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Climate Change, Carbon Dioxide, and Pest Biology: Monitor, Mitigate, Manage

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ABSTRACT: Rising concentrations of atmospheric carbon dioxide ([CO_2]) and subsequent changes in climate, including temperature and precipitation extremes, are very likely to alter pest pressures in both managed and unmanaged plant communities. Such changes in pest pressures can be positive (migration from a region) or negative (new introductions), but are likely to be accompanied by significant economic and environmental consequences. Recent studies indicate the range of invasive weeds such as kudzu and insects such as mountain pine beetle have already expanded to more northern regions as temperatures have risen. To reduce these consequences, a better understanding of the link between CO_2/climate and pest biology is needed in the context of existing and new strategies for pest management. This paper provides an overview of the probable biological links and the vulnerabilities of existing pest management (especially chemical control) and provides a preliminary synthesis of research needs that could potentially improve the ability to monitor, mitigate, and manage pest impacts.

KEYWORDS: *climate change, carbon dioxide, weeds, insects, disease, management*

INTRODUCTION

Since the onset of organized agriculture, approximately 10,000 years ago, unwanted biological species, or pests, have hampered human efforts in land management. These pests can, in a broad sense, be defined as those microbes, insects, or plants that directly reduce the quantity and quality of products obtained from managed systems, such as agriculture, forestry, or rangeland, or that can, once introduced, dominate the landscape so as to diminish species diversity and ecosystem function. They are well-recognized as having significant economic impacts (Table 1),[1] but can, as with invasive species, also negatively affect ecosystem function.

Table 1. Average Annual Losses in the United States from Pest Populations from Pimentel et al. (2000)

pest	% invasive[a]	% loss	crop loss ($ billion)	cost of control ($ billion)
insects	40	13	14	0.5
plant pathogens	65	12	21	0.6
weeds	73	12	23	3.0
total		37	58	4.1

[a] "Percent invasive" is the percentage of that pest population considered to be invasive.

As a consequence, pest management has been an integral aspect of human civilization, and the strategies used to limit pests' impact range from the simple (hoeing) to the sophisticated (insect pheromones, biopesticides). At present, these strategies vary greatly and include the identification and implementation of cultural, mechanical, chemical, and biological options. For developed countries such as the United States, Canada, Europe, and Japan, the application of chemicals remains among the most widely used methods for pest control for land managers. All pest management strategies, however, are a reflection of the kind of pest encountered, the available tools at hand, and the potential efficacy of the control measure.

The ongoing increase in atmospheric carbon dioxide concentration, [CO_2], will change pest biology in two fundamental ways. The first is indirect and reflects the changes in climate stability associated with the radiation trapping ability of CO_2 and other anthropogenic gases. An increase in the concentration of these gases will lead to an increase in global surface temperatures, with subsequent consequences on weather patterns, particularly precipitation frequency and amounts, as well as the occurrence of extreme weather events.[2] These changes in climate will affect the establishment, competitive ability, spread, and impact of pest species within managed and unmanaged systems. A second fundamental consequence is the "fertilization" effect of CO_2 on plant biology. Plants evolved at a time of high atmospheric carbon dioxide (4−5 times present values), but concentrations appear to have declined to relatively low values during the past 25−30 million years.[3] During this time evolution has selected for a small percentage of plants, principally tropical grasses, which have maximum photosynthetic rates even at the current low level of [CO_2]. However, these grasses (termed "C_4" plants) comprise only about 3−4% of all known plant species, the bulk (∼95%) of the 250,000+ plant species (termed "C_3" plants) lack optimal levels of [CO_2] needed to maximize photosynthesis and growth. For these plants, the recent and projected

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rise in atmospheric carbon dioxide represents a rapid increase of an essential resource. Numerous reviews and meta-analyses indicate that the ongoing increase in anthropogenic [CO_2] will stimulate photosynthetic rates, growth, and reproduction for numerous plant species.[4−7] The ongoing increase in [CO_2] therefore will directly stimulate the evolution and fecundity of weeds but will also indirectly affect insect and pathogen interactions in regard to their crop and weed hosts.[8]

