2022).
Biochar soil amendment. Biochar is a charcoal-like substance that is produced from agricultural and forest waste by decomposition at high temperatures in a controlled process, called pyrolysis (Lehmann & Joseph, 2015). Due to its high porosity, stability, and richness in carbon, when used as a soil amendment, biochar can improve physical, chemical, and biological properties by increasing cation exchange capacity, increasing pH, increasing soil surface area and water-holding capacity, and increasing plant nutrient availability (Allohverdi et al., 2021; Lehmann et al., 2021; Schmidt et al., 2021; Woolf et al., 2010). Adoption of biochar in agriculture is limited, but it has been increasingly promoted for small- and large-scale production (Dumortier et al., 2020; Nyambo et al., 2020).
Integrated crop-livestock system. Integrating animals into cropping has been practiced traditionally but is not commonly used in large-scale industrialized agriculture. Integrated crop-livestock systems are being adopted because they can improve crop nutrition and nutrient cycling, support insect pest management, and provide additional returns from the land (Adhikari & Menalled, 2020; Peterson et al., 2020; Seo, 2010).
Landscape scale climate-smart measures. These include promoting diversification of field borders, hedgerows, and preservation of other seminatural habitats. These practices preserve ecosystem services

(Continues)

Box 1: (Continued)
important for agroecosystem functioning, imparting resilience to climate change and variability. This typically needs to occur at regional levels to ensure adequate habitat diversity is achieved (Garibaldi et al., 2021; Scherr et al., 2012; Tscharntke et al., 2021) posing challenges to policymakers (Steenwerth et al., 2014).

crops can also support pollinators, depending on crop species used in the cover crop mix (Bryan et al., 2021; Eberle et al., 2015; Mallinger et al., 2019). Cropping system diversification can offset the negative effects on pollinators resulting from agricultural intensification (Ellis & Barbercheck, 2015; Kovács-Hostyánszki et al., 2017; O'Brien & Arathi, 2020).

4.2.2 | Reduced tillage

Pests and natural enemies: Reduced tillage improves agroecosystem biodiversity and associated ecosystem services (Stinner & House, 1990). A meta-analysis based on 59 studies (Rowen et al., 2020) found that the abundance of insect pests overall did not differ between reduced and conventional tillage but that foliar pests specifically were more abundant, and soil-dependent predators were less abundant under high- versus low-disturbance tillage. Tillage tends to negatively affect the abundance, species richness, and diversity of some ground dwelling predators, especially ground beetles (Coleoptera: Carabidae), likely because tillage eliminates alternative food resources and disrupts their habitats (Kromp, 1999). On the other hand, effects of tillage on ground beetles are variable, likely due to interactions with other management practices (Muller et al., 2022). In addition, in one long-term study with spring cereals, although plots with reduced tillage had fewer carabids, there was no effect on another important ground predatory taxon, rove beetles (Coleoptera: Staphylinidae) (Andersen, 2003).

Pollinators: More than 70% of wild bee species nest and spend much of their life cycle within the soil. Tillage, regardless of intensity, disturbs these ground-nesting bees (Harmon-Threatt, 2020; Williams et al., 2010). Conservation tillage, reduced tillage, or zero tillage can therefore have multiple benefits on pollinators and on crop pollination (Adhikari et al., 2019; Ullmann et al., 2016) with benefits for crop yield, farm income, and resilience to disturbances (Cusser et al., 2023).

4.2.3 | Reduced agrochemical use

Pests and beneficials: Long-term reliance on insecticides for pest control has well-recognized negative effects on non-target organisms, including natural enemies of pests that can cause secondary pest outbreaks, increase production costs, impose human and environmental health hazards, and increase pesticide resistance in target pests (Devi et al., 2022; McLaughlin & Mineau, 1995; Pimentel & Andow, 1984; Pimentel et al., 1992). Reducing pesticide use to address these vulnerabilities has been a motivating paradigm for decades of research and application (Jacquet et al., 2022; Lechenet et al., 2017; Pimentel, 1997).

Pollinators: Multiple studies have also shown that insecticides, herbicides, and fungicides are detrimental to pollinators through lethal and sublethal effects (Bloom et al., 2021; Crall et al., 2018; Siviter et al., 2021; Thompson et al., 2014; Tosi et al., 2022; Weidenmüller et al., 2022). Reducing these inputs as part of climate-smart agriculture will help conserve ecosystem services such as biological control and pollination.

4.2.4 | Biochar soil amendment

In agricultural systems, research on biochar and insect pests is limited to the effects of biochar on pesticide persistence and degradation in soils (Varjani et al., 2019). It is possible that biochar, through indirect effects on crop plants, can alter pest performance (Chen et al., 2018; Hou et al., 2015).

