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Review

Climate Change, Carbon Dioxide, and Pest Biology, Managing the Future: Coffee as a Case Study

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Abstract: The challenge of maintaining sufficient food, feed, fiber, and forests, for a projected end of century population of between 9–10 billion in the context of a climate averaging 2–4 °C warmer, is a global imperative. However, climate change is likely to alter the geographic ranges and impacts for a variety of insect pests, plant pathogens, and weeds, and the consequences for managed systems, particularly agriculture, remain uncertain. That uncertainty is related, in part, to whether pest management practices (e.g., biological, chemical, cultural, etc.) can adapt to climate/CO₂ induced changes in pest biology to minimize potential loss. The ongoing and projected changes in CO₂, environment, managed plant systems, and pest interactions, necessitates an assessment of current management practices and, if warranted, development of viable alternative strategies to counter damage from invasive alien species and evolving native pest populations. We provide an overview of the interactions regarding pest biology and climate/CO₂; assess these interactions currently using coffee as a case study; identify the potential vulnerabilities regarding future pest impacts; and discuss possible adaptive strategies, including early detection and rapid response via EDDMapS (Early Detection & Distribution Mapping System), and integrated pest management (IPM), as adaptive means to improve monitoring pest movements and minimizing biotic losses while improving the efficacy of pest control.

Keywords: adaptation; crop protection; food security; global warming; insect-plant interactions; modelling; plant disease; range expansion; temperature

1. Introduction

Managed land use, for forestry, horticulture, or food, must exclude or minimize pest pressures to maximize production and economic return. Pests can be defined as those organisms (insects, plants, microbes, animals) that can reduce the quantity and quality of any product obtained from the managed plant system. Pest management is, therefore, an integral part of maintaining viability in these systems (e.g., the reduction of pest losses from agriculture during the Green Revolution) [1,2]. Such efforts

can encompass simple to sophisticated strategies (e.g., from hoeing to modifying the environment to utilize ecosystem services) to manage pest populations and ensuing damage.

Recent and projected increases in atmospheric carbon dioxide (CO₂) concentration are expected to continue with a potential 2× increase over current CO₂ levels, and subsequent, concomitant increases in average temperature between 0.15 and 0.3 °C, per decade, by 2100 [3,4]. Such projections, as well as recent potential changes in extreme events, increase the degree of uncertainty of how these environmental changes could impact pest biology (insects, plant pathogens, weeds), and the consequences for future biotic losses from managed plant systems.

Recent and projected increases in atmospheric CO₂ could change pest biology in two essential ways. The first is related to physical changes in the environment incurred as CO₂ increases. Such increases, along with other radiation trapping gases (e.g., CH₄, N₂O), will increase surface temperatures [5], cause changes in precipitation frequency [6], and alter the diurnal temperature range (DTR) [7], as well as the magnitude and distribution of extreme weather events [8]. A second essential consequence is the “fertilization” effect of rising CO₂ on plant photosynthesis; approximately 95% of plant species, those that rely solely on the C₃ photosynthetic pathway, could increase growth and reproduction as CO₂ increases, including agronomic and invasive weeds. There are hundreds of studies and several meta-analyses showing that both recent and projected increases in atmospheric CO₂ can have numerous physiological effects for a wide variety of C₃ plants [9–12].

From a pest biology view, changes in regional and global climate, from temperature to DTR, to precipitation, are likely to affect the establishment, spread, and impact of pest species within managed systems [13–16]. For example, the continuous increase in CO₂ can directly stimulate the growth and fecundity of weedy species, but also has implications for qualitative changes for host plants, and for insects and plant pathogens [17].

Biotic losses in managed systems, such as agriculture, can be substantial (more than 40% worldwide [2]). Consequently, the nature and outcomes of potential changes in pest impacts arising from environmental change are of immediate concern. However, the potential outcomes of rising CO₂ and environmental perturbations on pest biology are difficult to quantify, in part, because it is unclear if current management paradigms will be sufficient to negate any additional pest pressures. Our goal here is to review the probable interactions between climate, CO₂, and pest biology; illustrate those links using coffee (*Coffea arabica* L. and *C. canephora* Pierre ex. A. Froehner) as a case study; highlight vulnerabilities in the context of current pest management; and propose ideas that can help adapt and strengthen future control.

2. Overview of Climate and CO₂ Effects on Pest Biology

2.1. Insects

Temperature is generally considered a primary environmental parameter controlling insect biology. Insect phenology, reproduction, and developmental rates are significantly affected when populations are exposed to different climatic regimes. Minimum temperatures are particularly important as a significant driver in insect spread and demography.

Since insect pests are ectotherms, warming temperatures provide a strong advantage, enabling insects to expand their ranges to higher latitudes and altitudes [18], as well as increasing the number of generations, due to longer growing seasons. Thus, insect outbreaks are increasing globally ([19] and references therein). Similarly, longer growing seasons also support an increase in pest populations. For example, a 20-year study in the United Kingdom showed that even a small (1 °C) rise in winter temperature advanced the migration phenology of aphids by 19 days [20]. In addition, DTR can also alter insect emergence rates. Grape berry moth (*Paralobesia viteana* (Clemens)) has delayed adult emergence and decreasing voltinism with smaller-than-current DTR, and earlier adult emergence and increasing voltinism with larger-than-current DTR [21].

Less direct management of insect pests might also be affected by altered precipitation. Climate change is likely to create a “peakier” hydrologic cycle, and an increase in both droughts and above average rainfall events could occur in the same location [22]. Following an extreme drought in 2015–2016, gypsy moth caterpillars (*Lymantria dispar* (L.)) demonstrated their first major outbreak in the Northeast U.S. in over 30 years [23].