Overall, these elementary biological aspects associated with rising [CO_2] and subsequent changes in climate are likely to alter pest distribution and impact, and it is unclear if previous management paradigms will be adequate to compensate for additional pest pressures. In this U.S.-based perspective our goals are two-fold: to elucidate and review the published links between climate change and the establishment, dominance, and spread of pest species; and to illustrate how change in climate and [CO_2] can alter current management practices. Weeds will be emphasized simply because most of the published research on climate/CO_2 and pests has focused on weed biology (agronomic and invasive); however, we would also stress that there are numerous aspects of climate change that are also likely to affect other economic or environmentally important pests of managed systems. Overall, we hope to identify specific vulnerabilities and begin a preliminary assessment of key research products that can help adapt and strengthen future management efforts.

■ CLIMATE AND CO_2 IMPACTS ON PEST BIOLOGY

Biogeography. Temperature, particularly minimum winter temperatures, can be a significant driver of shifts in insect, weed, and pathogen demography.[9,10] As temperature warms, species may expand or migrate. With climate change, such warming is projected to occur as a function of increasing latitude or altitude.[11]

The mountain pine beetle (MPB, *Dendroctonus ponderosae* Hopkins) is the largest contributor to insect-caused mortality for forests in western North America.[12] As determined by Mitton and Ferrenberg,[13] recent epidemics of the MPB are larger than any previously recorded, with damage observed at higher elevations and latitude than have previously been observed. As noted by other researchers,[14] because MPB do not experience diapause, their growth is determined by temperature, with evidence indicating that the life cycle in some broods has increased from one to two generations per year.[13] Overall, these data indicate that MPB are responding to climate change through faster development and increased range expansion with subsequent consequences on tree mortality.

In addition to rising temperature per se, seasonal temperatures are also projected to rise disproportionally more rapidly during the winter.[11] Winter is recognized as a significant factor in pathogen mortality with more than 99% of pathogen populations experiencing mortality.[15] As such, mild winters as well as warmer weather are associated with increased outbreaks of powdery mildew, leaf spot disease, leaf rust, and rhizomania disease.[16] Storm severity may also be a consideration. For example, the soybean rust pathogen (*Phakopsora pachyrhizi*) was probably introduced to the continental United States by hurricane Ivan.[17] Projected changes in storm severity or frequency could therefore contribute to increased vulnerability to new pathogen invasions.

Kudzu (*Pueraria lobata*) is well-recognized as a ubiquitous invasive vine found throughout the southeastern United States. Over 20 years ago, scientists at Duke University made a prediction as to the northward migration of kudzu with climate change.[18] Recent data from the Early Detection and Distribution Mapping System (EDDMapS)[19] relative to the original distribution as outlined by Sasek and Strain[18] are consistent with these predictions and indicate that kudzu has, in fact, migrated northward. Although additional work is needed, this northward movement may be associated with an increase in minimum winter temperatures.[10] Additional research on unwanted plant species by Sandel and Dangremond[20] used a trait−climate relationship between invasive and native grasses to demonstrate that warmer areas of California grassland contained a higher number of exotic plant species. The study provided an in situ evaluation regarding rising temperatures and species invasions over a broad geographic and taxonomic scale. Similar work for Europe has shown that in recent decades warming temperatures have resulted in transformations in the weed flora as thermophilic weeds, late-emerging weeds, and opportunistic weeds have become more prominent in cropping systems.[21]

Competition and Selection. Although the distribution of pests is being, or is likely to be, altered by climate change, it is also important to understand the role of climate and/or [CO_2] in their competitive success following establishment. At present little is known regarding competitive interactions among insects and microbial organisms, but a number of studies have examined the role of [CO_2] in altering growth and competitive ability for both agronomic and invasive weeds.