4.2.5 | Landscape-scale climate-smart measures

Pests and natural enemies: Landscape diversification can influence pests, especially by providing habitat for natural enemies (Aguilera et al., 2020; Altieri et al., 2015; Landis, 2017; Lin, 2011). This can include woodlots, hedgerows, and seminatural habitats on the farm or landscape scale. Although there are recognized principles for management of farming landscapes for beneficials (Bianchi, 2022; Haan et al., 2021; Petit et al., 2023), a review of a large number of studies found that benefits for pest control can be variable, sometimes with tradeoffs that can cause reduced yields (Karp et al., 2018).

Pollinators: Pollinators are also affected by farm and landscape diversity (Aguilera et al., 2020; Landis, 2017). Climate-smart practices such as increased heterogeneity of agricultural landscape with seminatural habitats, field borders, beetle banks and hedgerows, and native flower strips enhance pollinator biodiversity (Donkersley et al., 2023; Garibaldi et al., 2021; Tscharntke et al., 2021). For example, hedgerows support pollinators in adjacent orchard and vegetable fields (Miñarro & Prida, 2013; Morandin & Kremen, 2013). Even "weeds" present in seminatural habitats and field borders provide floral resources for pollinators that help sustain them when no other resources are available (Bretagnolle & Gaba, 2015).

4.2.6 | Climate-smart measures and insects—Summary

In summary, most climate-smart production practices will have effects on insect pests, natural enemies, and pollinators, but effects are not consistent within any practice, complicating anticipated effects of climate change on pest management (Juroszek & von Tiedemann, 2013). For example, few studies of intercropping documented the specific ecosystem services that influenced the effects on pests (Huss et al., 2022), leaving principles that could shape management practices uncertain. Studies of these effects also tend to be siloed, examining the effects of diversification on natural enemies or pollinators, but rarely assessing the combined effects of these services (Garibaldi et al., 2018). A recent study (Martínez-Salinas et al., 2022) showed that biological control of a key pest of coffee, the coffee berry borer or broca (*Hypothenemus hampei*) (Coleoptera: Curculionidae), and pollination of the crop act synergistically to improve yields and farmer income. With an improved understanding of these effects, they can be optimized while implementing climate-smart practices.

5 | CLIMATE CHANGE AND INSECT MANAGEMENT IN AGRICULTURE

The ongoing and anticipated effects of climate change on insect pests and beneficial insects, whether these are direct effects of climate on their biology and ecology or indirect effects arising from changing agricultural practices, will affect approaches for their management. The principles of integrated pest management (IPM) (Barzman et al., 2015; Kogan, 1998) will become more important since they are designed to mitigate the potential for pest colonization and respond appropriately when pests reach injurious levels, which are likely to be more variable if not severe under climate change (Gregory et al., 2009). Similarly, approaches to ensure pollinator abundance and diversity in the production systems at the same time as pests are managed will be essential (Deguine et al., 2021). The importance of taking these measures simultaneously and ensuring they are compatible has led to a synthesis in integrated pest and pollinator management (IPPM) (Biddinger & Rajotte, 2015; Egan et al., 2020; Lundin et al., 2021). Furthermore, since climate trends and pest responses to these trends differ among regions and pests (Schneider et al., 2022), IPM principles should be employed flexibly for use in locally adapted and diversified, climate-smart production systems (Juroszek & von Tiedemann, 2013; Macfadyen et al., 2018). For managers, this means greater importance of designing systems that suppress pests and support pollinators, and vigilance in monitoring and decision-making for pest management.

5.1 | Climate-smart Integrated Pest and Pollinator Management

Pest management itself can be designed to be climate-smart in that it can enable effective insect management under climate change while reducing agriculture's contributions to greenhouse gas emissions (Heeb et al., 2019). Heeb et al. (2019) propose a framework for climate-smart integrated pest management (CSIPM) within climate-smart agriculture. Their approach includes management practices, support, education, policy, and international cooperation. The CSIPM framework can readily be extended to include pollinators in a CSIPPM approach that includes established practices for IPM (Barzman et al., 2015) extended to IPPM (Lundin et al., 2021), modified to reflect the additional challenges and opportunities presented by climate change (Table 1).