The consequences of rising CO₂, per se, on insect pests is less certain. However, it is probable that insects will be affected by the indirect physiological effects of CO₂ on host plant metabolism. Such effects may include CO₂-induced increases in C/N ratios, reduced protein concentration [24] and potential changes in defensive compounds [25]. Such metabolic changes are difficult to predict, in part because of the complexity of insect physiology and behavior. However, the initial, documented, current observations regarding warming and insect spread; increased damage of plants within managed systems [26]; and CO₂-induced changes in feeding behavior; highlight insect vulnerabilities [25].

2.2. Plant Pathogens

Plant pathogens, including fungi, bacteria, and viruses, are significant biotic limitations to production in managed agricultural and forest systems. Temperature, relative humidity, and precipitation are major factors contributing to the incidence and severity of plant diseases. Many plant pathogens co-evolved with their hosts, developing optimal growth conditions in concurrence, so that outbreaks may occur under otherwise optimal agronomic conditions [27]. Plant pathogens can thrive in high moisture environments, which favor establishment, growth, and infection of susceptible hosts. Moderate rain events can increase disease in susceptible crops, as fungal spores are splash-dispersed onto wet plant surfaces [28].

Warmer conditions have been associated with increased outbreaks of powdery mildew, leaf spot disease, leaf rust, and rhizomania disease [29]. This may be due, in part, to warmer winter temperatures that increase the amount of initial inoculum present in the spring. Potato late blight (*Phytophthora infestans* (Mont.) de Bary) has a complex association with DTR and mean temperature; but it does experience changes in incubation, latency progression, lesion growth rate, and sporulation, with DTR changes at various mean temperatures [30].

Some extreme weather events linked with climate change, like flooding, may increase the regional risk of disease outbreaks by providing a more conducive environment for pathogen growth [8]. In addition to increased risk of outbreaks, other extreme weather events, like droughts, can exacerbate postharvest yield losses by increasing production of mycotoxins in some disease systems [31].

Overall, as climate change alters environmental conditions, plant pathogen demographics will be affected. The geographic range of plant pathogens is often limited by the overwintering and oversummering conditions required by the pathogen [32]. CO₂-induced changes in plant hosts are also likely to alter pathogen biology. Barley plants infected with *Barley yellow dwarf virus* (BYDV) at higher CO₂ concentrations had higher virus titer inside their leaves, which could lead to more severe epidemics of BYDV and reduced yield in the future [33]. Repeated infection of the fungal pathogen *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc., at increased CO₂ concentrations, was linked to recovery of isolates with increased fecundity [34]. Elevated CO₂ concentration can also alter the C/N ratio in host plants. For example, Wolf et al. [35] observed that a higher C/N ratio in the host plant was positively correlated with increased sporulation in *Alternaria alternata* (Fr.) Keissl. On the positive side, rising CO₂ can reduce stomatal aperture, and limit pathogen transmission into the leaf; similarly, improved drought resistance, and/or plant growth with higher CO₂ could improve plant health and limit pathogen establishment [36].

Projecting these environmental and physiological changes to plant pathogen responses remains difficult. There are indications that slight changes in climate can lead to widespread epidemics. For example, recent increases in temperature and lower than average rainfalls may have contributed to the selection of a new strain of yellow rust (*Puccinia striiformis* Westend.) that can now produce spores

at warmer temperatures [37]. The rapidity by which pathogens can adapt to these changing conditions, and the consequences for disease outbreaks in managed plant systems, is cause for concern.

2.3. Weeds

Temperature and precipitation remain primary physical factors that control vegetative establishment and population success [38], and as such, will impact the geographical distribution of weeds with subsequent effects on their growth, reproduction, competition, and impacts in managed plant systems. A recent meta-analysis compared responses of invasive vs native plants to rising temperatures and altered precipitation, in terms of plant growth, fitness, and physiology [39]. Invasive plants performed significantly better than native plants under elevated temperature; the two groups performed similarly with increased precipitation, but invasive plants performed marginally worse with decreased precipitation [39]. For existing weeds, changes in DTR can also impact shoot and root sprouting. For example, root and shoot emergence from purple nutsedge (*Cyperus rotundus* L.) tubers increased with increasing DTRs, compared to smaller DTRs [14]. Together, these results suggest that rising temperature and altered precipitation will not be an automatic win for weedy plants, but instead, will depend on location as well as magnitude and direction of change [40].

Increasing temperatures may allow expansion of existing or introduced weeds to higher latitudes or altitudes [41]. In agronomic systems, many of the weeds associated with warm season crops originated in tropical areas, thus, climate warming could expand their range northward [29]. Many agricultural weeds, relative to crops, have short reproductive times, high fecundity, and long-distance dissemination, suggesting a rapid ability to spread. To that end, McDonald et al. [42] introduced the concept of the “damage niche”, modeling projected shifts in weed species for the U.S. Corn Belt, with subsequent effects on crop–weed competition and weed constraints on crop production.

Rising CO₂ can also directly alter weed biology and impact. Numerous studies have documented the positive influence of rising CO₂ on growth and competitive outcomes for weeds in managed systems, including forests, pastures, and agriculture [43]. For example, in a meta-analysis of over 90 studies of response to elevated CO₂, Liu et al. [39] identified a significantly more positive response in invasive plant growth, fitness, and physiology relative to native plants. Although some initial agronomic studies hypothesized that a difference in photosynthetic pathway could favor crops (many weeds have the C₄ pathway, which shows a minimal response to CO₂, whereas crops often have the C₃ pathway, which shows a stronger response), this hypothesis has not been supported. Early studies did not capture the complexity of agroecosystems where, on average, each crop competes with 8–10 weed species [44]. Moreover, a competitive advantage for C₃ crops over C₄ weeds is likely to occur only under rising CO₂ without concomitant changes in climate. For example, at higher temperatures and increased drought, C₄ weeds can still benefit [45,46]. Additionally, the “worst” weeds are often wild or uncultivated relatives of the crop species, with the same photosynthetic pathway, but often more responsive to CO₂. For example, Ziska et al. [47] and Ziska and McClung [48] showed that weedy rice is much more responsive to rising CO₂ than cultivated rice, suggesting that many of our current crops will be less able to take advantage of additional CO₂ than their weedy relatives.