In agronomic evaluations, emphasis is placed on the different photosynthetic pathways when considering the impact of rising [CO_2] levels. That is because a commonly accepted axiom is that weeds possessing the C_4 photosynthetic pathway will show a minimal response to rising CO_2 levels, whereas most crops have the C_3 photosynthetic pathway and should, ostensibly, show a stronger growth response (relative to the C_4 weed) as [CO_2] increases.

However, a more realistic assessment should include a broader view of agro-ecosystems, where, on average, each crop competes with 8−10 weeds that are considered "troublesome".[22] In no instance does a C_3 crop compete solely with a C_4 weed (or vice versa). Instead, the most troublesome weeds (i.e., those that compete most effectively against a crop) are those that share similar morphological or phenological traits that are selected for in a given set of agronomic practices.[23] Often these weeds are simply wild relatives of the domesticated crop, for example, oat and wild oat, sorghum and shattercane, or rice and red rice. Consequently, in these circumstances, competitive outcomes in response to rising [CO_2] levels cannot be predicted solely on the basis of photosynthetic pathway.[24,25]

For those studies, however, that have examined the relative responses of crops and weeds with the same photosynthetic pathway to rising [CO_2], there is evidence to suggest that weeds, in general, show a stronger positive response to [CO_2] than the crop, with a greater reduction in crop yields as a consequence.[10,23] The basis for this increased competitive ability of weeds is unclear, but may be related to the greater genetic and phenotypic plasticity among wild species associated with environmental change.

For less managed plant communities, such as rangelands, forests, and pastures, the role of [CO_2] and/or climate change on invasive weed establishment and dominance is of obvious importance. It has been estimated that >200 million acres of natural habitat (primarily in the western United States) have

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already been lost to invasive weed species, with an anticipated loss of 1200 ha per day.[26]

The response of individual invasive plants suggests that they may respond strongly to [CO_2]. For example, cheatgrass (*Bromus tectorum*), a ubiquitous invasive weed of the great basin, is associated with the frequency and spread of natural and anthropogenic fire outbreaks. Ziska et al. and Blank et al. demonstrated that recent and projected [CO_2] levels could exacerbate fire frequency by increasing both the biomass and flammability of this species.[27,28] Biomass burning, in turn, is an important source of not only CO_2 but also black carbon, an important short-term climate forcer.[29] Overall, there are a number of studies of individual invasive weeds that suggest a stronger than anticipated growth response relative to other species.[30−32]

In addition, there are an increasing number of studies demonstrating that [CO_2] could preferentially select for invasive species growth and seed production within a plant community (Table 2).[33−38] As with agronomic weeds, the biological basis for the greater observed response among invasive plant species to rising [CO_2] is not entirely clear. Blumenthal[39,40] has suggested fast-growing species that escape their natural enemies (e.g., invasive plants) may benefit more from additional resources such as nitrogen deposition or CO_2 enrichment. However, other environmental parameters associated with climatic change, including drought, temperature, and longer growing season, have not been explicitly examined in conjunction with rising [CO_2] as a possible explanation for the greater response of agronomic or invasive weeds.

Table 2. Invasive Plant Species, Associated Plant Community, and Whether Increasing [CO_2] Favors the Relative Abundance (Greater Fraction of Total Biomass) of the Invasive Species within That Community

invasive plant species	community	favored?	ref
honey mesquite	Texas prairie	yes	33
red brome	desert	yes	34
Japanese honeysuckle	forest understory	yes	35
cherry laurel	forest understory	yes	36
yellow star thistle	california grassland	yes	37
dalmation toadflax	mixed-grass prairie	yes	38

CLIMATE AND CO_2 IMPACTS ON PEST MANAGEMENT

Detection. Foremost among land managers is the axiom of "know your enemy". Recognizing and responding to those biological threats that are associated with economic or environmental harm for a highly managed agro-ecosystem (soybean farm) or less managed plant community (pine plantation) remain basic principles of effective pest management. Early detection is especially critical as costs and impact increase exponentially with pest establishment.[41]

Climate change, in combination with increased global trade and travel, is likely to alter pest distribution. For example, as arctic ice melts, new routes for transport are likely with new introductions of invasive pest species for that system. The spread of pests between continents, and their further spread as a result of a changing climate, emphasize the need to increase our knowledge of pest species to include those which heretofore may not have been present for a specific region but are recognized globally as an economic or environmental threat.