6 | CHALLENGES AND RECOMMENDATIONS FOR RESEARCH AND IMPLEMENTATION OF CSIPPM

Insect pests constrain agricultural productivity and profitability, while beneficial insects including predators and pollinators are essential for this productivity. Ongoing and projected climate change will affect these species in various ways through diverse pathways that are biological and systemic (Figure 1). Although there are some trends in the direction of these effects, there is no simple formula for anticipating them or no general trends that can serve as useful guides. Rather, climate change adds "another layer of complexity" to the already difficult problem of managing insects in agricultural systems. This apt assessment was offered concerning plant disease management and climate change more than two decades ago (Coakley et al., 1999) and has remained relevant for insects (Juroszek & von Tiedemann, 2013; Sutherst et al., 2007). More recent work as reviewed in this study has not changed this assessment. Rather, for the foreseeable future, the best response will be to increase commitment to the principles of IPM and the emerging IPPM framework as outlined in Table 1 within the broader context of climate-smart agriculture (Box 1). Doing so will often imply greater costs associated with monitoring, application methods, constraints on timing, and often more expensive materials, difficult to justify in terms of simple economic short-term returns. So-called agroecological crop protection (Deguine et al., 2021) or IPM more broadly defined for longer term sustainability (Barzman et al., 2015; Egan et al., 2020) should, nonetheless, guide pest and pollinator management within the context of climate change.

6.1 | Research needs to support CSIPPM

Research on individual pests and beneficial species is a continuing need, especially given the limited value of general trends for anticipating climate-related changes and the possibility that these changes happen idiosyncratically and perhaps rapidly.

Among the pests that have been studied, approaches vary widely from long-term observational data sets, field experiments, controlled greenhouse studies, and modeling. Most pests have been examined using just one or a few of these approaches. For example, among pests affecting wheat, worldwide methods vary widely, as do projections about changes in their abundance or severity (Eigenbrode & Macfadyen, 2017). There is a taxonomic bias in which species have been studied, with Lepidoptera and Hemiptera overrepresented (Juroszek & von Tiedemann, 2013). Within a given system, examinations of the interactions among pests or other species are infrequent, despite the importance of assessing species interactions as part of climate change research (Gilman et al., 2010; Urban et al., 2016).

6.2 | Prioritizing research and monitoring efforts

Given the limitations of resources, research and monitoring efforts should be prioritized whenever possible to focus on pests of greatest concern or potential vulnerability. In the United Kingdom, the Plant Health Risk Register (https://planthealthportal.defra.gov.uk/pests-and-diseases/uk-plant-health-risk-register/) attempts to prioritize where resources should be allocated to anticipate emerging pest issues in the United Kingdom, based on various criteria. Similar systems could be initiated, for crop pests at the national or international level. These would require foundational research to assign such priorities and the political will to support them. The needed research is not only for individual insect species responding to climate drivers but as we have emphasized in this study, insects within production systems altered to improve sustainability, including resilience to climate change. In the United States, the Long-Term Agricultural Research (LTAR) Network (https://ltar.ars.usda.gov) includes 18 sites nationally where business-as-usual and so-called "aspirational cropping systems" are compared for performance,

TABLE 1 Principles and elements of Climate-smart Integrated Pest and Pollinator Management (CSIPPM).

Principles and components	Actions
Prevention and suppression—Preemptive measures to reduce pests and enhance pollinators	
• Host plant resistance	• Ensure resistance expression is stable under elevated temperatures or other climate variability • Include pollinator attractiveness in breeding goals along with pest resistance
• Conservation biological control and pollinator conservation	• Include natural and semi-natural habitats in farmscapes and landscapes as habitats for natural enemies and pollinators (Landis, 2017; Tscharntke et al., 2021; Wratten et al., 2012) • Design these for resilience to anticipated climatic conditions • Assess impacts of farm operations (e.g., tillage, agrochemicals, crop, and farmscape diversity) on beneficials
• Classical and augmentative biological control	• Where available and safe, release specialized biological control agents for target pests • Include stable habitats on farm to support these agents. Monitor their populations and efficacy and manage habitats, being alert to the potential variable effects for biological control and pest suppression (Haan et al., 2021; Karp et al., 2018) • Consider climatic requirements of agents such as thermal tolerance in selection criteria for candidate agents (Eigenbrode et al., 2015; Furlong & Zalucki, 2017)
Monitoring—Measures to detect pests, natural enemies, and pollinators	
• Monitoring and scouting • Identification • Monitoring networks • Forecasting	• Monitor crops regularly at appropriate times in the cropping cycle to detect pest presence and abundance and evidence of natural enemies • Monitor pollinator-dependent crops for abundance and diversity of pollinators • Ensure correct identification of pests and beneficials to the appropriate taxonomic level • Be vigilant to the presence of new invasive pests; use available extension services or equivalent to identify these pests (e.g., Cock, 2011) • Use climate-based forecasting tools where available to guide monitoring (Barker et al., 2021; Crimmins et al., 2020; Lambert et al., 2019; Washington State University, 2022) • Use or develop local or regional monitoring networks and online delivery methods • Use or develop remote sensing methods for detecting infestations where pest symptoms and technology allow • Develop and use artificial intelligence-based identification tools • When alternative practices are introduced (cover cropping, intercropping), adjust monitoring to detect new and existing pests that may utilize these as resources or green bridges