There is a growing consensus that climatic change and rising CO₂ levels may already be affecting weed biology. There are a number of studies showing that rising CO₂ consistently selects for invasive plants within managed and unmanaged plant communities [49,50]. A European evaluation of agronomic areas indicates that, in recent decades, warming temperatures and drier conditions have resulted in demographic changes in weed flora, with thermophilic weeds, later-emerging weeds, and opportunistic weeds becoming more prominent [51].

3. Coffee as a Case Study

3.1. Why Coffee?

We have chosen coffee as a case study due to its economic as well as its social importance in the tropics. For example, coffee is the largest component of the agricultural gross domestic product (GDP) in Latin America [52]. In Tanzania, ca. 2.4 million individuals depend on coffee production for their livelihood [53], while in Ethiopia, ca. 4 million households cultivate coffee [54]. In addition, coffee production is a primary example of efforts to design agriculture to provide additional ecosystem services [55], e.g., where shade-grown coffee can provide a useful wildlife habitat, and where ecological interactions affecting pest risk have been evaluated [56]. If production is threatened by climate change, the full range of ecosystem services may be compromised.

Coffee is planted in ca. 11 million hectares in ca. 78 countries [57] throughout the tropics, and in some areas outside the tropics, e.g., Nepal, China, and the United States (California). Coffee production is measured in 60 kg (132 lb.) bags, and the 2017–2018 forecast [58] for *C. arabica* is 93,996,000 bags and 65,892,000 bags for *C. canephora*, equivalent to 59% and 41% of total production, respectively. Brazil, Colombia, and Honduras are the top three *C. arabica* producers, while Vietnam, Brazil, and Indonesia are the top *C. canephora* producers for 2017–2018 [58]. In 2012, the estimated value for the worldwide coffee industry was ca. US \$173 billion [59].

3.2. Climate Impacts on Current Coffee Production Areas

Several papers have been published on the projected impacts of climate change on various coffee-producing areas. Among these, Läderach et al. [52] reported that by 2050, due to increases in temperature and reduced rainfall, suitable coffee-growing areas in Mexico and Central America will be negatively affected. For example, coffee production in the Sierra Madre de Chiapas, the most important coffee-producing area in Mexico, is projected to be reduced from 265,400 ha to 6000 ha, a 97% reduction [52]. In addition, climate change models project that the optimal coffee growing area in Central America will be above 1600 m above sea level (masl) by 2050, in contrast to the current 1200 masl; this will have severe impacts on coffee production in Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua [52]. A similar altitudinal change is projected for Kenya, where the current optimal areas (1400–1600 masl) are expected to shift to 1600–1800 masl by 2050 [60]. A 65% reduction in indigenous *C. arabica*-growing areas in Ethiopia is projected by 2050; by 2080, the reduction is projected to increase to close to 100% [61]. Projections for Puerto Rico are also dire; by 2071–2099, only 24 km² are projected to be suitable for coffee production [62]. Projected reductions in suitable coffee growing areas by 2050 in many other countries have also been reported [63–65].

In Tanzania, climate change has been implicated in reduced yields due to an increase in the minimum nighttime temperatures between 1961 and 2012 [53]. For every 1 °C increase in the minimum nighttime temperature, yields have decreased by 137 kg/ha [53].

3.3. Climate Change and Coffee Insect Pests

Commonly reported effects of climate change on insects include faster developmental rates, with consequent increased number of generations and insect abundance; increased winter survival and earlier flight dates in temperate countries; and expanded insect range to higher elevations and northwards [66,67]. Here, we summarize the results of studies involving three coffee insect pests: the coffee berry borer, the coffee leaf miner, and the coffee white stem borer.

3.3.1. The Coffee Berry Borer (*Hypothenemus hampei* (Ferrari))

The coffee berry borer is a small bark beetle that feeds on the coffee seeds inside the coffee berry (Figure 1). The insect is endemic to Africa, but has disseminated to most coffee-producing countries worldwide, where it is quite difficult to manage as it spends most of its lifecycle inside the coffee berry [68]. Losses due to the insect in Brazil have been estimated at US \$215–358 million [69].

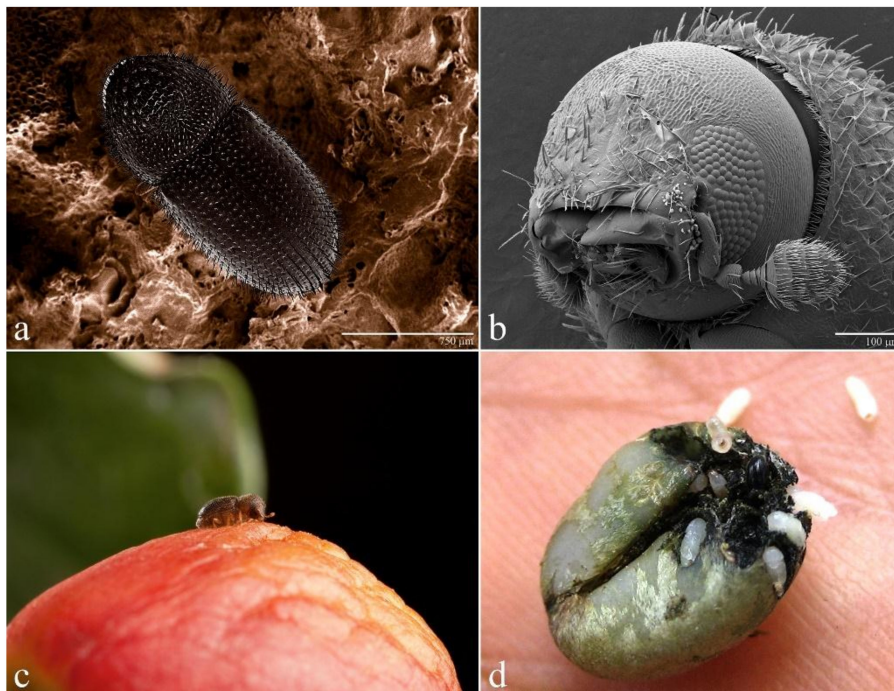


Figure 1. Dorsal view (a) and detail (b) of an adult female coffee berry borer. Female adult on a coffee berry (c). Damage caused by larval feeding on the coffee bean (d). Photos by Eric Erbe (a; USDA-ARS); Gary Bauchan (b; USDA-ARS); Peggy Greb (c; USDA-ARS); and Francisco Infante (d; El Colegio de la Frontera Sur, Mexico).

