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CLIMATE CHANGE, BIOLOGICAL INVASIONS AND CHALLENGES FOR SUSTAINABLE CONTROL OF PESTS AND DISEASES IN AGRICULTURAL CROPS

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Abstract: Present-day global agriculture is strongly affected by climate change. Droughts driven by reduced precipitation and higher evapotranspiration directly limit plant growth and yields, while rising temperatures indirectly alter crop cycles and weed communities. Climate change is also expected to intensify pest infestations by enhancing pest reproduction and facilitating biological invasions, whose stages (introduction, colonization, establishment, and spread) are climate dependent. Agroecosystems, due to low biodiversity, are especially vulnerable to biological invasions, increasing the phytosanitary relevance of both invasive and native pests and creating the need to intensify research on control possibilities of their infestations.

Keywords: Global warming, Harmful invasions, Agro-ecosystems, Pest control, Future expectations

INTRODUCTION

Agricultural sustainability is increasingly threatened by the accelerating pace of global environmental change, which is reshaping the functioning and resilience of agroecosystems worldwide. Modern agricultural systems are exposed to a wide range of interacting stressors, among which climate change and biological invasions are particularly significant due to their broad and long-lasting effects on pest and disease dynamics. Climate change modifies key environmental drivers such as temperature regimes, precipitation patterns, and seasonal variability, while also increasing the frequency and intensity of extreme weather events, including droughts, heatwaves, and floods. These changes directly influence the survival, reproduction, and geographic distribution of crop pests and pathogens, often favouring their proliferation and spread (Skendžić et al., 2021). At the same time, the expansion of global trade, human mobility, and landscape modification facilitates the introduction and establishment of invasive species beyond their native ranges. Once established, invasive pests and pathogens can disrupt ecological balances, outcompete native species, and exploit crops that lack effective natural defenses. The combined effects of climate change and biological invasions intensify pest and disease pressures, undermine the effectiveness of conventional control measures, and increase uncertainty for farmers and decision-makers. Addressing these challenges requires the development of innovative, integrated, and sustainable crop protection strategies that are capable of adapting to rapidly changing environmental conditions while minimizing ecological and socio-economic impacts.

CLIMATE CHANGE AND PEST/DISEASE DYNAMICS

Climate change influences agricultural pests and diseases through a combination of direct effects on the physiology, behaviour, and life history traits of these organisms, as well as indirect effects mediated by host plants, natural enemies, and broader ecosystem processes. Among climatic variables, temperature plays a central role in regulating insect metabolism, development rate, survival, and reproductive success. As temperatures rise, insect life cycles often accelerate, leading to shorter generation times and an increased number of generations per growing season. This phenomenon can result in rapid population growth and higher damage potential in many economically important pest species (Bale et al., 2002; Eickermann et al., 2023). In addition, milder winters associated with climate warming tend to reduce overwintering mortality, enabling pests to persist at higher densities and expand their geographic ranges into regions that were previously climatically unsuitable. Such range expansions have been documented for several major agricultural pests, including the Colorado potato beetle, *Leptinotarsa decemlineata* (Say), as well as numerous aphid species (Deutsch et al., 2018).

Plant pathogens are similarly sensitive to climatic conditions, particularly temperature and moisture. These factors strongly influence fungal and bacterial sporulation, dispersal mechanisms, infection efficiency, and disease progression. Warmer and wetter environments can intensify the incidence and severity of major diseases such as rice blast and wheat rusts (Strange and Scott, 2005). Moreover, alterations in rainfall patterns affect pathogen transmission pathways and soil moisture regimes, often creating favourable conditions for soil-borne and root-infecting diseases (Pautasso et al., 2012). Extreme climatic events, including prolonged droughts and heat waves, further exacerbate these dynamics by imposing physiological stress to plants. Such stress can weaken plant immune responses and defense mechanisms, increasing crop vulnerability to opportunistic pathogens and pest outbreaks. Together, these direct and indirect effects underscore the complex ways in which climate change reshapes pest and disease pressures in agricultural systems.

BIOLOGICAL INVASIONS: DRIVERS AND CONSEQUENCES

Alien species can be defined as “invasive” when they become introduced into areas outside their natural range, where they negatively impact native biodiversity and ecosystem services. Biological invasions are facilitated by human activities including international trade, travel, and landscape disturbance. Invasive species often exhibit high reproductive rates, broad environmental tolerance, and the ability to exploit novel niches (Lockwood et al., 2013). In agricultural contexts, invasive insects, mites, nematodes, and pathogens can rapidly become dominant pests especially because their native natural enemies may be absent or ineffective.