(Continues)

TABLE 1 (Continued)

Principles and components	Actions
Decision making—Use of empirically developed methods to determine the timing of interventions	
• Treatment thresholds	• Develop and utilize economic injury levels and treatment thresholds for key pests • Take advantage when pest pressures decline with climate change by reducing insecticidal treatments (Macfadyen et al., 2018; Eigenbrode & Macfadyen, 2017) • Adjust or modify thresholds based on environmental conditions such as: o temperature o presence and abundance of natural enemies o cultivar • Adjust thresholds based on pollinators (joint economic impact level)
Pesticides and other interventions to suppress pests	
• Treatment selection and implementation	• Use insecticides that are not harmful to beneficials or pollinators; avoid broad-spectrum and long residual life (Knapp et al., 2022; Veres et al., 2020) • Weigh risks to pollinators vs. benefits for pest management (Mourtzinis et al., 2019) • Time insecticide applications to avoid harming beneficial insects • Minimize pesticide rates and frequency of applications • Use alternatives to insecticides when cost effective and satisfactory including mechanical methods. Consider greenhouse gas emissions associated with these methods. • Monitor greenhouse gas emissions associated with pesticide use and strive to minimize these emissions (Heimpel et al., 2013) • Rotate and diversify modes of action and take other measures to avoid selecting for pesticide resistance

effects on soil health, and reduced greenhouse gas emissions. LTAR efforts are coordinated aiming to generate widely applicable knowledge for the nation's agricultural sector under change. Although lacking so far, an LTAR-wide coordinated effort to monitor pests in business–as–usual and aspirational cropping systems could help detect vulnerabilities and target pests or pollinators for greater investment. For example, if cover crops improve pollination and biological control services but also introduce new pests or green bridges for existing pests, this will be best detected using whole system implementation and adequate monitoring. Funding is clearly a limitation to any such increased research effort, but insects must be viewed as essential in any long-term investments in preparing agriculture for climate change through initiatives under way in the United States (e.g., Inflation Reduction Act) and the EU (within the Common Agricultural Policy).

6.3 | Promoting adoption of CSIPPM

Adoption of IPM and IPPM and many climate-smart practices (Box 1) has historically been slow because of the uncertainty and expenses of adoption and the lack of understanding by farmers and managers. Research agendas must be complemented by effective education and clear delineation of the barriers to adoption confronting farmers and by providing incentives to help overcome these barriers. The economic and labor costs of climate-smart practices are largely omitted from studies of their effects on pests, weeds, and diseases (Huss et al., 2022), and this must change in order to inform realistic efforts to support adoption. Supportive policies could include crop insurance that provides coverage to diversified systems or even offers coverage at reduced premiums if these practices can be shown to reduce actuarial risks of losses due to pests (Roesch-McNally et al., 2018). CS and CSIPPM practices at the landscape scale can be promoted through federal programs (e.g., Conservation Reserve Program, Conservation Stewardship Program, and Environmental Quality Incentives Program) of the NRCS in the United States. Internationally, CSIPPM can be promoted through national plant protection organizations in the concept and coordination (see www.ippc.int/en/countries/nppos/list-countries/) as recommended by Heeb et al. (2019) and guided by the International Plant Protection Convention of the FAO (https://www.ippc.int/en/). Some incentives for adoption of IPM, IPPM, and CSIPPM may be market based. Consumer awareness of the importance of sustainable production and food and environmental safety and evidence for willingness to pay for the practices in the form of premiums on commodities can provide this incentive for some crops, markets, and societies (Carlisle et al., 2022; Macfadyen et al., 2018; Mortensen & Smith, 2020; Roesch-McNally et al., 2018).

6.4 | A bigger picture

Finally, although this study has focused almost entirely on insects, farming systems must also cope with pressures from weeds, plant pathogens, and vertebrate pests all of which are being affected by climate change (Juroszek & von Tiedemann, 2013, 2015) (Figure 1). Plant pathogens include those that are transmitted by insect vectors, which introduces a much more complicated set of ecological and anthropogenic factors (Finlay & Luck, 2011; Jones, 2016). We hope this study incentivizes a comprehensive effort to anticipate and respond to the effects of climate change on the biotic constraints to agricultural productivity worldwide.

AUTHOR CONTRIBUTIONS

Sanford D. Eigenbrode: Conceptualization; investigation; visualization; writing—original draft; writing—review and editing. **Subodh Adhikari**: Conceptualization; investigation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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