In a study aimed at determining the thermal tolerance of the coffee berry borer, Jaramillo et al. [70] assessed developmental time (days) from egg to adult using eight different temperatures (15, 20, 23, 25, 27, 30, 33, or 35 °C). The insect was unable to develop at 15 and 35 °C, but growth at all other temperatures showed that development was faster as temperatures increased, with developmental time from egg to adult taking 53.7 ± 0.7 days at 20 °C, in contrast to 23.3 ± 0.3 at 30 °C, a highly significant difference. A consequence of a shorter developmental time is more insect generations, more damage, and wider insect dispersal. The insect can now complete several generations at elevations where it was not usually present in Colombia, Ethiopia, Indonesia, Kenya, Tanzania, and Uganda, due to increased temperatures in those areas [70,71]. Based on climate change models results, Jaramillo et al. [72] projected an increase by 2050 in the number of coffee berry borer generations in East Africa from the current 1–4, to 5–10 generations at high elevations, and 11–16 at low elevations. Magrath and Ghazoul [73] projected that by 2050, there will be an overall increase in the surface area under coffee cultivation infested by the coffee berry borer from a current 57% and 50% for *C. arabica* and *C. canephora*, respectively, to 78% and 93%, respectively.

3.3.2. Coffee Leaf Miner (*Leucoptera coffeella* Guérin-Mèneville & Perrottet)

The coffee leaf miner is a small moth (ca. 4 mm long) that oviposits on the adaxial surface of coffee leaves. Upon hatching, larvae bore into the mesophyll and start consuming the palisade parenchyma tissue, consequently reducing photosynthetic area and causing leaf senescence, with subsequent effects on yield and quality [74,75]. It has been reported in coffee-producing countries throughout the Neotropics, and is considered an even more important pest than the coffee berry borer in Brazil [75,76]. In Brazil, an increased number of coffee leaf miner generations per month using two climate change models have been projected for 2020, 2050, and 2080 [76].

3.3.3. Coffee White Stem Borer (*Monochamus leconotus* (Pascoe))

The coffee white stem borer is a 3.0–3.5 cm long beetle, and an economically important coffee pest in several countries in Africa [77,78]. Females lay eggs under the bark, and the lifecycle from egg to adult can last up to 24 months, with development of seven larval stages taking ca. 20 months [78]. Larval feeding inside the bark can cause ring barking, which kills the plant; other symptoms include stunted growth, wilting, defoliation, shoot die-back, and lower yields. The insect is extremely difficult to control, and infested plants usually need to be removed from the plantation.

In contrast to studies regarding temperature (e.g., coffee berry borer and coffee leaf miner), Kutuwayo et al. [79] found that precipitation is more important than temperature in determining the projected range of the coffee white stem borer, with several areas in Zimbabwe likely becoming more suitable for increased infestations.

3.4. Other Coffee Pests

3.4.1. Root-knot nematode (*Meloidogyne incognita* (Kofoid & White) Chitwood)

Root-knot nematodes of the genus *Meloidogyne* can cause severe damage to coffee production, and are widely distributed throughout coffee-producing countries. Several species of *Meloidogyne* are known to infect coffee, and mixtures of species are often present within a single sample [80]. Root infection causes cell hypertrophy and the formation of galls, eventually destroying the root system and impeding the absorption of nutrients. Root-knot nematode infection can result in severe yield reduction, with estimated losses up to 45% [81]. In Brazil, an increased number of nematode generations with increasing temperatures have been projected for 2020, 2050, and 2080 [76].

3.4.2. Coffee Leaf Rust (*Hemileia vastatrix* Berk. & Broome)

Coffee leaf rust is a fungal pathogen present throughout most of the coffee-producing world. It is responsible for the devastation of the coffee industry in Sri Lanka (1860–1880) and its replacement with tea plants [82]. Coffee leaf rust symptoms include the appearance of orange powdery lesions on the underside of the leaf. Infection results in premature defoliation with consequent reduction in photosynthesis; severe infections can lead to branch death [83]. A succession of coffee rust epidemics from 2008 to 2013 in Mexico, Central America, Colombia, Ecuador, and Peru were suspected to be related to climate change, but based on a 25-year analysis of coffee leaf rust incidence, Bebbler et al. [84] concluded that climate change was not responsible. Instead, leaf wetness duration, increased canopy temperatures, and reduced fertilizer use with subsequent decline in plant vigor, may have contributed to the outbreaks [83,84]. Results of climate change projections for 2020, 2050, and 2080 in Brazil indicate that warmer temperatures could reduce the incubation period of the fungus, i.e., the time from infection to expression of symptoms [85].

4. Pest Management Vulnerabilities

As illustrated with coffee, there are immediate and significant concerns regarding the impact of climate change on production, but also evidence that recent climate change may be affecting pest populations and their impacts in managed systems. Such impacts are worrisome, in part, because of the long-term nature of managed plant communities (e.g., coffee, cocoa, forests), and the temporal uncertainty of climate change.

The impact of pest pressures on managed plant systems is already significant. For example, it is estimated that 15–20% of the global harvest is lost to plant diseases [2]. Recent evaluations for potential corn yield losses from weeds (in the absence of weed management) in North America put the figure at ca. 50% [86]. Overall, pest management per se, is a crucial aspect of maintaining production in agriculture and other managed systems. However, in a changing climate, with additional CO₂, are current pest management efforts sufficient to negate additional pest pressures? What are their potential vulnerabilities to climate change and rising CO₂?