Examples of impactful invasions for the EPPO area may include the spotted wing drosophila (*Drosophila suzukii* Matsumura), which infests soft fruits across temperate regions (Cini et al., 2012; Sario et al., 2024), and the fall armyworm [*Spodoptera frugiperda* (Smith)], which has recently spread from the Americas to Africa and Asia, causing significant maize yield losses, and is presently representing a quarantine risk for many crops in south European countries (Goergen et al., 2016). Similarly, the bacterial pathogen *Xylella fastidiosa* Wells et al. has decimated olive groves in the Mediterranean, showing how invasive microbes can transform agricultural landscapes and economies (Bucci, 2018).

Invasions can also interact with climate change. All phases of a biological invasion (e.g.: introduction, colonization, establishment, and spread) are influenced by climate change, which facilitates the spread of many alien species and creates new opportunities for them to become invasive, but also reduces the resilience of habitats to biological invasions, with the agroecosystems being particularly vulnerable due to their low diversity. Climatic suitability models suggest that many invasive species will expand their potential ranges under future climates, exposing new crops and regions to invasion risk (Early et al., 2016). Climate-driven phenological shifts may synchronize invasive herbivore activity with vulnerable crop stages, amplifying damage potential.

INTERACTION BETWEEN CLIMATE CHANGE AND BIOLOGICAL INVASIONS

The interplay between climate change and biological invasions presents complex and often synergistic challenges for agricultural and natural ecosystems. Climate change can weaken ecological resistance to invasions by altering competitive interactions, disrupting mutualistic networks, and modifying the availability of critical resources. For instance, drought stress or prolonged heat events may reduce the vigour of native plant species, creating ecological niches that can be rapidly exploited by invasive weeds. These invaders often possess traits that allow them to outcompete crops and native vegetation for water, nutrients, and light, thereby intensifying their negative impacts on agroecosystem productivity and stability. At the same time, climate change can enhance the reproductive success, survival, and dispersal capacity of invasive pest species. Rising atmospheric CO_2 concentrations, for example, may increase overall plant biomass while simultaneously altering leaf chemistry, reducing plant defenses, and creating more favorable conditions for herbivores and other pests (Robinson et al., 2012). When coupled with warmer temperatures, these changes can facilitate the establishment and expansion of invasive pest populations into higher latitudes and previously unsuitable regions. Within agricultural systems, such interactions often contribute to the emergence of pest complexes, in which multiple pest species co-occur and inflict simultaneous damage to crops, significantly complicating pest management strategies. Furthermore, shifting climate patterns can promote the spread of novel disease vectors or expand the ranges of already established ones, heightening the risk of outbreaks. Examples include the changing distribution of virus-transmitting whiteflies, which are becoming more prevalent in regions experiencing warmer conditions, posing additional threats to global food security (Aregbesola et al., 2019; Milenovic et al., 2023a). Understanding and mitigating these intertwined effects are therefore critical for developing resilient, adaptive, and sustainable approaches to crop protection in the face of ongoing environmental change.

CHALLENGES FOR SUSTAINABLE CONTROL

Achieving sustainable control of pests and diseases in the context of climate change and increasing pressures from biological invasions requires a multifaceted approach that addresses interconnected challenges. Solutions must integrate ecological understanding, innovative technological tools, and socio-economic considerations, ensuring that management strategies are resilient, adaptable, and effective across diverse agricultural systems while minimizing negative impacts on ecosystems and communities.

Limitations to Conventional Strategies

Traditional pest control strategies have historically depended heavily on chemical pesticides, particularly within monocultural crop systems. While initially effective, the repeated and widespread use of chemical control has often led to the evolution of resistance among pest populations, creating a major challenge for maintaining long-term pest management effectiveness (Vorley and Dittrich, 1994). This problem is further compounded under climate change, which can reduce pesticide efficacy by increasing pest metabolic rates, accelerating development, and altering feeding or reproductive behaviours, thereby diminishing the intended impact of chemical applications. Invasive pest species add an additional layer of complexity, as they often lack co-evolved susceptibilities to pesticides designed for native or regionally established pests. Their novel interactions with local crops and ecosystems can render conventional chemical programs less effective, requiring higher doses or more frequent applications, which in turn can exacerbate resistance development and environmental impacts. Together, these factors highlight the urgent need for integrated, adaptive, and ecologically informed pest management strategies that move beyond sole reliance on chemical controls while addressing the dynamic pressures posed by climate change and biological invasions.