Chemical Control. Although increasing the capacity of land managers to detect new pest threats associated with climate change and increasing [CO_2] is of obvious importance, attention must also be paid to those practices that can be utilized to keep pest populations at acceptable levels and how, in turn, those practices are likely to be affected by climate or increasing [CO_2]. Such practices vary widely and include cultural, mechanical, chemical, and biological options. However, for developed countries such as the United States, chemical application of pesticides remains, by far, the most widely used means to control pest populations. Among pesticides, herbicides are the most widely applied class of pesticides, reflecting the greater limitations imposed by weeds in managed systems[23]

Physical changes in the environment associated with climate change can influence chemical efficacy. For example, an increase in the number of extreme weather events (e.g., heavy rains) can reduce field access necessary for pesticide applications. Similarly, variability in wind speed, humidity, soil/air temperatures, etc., can reduce the effectiveness of application or coverage as well as pesticide degradation and volatilization. Windier conditions would reduce suitable opportunities for application by increasing drift risk. Overall, increased environmental variation would reduce application opportunities, alter pesticide persistence, and increase the potential injury of nontarget organisms.

The role of rising temperature on pest populations and pesticide use was examined for commercial soybean grown over a 2100 km north−south transect that varied in minimum temperatures from −28.6 to −5.2 °C.[42] Although soybean yield per hectare did not vary by state, total pesticide applications increased for all classes of pesticide (fungicide, insecticide, and herbicide) as a function of rising minimum temperature. For herbicide use, the increase was associated with a greater number

Table 3. Summary of the Effects of [CO_2] and Herbicide Resistance to Date

weed species	photosynthetic pathway	herbicide (active ingredient)	change in efficacy?	ref
Canada thistle (*Cirsium arvense*)	C_3	glyphosate	declined	43
Canada thistle (*Cirsium arvense*)	C_3	glufosinate	declined	Ziska (unpublished)
dallisgrass (*Paspalum dilattatum*)	C_4	glyphosate	declined	44
lambsquarters (*Chenopodium album*)	C_3	glyphosate	declined	45
lovegrass (*Eragostis curvula*)	C_4	glyphosate	declined	44
quackgrass (*Elytrigia repens*)	C_3	glyphosate	declined	46
red-root pigweed (*Amaranthus retroflexus*)	C_4	glyphosate	none	45
Rhodes grass (*Chloris gayana*)	C_4	glyphosate	declined	44
smut grass (*Sporobolus indicus*)	C_4	glyphosate	none	44

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of perennial weeds in southern, relative to northern, states. Short-term projections (to 2023) indicated that pesticide use is likely to increase overall for all states along the measured transect as winter temperatures warm.[42]

As weeds are likely to respond independently to rising [CO_2], there have been a number of greenhouse and field studies that have examined the interaction between elevated [CO_2] and herbicide efficacy. Although additional trials are needed, the data, while preliminary, suggest that elevated [CO_2] can reduce the efficacy of glyphosate, the most widely applied herbicide in North America, in the majority of species studied (Table 3).[43−46]