4.1. Rapid Demographic Shifts

As the climate shifts, so will pest activity and movement. The rapidity of this movement, and the consequences for new pest threats are becoming more relevant. For forestry, the spread of the southern pine beetle (*Dendroctonus frontalis* Zimmermann) into New Jersey [87], and the northward migration of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) into Canada [88], are related to warming winters. Similarly, kudzu, (*Pueraria montana* var. *lobata* Willd.), an invasive vine of forests, also appears to have migrated northward in recent decades [89]. Diseases, such as coffee leaf rust, will also be impacted by temperature, as will Asian soybean rust (*Phakopsora pachyrhizi* Syd. & P. Syd.), a significant, current, threat to U.S. soybean production, which is favored by a warm humid climate [90]; and could, potentially, migrate to important soybean production regions in the Midwestern U.S. [91,92]. Pest demography can, and will, shift quickly with climate change, and consequently, pest management must recognize and incorporate such shifts in pest management strategies [93].

4.2. Evolution and Fitness

Climate change and increasing CO₂ will generate new selection pressures on pest populations. It is widely recognized that insects and plant pathogens can evolutionarily adapt to precipitous climate shifts [94,95]. Rapid evolutionary adaptation (i.e., within a few generations) has also been observed in response to climate for weed populations in studies involving flowering and temperature [96], and drought [97]. In addition, there are reports suggesting that recent increases in atmospheric CO₂ may have also altered gene flow between cultivated and weedy rice [98].

Overall, as climate and CO₂ change, it seems unlikely that artificial and natural selection for fitness between crops and weeds (or plant pathogens and insects and their managed plant hosts) will proceed at the same temporal pace. Indeed, given the narrower range of genetic variation and monoculture emphasis in managed plant communities relative to genetic variation in pest populations, such differential fitness responses to climate and CO₂ seem all but certain. Differential responses are likely, in turn, to affect pest management. For example, breeding for plant pathogen or insect resistance is an integral aspect of managed plant communities in responding to changing biotic threats [99]. A vast coffee breeding program aimed at developing resilient coffee varieties adapted to climate change is currently being spearheaded by World Coffee Research (<https://worldcoffeeresearch.org/work/breeding-future/>) [100], a research and development program sponsored by the global coffee industry.

4.3. Pest Management Efficacy

At present, there are many recognized and widely applied strategies to negate pest pressures. These methods vary, both economically and culturally, and can include mechanical, biological, and chemical control. For example, in most developed countries, herbicides are used in agronomic systems because of uniform applications, high efficacy, and cost reductions associated with agricultural mechanization and time [101]. Will climate and/or CO₂ affect the efficacy of these current control practices?

At present, there is substantial uncertainty regarding this issue. For example, climate can influence physical and biological aspects of chemical control, from weather extremes that skew spray coverage and field access, to direct effects of CO₂ and/or temperature on weed physiology [102]. Such influences can be negative (e.g., increases in ambient temperature can alter the toxicity of insecticides) or positive (e.g., higher CO₂ could limit water use and maintain normal metabolism of some weed species during drought, increasing herbicide efficacy). Changes in available resources may also affect cultural control. For example, flooding is used as a traditional tool for weed control in paddy rice. However, with changes in water supply and more severe droughts, rice systems have shifted to direct seeding, with subsequent changes in the weed flora. However, the impact of this flora on rice pest management is still being evaluated [103]. Similarly, it is likely that climate, particularly seasonal temperature,

could differentially affect the biocontrol agent and the phenology of the targeted pest; however, we are unaware of any experimental data regarding the impact of a climatic change variable on biocontrol efficacy in managed plant systems to date. Overall, there is a fundamental lack of information regarding the efficacy of current control methods in the context of ongoing and projected climate and CO₂ changes, leading, in turn, to increasing ambiguity regarding future pest management.

5. How to Reduce Uncertainty in Pest Management: Some Ideas

5.1. Increase Monitoring Capacity: EDDMapS

Expanding global trade, exchange of new species across environmental regions, and a changing climate, will contribute to increased uncertainty regarding current and potential pest threats. At present, the USDA, through the Animal Plant Health Inspection Service (APHIS) has a primary role in detecting incoming pests, especially through trade, but they only monitor specific plant pest species once they are found outside of inspection stations. Enhanced monitoring and assessment of these threats will be crucial in improving future pest management.

The early detection and distribution mapping system (www.EDDMapS.org) [104], based at the Center for Invasive Species and Ecosystem Health at the University of Georgia, tracks the distribution of invasive species across the United States and in parts of Canada (Ontario and Alberta) in real time. EDDMapS is funded by federal and state agencies, non-profit organizations, and universities. There are many programs that use EDDMapS as their sole database for recording invasive species occurrence data, while other management efforts may maintain their own internal database and contribute data to EDDMapS on a regular basis. EDDMapS has also incorporated information from programs that were foundering, thus preventing data loss [105].

Aggregating topically similar data and information into one database allows for disparate programs to contribute to a common dataset and for subsequent re-use of the data for quality checks and additional analysis without duplication. As with any data aggregator, data standardization is crucial. There may be many standards if data are shared from different research fields, but crosswalks can be drawn between the different standards to ease the transition and moving from one database to another. However, shared data allows for quality checks, and further research and experimentation, without requiring duplicate efforts of data collection [106–108].

Sharing to an aggregate database also allows for individuals interested in a single topic to be able to download a large dataset at one time. For example, a researcher interested in brown marmorated stink bug (*Halyomorpha halys* Stål) can retrieve data from EDDMapS, rather than having to solicit the data individually from state agencies, academic institutions, federal agencies, cooperative invasive species management areas, etc. These data can be then made available to the scientific community and the broader public in easily consumable and accessible visualizations.