The basis for the reduction in herbicide efficacy with elevated [CO_2] is unclear. For Canada thistle (*Cirsium arvense*) glufosinate or glyphosate applications resulted in complete plant desiccation 2 weeks after application;[43] however, regrowth of the elevated [CO_2] treated plants occurred within a month after spraying. The ability to regrow after herbicide application could be associated with a greater stimulation of belowground root biomass with additional CO_2 and dilution of systemic herbicides such as glyphosate. Lack of root kill, in turn, would give rise to asexual regeneration, a characteristic of Canada thistle fecundity. However, there are numerous other potential mechanisms related to how increasing [CO_2] and/or climate could alter herbicide chemistry. Of particular note is the role that [CO_2] and climate change, particularly longer growing seasons, could play in altering flowering times. Such alterations could change floral synchronization and gene transfer between related plant species. For example, as [CO_2] increased from 300 to 600 ppm, gene flow from weedy rice to cultivated, herbicide-resistant rice increased from 0.22 to 0.71%.[47]

Alternatives to Chemical Management. Considerably less research has examined the role of climate and/or increasing [CO_2] on alternative means of pest control, most notably, mechanical, biological, and cultural. However, there are a number of potential and some empirical observations that merit attention in this regard. For example, the removal of weeds via physical cultivation would be affected by rising [CO_2] with faster time to vegetative cover and/or extreme weather (e.g,. precipitation), with both events limiting available tillage times. If, as observed with Canada thistle and other perennial weeds, more CO_2 results in greater root or rhizome growth and an enhanced capacity for asexual reproduction,[43,48] physical fragmentation of belowground plant parts could increase weed spread. For transgenics, more CO_2 could also alter plant chemistry and insect management. For example, in transgenic *Bacillus thuringiensis* (Bt) cotton, elevated [CO_2] reduced Bt protein production relative to the ambient [CO_2] condition.[49] The use of biocontrol agents is dependent on synchrony between different biological organisms. As climate or [CO_2] changes, the differential response among host, biocontrol agent, and pest target is likely to change. For example, increasing temperatures may differentially affect the physical distribution and/or phenology of host, agent, and target, with negative consequences for biocontrol efficacy. Culturally, the use of physical resources such as water to control pests might also be affected. For example, in rice, flooding, which is commonly used to control weeds in rice cultivation, would be affected by climate change, which is expected to limit fresh water supplies.

■ MOVING FORWARD

In the context of climate change, [CO_2], and pest biology/management, there are three broad areas that require additional research and measurement.

Measure: Identifying and Quantifying Key Unknowns. As the climate changes and [CO_2] rises, what are the biological parameters that will define where, when, and which pest species will occur? Is there both contraction and expansion of pest ranges with climate change as suggested by Bradley,[50] with potential opportunities for restoration? What is the role of climate and [CO_2] in phenotypic plasticity, evolutionary adaptation, and genetic change among pest populations? How will these biological changes alter competitive abilities and economic impact? Is there quantitative information for the likely impact (economic or environmental) should a new pest species be introduced? Does climate or [CO_2] change the "acceptable pest level" and how is that, in turn, defined for the specific crop or system being managed? What specific agro-ecosystems or managed plant communities are especially vulnerable to climate (e.g., MPB and forest plantations)? What aspects (chemical, cultural, physical, biological) of current control strategies will be efficacious with a shifting climate or more CO_2? How does this vary with the plant system being managed? What is the potential threat of climate and/or [CO_2] in gene transfer between GMOs and weedy relatives? Will rising winter temperatures result in greater pesticide applications to maintain economic yield thresholds (e.g., ref 39), and if so, what are the implications for increasing pesticide resistance?

Mitigate: Preventing New Pest Threats. Detection remains a fundamental aspect of preventing the establishment and spread of new and existing pest threats. As such, it will remain a necessary mitigation tool as climate shifts pest ranges; however, additional information and communication, particularly in regard to identification and location, will be crucial in this regard. Whereas many land managers have an historical knowledge of known pests of economic or environmental importance, they may be unfamiliar with new threats that may emerge with climate change. Familiarization using new tools can help identify and mitigate such threats and are (albeit slowly) becoming available. For example, EDDMapS[19] is a Web-based mapping system developed by the University of Georgia Center for Invasive Species and Ecosystem Health that documents and tracks the distribution of invasive pests with the United States. It synthesizes data from a number of public and private sources that are used to create a national invasive species database. Such a database can, over time, provide useful information as to potential new threats and shifts in existing pest species in the context of a warming climate.[51] For existing agronomic pests, there is ongoing work to examine climate-induced shifts in weed distribution and the "damage niche" in regard to cropping systems (e.g., corn, ref 52). Information in this regard is vital as land managers increasingly recognize that climate change and the international homogenization of pest threats through trade represent an urgent need to increase and coordinate detection efforts across scientific disciplines.