EDDMapS also serves as the National Pest Observation Repository within the Integrated Pest Information Platform for Extension and Education (iPiPE) [109]. Similar to its role for aggregating occurrence data on invasive species, this provides for both aggregation and real-time exchange of data on all agronomic pests. Participants can do this through direct or open sharing of data within EDDMapS or private sharing within the iPiPE platform (<http://www.ipipe.org>) [110]. As with invasive species data, sharing of pest occurrence information can lead to a more complete perspective of populations over time with improved risk prediction and area-wide management (Figure 2).

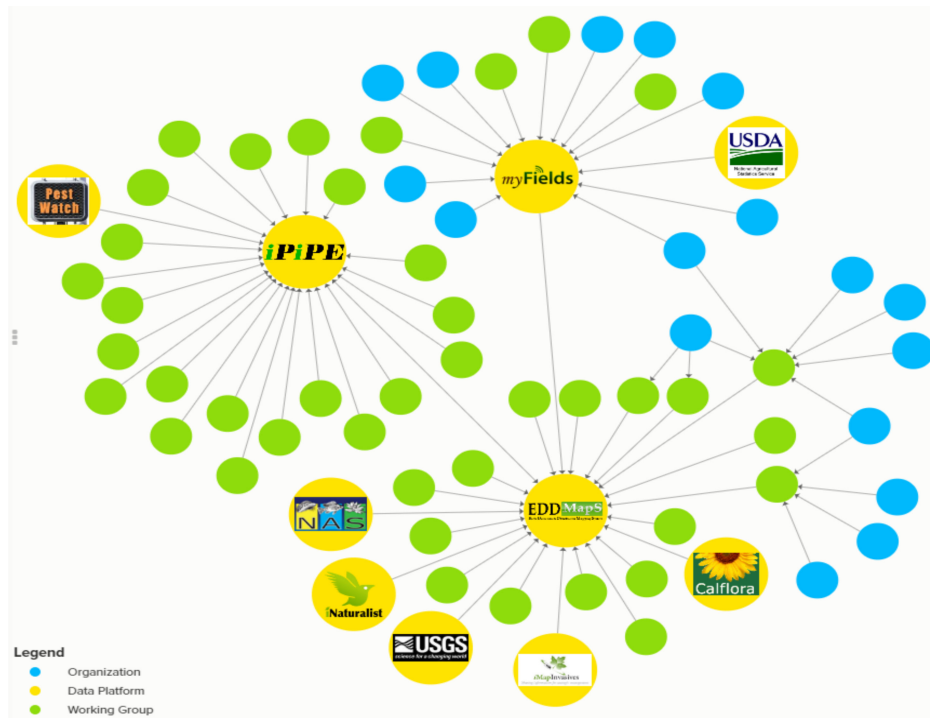


Figure 2. Illustration of the relationship of organizations (blue), working groups (green), and data platforms (yellow) that are currently engaged in data sharing to provide a more complete view of pests and invasive species. A full and current diagram of data sharers is available at <https://kumu.io/IPMC/data-sharing-networks> [111].

To help define and document the spread of new and emerging pest threats with rapid climate shifts, visualizations are essential. Maps, graphs, and other graphics are widely used by programs and researchers to provide context and impact. Many visualization programs, e.g., species maps in real time, are available, and can provide temporal value. EDDMapS has provided state, county, and point level maps for over a decade. Since 2012, EDDMapS has also offered Report Density and Literature vs Observation maps. In addition to simple visualizations of pest demographics, these maps can, with application of ArcGIS and other similar programs, offer more complex information, such as property ownership, habitats, soil types, etc.

However, as with any visualization, context is important. While aggregate data can provide a picture, missing data may be needed to provide a better sense of elapsed time. For example, when looking at spread over time for kudzu, the aggregate data would suggest that it began in Connecticut and jumped to Alabama, North Carolina, Illinois, and Tennessee, where it remained until further jumps in 2001 (Figure 3). However, kudzu was widely spread throughout.

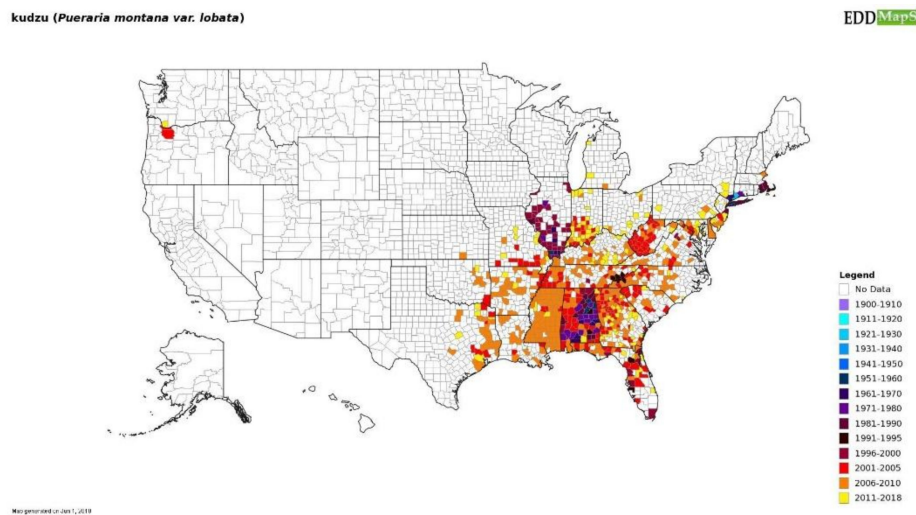


Figure 3. Aggregate reports of the presence of kudzu (*Pueraria montana* var. *lobata*) over time. The southeast prior to its appearance in Connecticut. This visualization suffers from inadequate early data from the southeastern U.S., to fully tell the story of kudzu’s spread.

In contrast, a visualization of the spread of kudzu bug began shortly after its introduction. Thanks to the efforts of the Megacopta Working Group, sufficient data was aggregated to allow for a valid representation of the real-world situation [112] (Figure 4). Yet, here too, the visualization can be taken out of context, because the data may not always reflect long-term persistence. That is, it may have been several years since kudzu bug has been reported for some of the older locations. Since its introduction, several parasitoids and an entomopathogenic fungus (*Beauveria bassiana* (Bals.-Criv.) Vuill.) have resulted in severe population declines, leading researchers to question where it is still active [113,114]. This highlights the need for continued monitoring and surveillance efforts of any new pest threat.

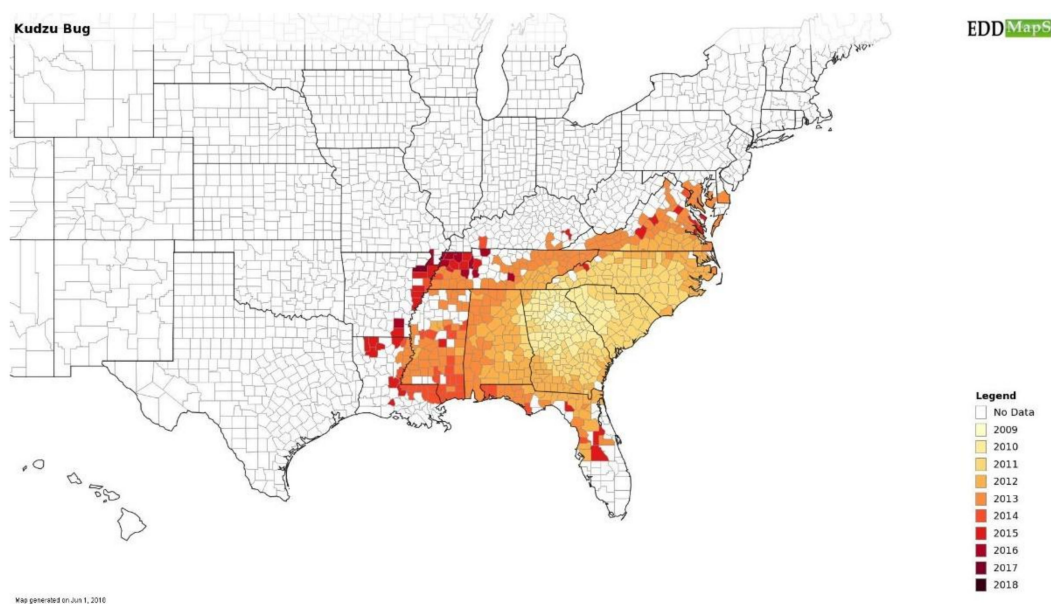


Figure 4. Change over time in the introduction and spread of kudzu bug (*Megacopta cribraria* (F.)).

The use and utility of these real-time visualization efforts, emblematic of EDDMapS, is essential to track pests in real time. While there are contextual issues, it is also clear that the ability to communicate

real-time pest shifts can be invaluable to policy-makers, growers, and scientists. In addition, such efforts can employ public participation, with favorable results [115]. There are a growing number of projects with a citizen science focus where the data can be harvested for research and use [116]. As with any publicly driven system, there will be users who participate once, and those who become invested and continue to engage with the system [117].

EDDMapS can be an example of how to improve monitoring pest shifts in real-time in a changing climate. Yet, current efforts could also be improved, including novel data standardization and data sharing; potential monitoring of pesticide resistance biotypes, pest-induced crop losses, obtaining and analyzing long-term environmental data for a given pest to determine baseline parameters; geographic information system, (GIS) data that documents shifts in the pest species in real time; cross-collaboration of these data to improve model projections specific to population dynamics and pest outbreaks; and identification and prioritization of pest threats and modelling near-term vulnerability of plant systems to that threat.

There are also other, newer, technologies that could be considered. For example, the growing ubiquity of smartphones on a global level (<https://www.ericsson.com/en/mobility-report/reports/june-2018>) [118] could allow for photo sharing and documentation of pest outbreaks and relative threats at both a regional and international level (if specific apps were available to integrate effective image analysis of pests/symptoms). Improved remote sensing to aid in temporal geospatial models of pest occurrence, particularly in agricultural areas, could also be effective; for example, the use of remote drones and software to monitor new or problematic pests, and to determine the efficacy of local control measures.

5.2. Chemical Control vs Integrated Pest Management

For many managed plant systems, particularly agricultural, pesticides represent the primary means of pest control. Still, chemical control as a “one-size fits all” strategy is becoming increasingly challenging. Pests are often defined by high fecundity and short generation times; consequently, overuse of broad-spectrum pesticides (i.e., increased selection pressure) and subsequent intensification of resistance is making the efficacy of chemical control problematic [119–121] (Figure 5).

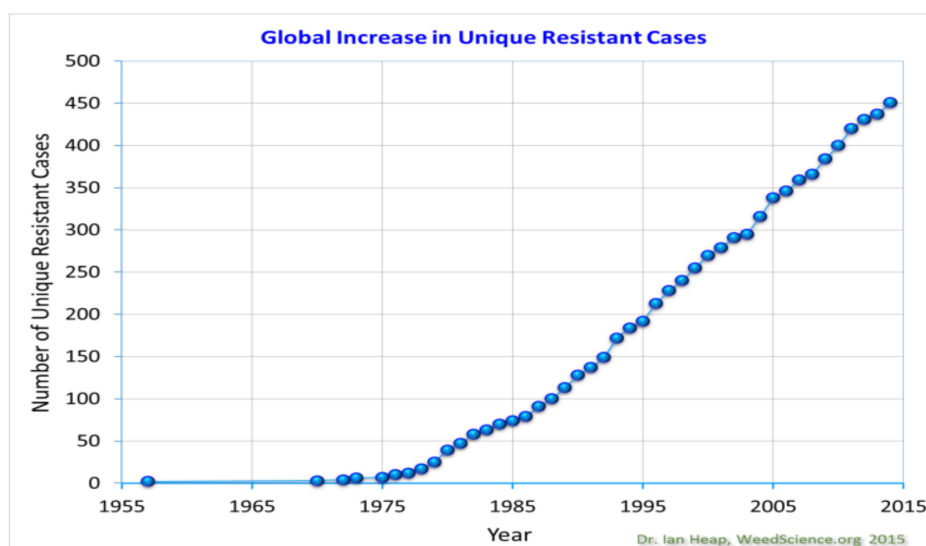


Figure 5. Change in herbicide resistance over time (from Heap [120]).