Manage: Improving Pest Control in an Uncertain Climate. There are, in addition to the biological and managerial aspects of climate change/[CO_2] discussed here, a myriad of other concerns regarding pest management, from increased pesticide resistance to trade barriers. Consequently, new management strategies must encompass not only climate

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change but a host of other environmental and/or social consequences.

Given these ongoing challenges, there remain a number of prosaic approaches to pest management. For example, cotton growers in Georgia were met with simultaneous drought and significant increases in glyphosate-resistant amaranth (*Amaranthus palmerii*).[53] Growers responded by implementing what has been termed "herbicide resistance management (HRM)". This included using multiple strategies to slow the spread of glyphosate resistance by rotating with conventional cotton cultivars (i.e., no glyphosate application); increased crop rotation to improve water retention (cotton uses a lot of water) and reduce pest loads; using herbicides with different modes of action; and the increased use of other, nonchemical means (mechanical tillage, hand-pulling) to remove resistant weed populations.

The use of such a strategy is reflective of integrated pest management (IPM) practices that can, if properly applied, synthesize approaches into a time series of on-site evaluations beginning with monitoring, threat assessment, application of control measures, and an estimate of their efficacy. Implementation of IPM would begin with prevention, including, if applicable, cultural management such as crop rotation and cleaning of equipment to prevent pest transfer. Prevention would be concurrent with monitoring and identification so as to distinguish between likely and unlikely pest impacts. Should pest outbreaks occur, control measures, including chemical use, would be applicable only if a pest population threshold were reached. Ultimately, then, decisions regarding management should reflect an understanding of the threat, the potential economic cost, associated environmental damage, and long-term efficacy of the control measure.

An integrated approach is sufficiently versatile to include multiple aspects of detection and control options; however, these aspects, in turn, need to reflect new and updated information. As management encompasses a greater number of economic and environmental transitions, modeling efforts may be able to provide a framework to guide decision makers to more effectively integrate pest control with climatic uncertainty. For example, as CO_2 can result in a larger Canada thistle plant with greater potential impact on soybean yield in no-till conditions,[54] the threshold limit on the number of Canada thistle plants allowed prior to application of a control measure would decrease. Inclusion of information that quantifies the influence of climate and [CO_2] on pest biology can strengthen any integrated pest management approach.

SUMMARY

Although the links between climate change and food security are receiving justifiable attention, inclusion of additional risks to the food supply imposed by changes in pest biology is largely ignored, even as the role of pests in limiting the production of food, fiber, and feed is universally acknowledged. In this perspective, we have provided an overview of how climate change and rising CO_2 levels have, and will, continue to affect the distribution and biology of new and existing pest species in both managed (e.g., corn field) and less managed plant communities (e.g., pastures) in the United States. These changes, in turn, are likely to result in negative economic and environmental consequences from pest populations for a number of different land systems, even if opportunities for pest migration and land restoration are, potentially, possible. However, the overall consequences are not fully elucidated and a number of additional experimental measurements will need to be undertaken before the full extent of their impact can be quantified. In addition, mitigation efforts, primarily those related to early detection and response, will need to be updated to account for new pest species and, potentially, associated changes in their ability to incur damage. Finally, we suggest that a systematic and integrated management approach, one that reflects changing environmental and pest pressures, can be derived from traditional IPM practices, but with inclusion of innovative modeling efforts that encompass new biological paradigms regarding pest biology, [CO_2], and climate change.

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Notes

The authors declare no competing financial interest.

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