Prevention of pesticide resistance and management of pests could be improved by implementation of integrated pest management (IPM) practices. IPM is “knowledge intensive” [122] and is dependent on a broader set of strategies, including pest phenology, ecology, environment, economics, and available

technology, and it is not a single step, but a decision-making process that utilizes multiple tactics, including cultural, physical, mechanical, genetic, biological, in addition to chemical. IPM is intended to synthesize approaches into a time series of on-site evaluations, beginning with monitoring, threat assessment, application of pest management measures, and a follow-up estimate of their efficacy.

Given the inherent flexibility of IPM, it may provide a more versatile approach to dealing with climate-induced pest threats. Here is a simple example: cotton growers in Georgia were confronted with concurrent drought and increases in glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.). Growers responded by implementing a type of IPM, termed, “herbicide resistance management”, or “HRM (herbicide resistance management)”. This consisted of multiple strategies, including rotation with cotton cultivars tolerant to other herbicides or with stacked/multiple herbicide tolerance; increased crop rotation to increase management option and alter the weed species profile; using herbicides with different modes of action; and increasing other nonchemical means (tillage, hand pulling) to remove resistant Palmer amaranth [123,124]. While such initial changes can increase costs, they can, in the long term, be economically viable, depending on crop and regional resistance management [125]. Given the versatility of an IPM approach, it seems likely that it would be able to incorporate new technological advances (e.g., GIS pest monitoring) or management strategies (e.g., cover crops). Yet, given the over-reliance on pesticides, implementation of IPM may require a broader expertise among pest management specialists than is currently available. Nevertheless, it is important to recognize that IPM is not a new approach, and that it “has had only a limited impact in reducing overall use of pesticides” [122].

5.3. Basic Biology

Implementation of IPM will depend on improving our knowledge base regarding how climate and CO₂ alter pest–host biology. While there are numerous research topics in this regard, three are of especial concern: trophic interactions, pest evolution, and DTR.

With respect to trophic interactions, pest impacts are based on previous histories, i.e., a given pest species (“x”) inflicting “y” amount of damage in a managed system. This is an essential component of IPM in determining a given pest threat. However, this estimate is based on previous, consistent environments. Hence, as climate and CO₂ change, pests, their natural enemies, and their host plants will interact in different ways that, unfortunately, have not been adequately described or understood, due to their inherent complexity [126]. Yet, these changes are likely to result in temporal and spatial mismatches between pest and host, and between pest and natural enemy. Such mismatches in trophic interactions are likely to alter current understanding of pest threats, minimizing some, but exacerbating others. While this challenge is becoming increasingly recognized, (e.g., “damage niche”, “tritrophic relations”), a great deal of additional information regarding the behavior of pest, plant pathogens, and weeds in future circumstances is needed [42,127]. Progress in understanding agricultural microbiomes may support better mechanistic models of microbial responses to climate change [128].

Another critical uncertainty is the role of climate change/CO₂ on evolutionary adaptation. Over-reliance on chemical control is likely to increase selection pressure and pesticide resistance. Yet, fragmented natural environments and climate change, including extreme events, are also likely to impose new selection pressures on pest populations [129]. For example, Rodriguez-Trelles and Rodriguez [130] have documented adaptation to climate change in *Drosophila subobscura* Collin. Similar evolutionary adaptation has been suggested for plant pathogens [32,34] and weeds [131,132]. In contrast to pests, economic pressures often limit host genotypes to a narrower genetic range [133], limiting evolutionary response to climate and/or CO₂. A critical need exists to improve IPM efficacy by generating empirical data that tests evolutionary potential and fitness across groups of pest species. Increased genetic diversity among plant host species will also help to ensure that adaptation to changing conditions can be maintained, with targeted gene availability through global crop breeding networks and seed systems when needed [99]. The inherent uncertainty in predictions

for biotic interaction responses to climate change, suggests that a “no-regrets” adaptation strategy [134], i.e., actions that develop net social benefits regarding projected climate change and related impacts, should be a component of adaptation portfolios, through strengthening agricultural research and development infrastructures.

Finally, there is the issue not of warming, per se, but of DTR. Additional research needs to be conducted in pest species responses to DTR changes, as such changes can impact IPM strategies. Of specific note is that DTR can not only affect known pest populations, but may also bring new pest species into consideration.

6. Conclusions

As the climate changes, and as CO₂ increases, there will be risks associated with the global production of food, fiber, and feed. The physical nature of these risks, such as drought and temperatures for specific systems, such as food security, have been understandably well documented [135,136]. However, such risks should also consider the biological, as well as the physical constraints. Climate and CO₂ will also induce differential responses among pests that will alter their biology and evolution, and their subsequent impacts on managed plant systems, from crops to forests. At present, there is evidence to suggest that recent shifts in climate and rising CO₂ have already affected the distribution and biology of new and existing pest species in managed agricultural commodities, such as coffee. These shifts, and the economic and environmental consequences, will only be exacerbated with future climate and CO₂ projections.

This review acknowledges these changes, provides a specific context (coffee) where they can be evaluated, and offers a tentative (but by no means inclusive) list of vulnerabilities regarding current pest management. To respond to these vulnerabilities, it provides initial recommendations to strengthen the efficacy and resilience of future pest management efforts.

Overall, we believe that a systematic and integrated management approach—one that utilizes GIS technology, social networking, and visual assessments into traditional IPM practices to account for changing environments and pest biology—can meet these challenges.

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