Monitoring and Early Detection

The rapid detection and monitoring of invasive species, as well as shifting pest populations, is essential for effective and timely management. Early identification allows interventions before populations become firmly established, reducing both ecological damage and economic costs. However, existing surveillance networks are often fragmented and poorly coordinated across local, regional, and international scales, limiting their effectiveness. Delays in detection can allow invasive species to spread widely, making containment and control significantly more difficult and expensive. Climate variability further complicates monitoring efforts, as changes in temperature, rainfall, and seasonal patterns introduce unpredictability into pest life cycles and phenology. This uncertainty can disrupt established monitoring schedules and reduce the accuracy of risk forecasts, making it harder to anticipate outbreaks and allocate management resources efficiently. Improving coordination, integrating predictive modelling and expanding adaptive surveillance strategies, are therefore critical for enhancing the resilience of agricultural systems in the face of evolving pest threats.

Forecasting Under Uncertainty

Predictive models play a central role in risk assessment and in designing effective management strategies for agricultural pests and diseases. However, accurately forecasting pest and disease dynamics under changing climatic conditions remains highly challenging due to substantial uncertainties. Climate projections differ across emission scenarios, and the responses of pests, pathogens, and crops are shaped by complex, multifactorial interactions, including temperature, precipitation, extreme events, and biotic interactions. These uncertainties complicate decision-making and can limit the usefulness of single-factor models. To improve reliability, there is a clear need for integrated modelling approaches that combine climate projections with crop phenology, pest and pathogen biology and landscape-level structure and connectivity. Such comprehensive models can generate more actionable forecasts, guide timely interventions, and support adaptive management strategies capable of responding to dynamic environmental conditions and emerging pest threats (Garrett et al., 2011; Lamichhane et al., 2015).

Sustainable Alternatives and Integrated Approaches

To address these challenges, sustainable pest management must transition toward integrated and resilient strategies, with special emphasis on Integrated Pest Management (IPM) techniques, which combine biological control, host plant resistance, cultural practices, physical methods and a judicious use of pesticides to reduce pest impacts while minimizing environmental harm. Biological control agents, such as parasitoids, predators and entomopathogenic micro-organisms, can provide long-term suppression of pest populations when properly preserved and deployed (van Lenteren, 2012). Naturally, appropriate adaptations to modified environmental conditions resulting from climate change will have to be foreseen and planned, as suggested for example in recent studies on the prospects for biological control of the sweetpotato whitefly, *Bemisia tabaci* (Gennadius), under climate change scenarios (Milenovic et al., 2023b, 2023c). Crop diversification, rotations, and habitat management can also enhance natural enemy communities and disrupt pest life cycles.

Breeding crops for climate-resilient resistance to pests and pathogens is another key strategy. Advances in genomics and phenotyping accelerate the development of resistant cultivars tailored to anticipated climatic stressors (Poland et al., 2011). However, resistant varieties must be part of diversified systems to delay resistance breakdown.

Technological innovations including remote sensing, machine learning, and decision support systems can improve monitoring and targeted interventions. These tools can assimilate large datasets from environmental sensors and pest traps to inform dynamic management recommendations.

POLICY AND INSTITUTIONAL DIMENSIONS

Effective governance frameworks are essential to support sustainable pest and disease control under conditions of global environmental change. Policymakers play a key role in strengthening international cooperation on biosecurity, harmonizing quarantine regulations and investing in efficient monitoring and early-warning surveillance systems. In parallel, economic incentives that promote the adoption of sustainable agricultural practices, such as payments for ecosystem services, targeted subsidies, and long-term support for extension and advisory programs, can significantly accelerate farmer uptake of resilient pest management strategies. Strengthening linkages between research institutions, extension services, and stakeholders is also crucial to ensure that scientific knowledge and technological innovations are effectively translated into field-level applications. Furthermore, participatory approaches that actively involve farmers and local actors in the co-design and implementation of management strategies can enhance their relevance, feasibility, and long-term adoption, ultimately improving the resilience and sustainability of agroecosystems.

CONCLUSION

Climate change and biological invasions act synergistically to intensify the challenges associated with the control of pests and diseases in agricultural crops. Their combined effects modify pest and pathogen population dynamics, disrupt ecological interactions, and reduce the stability and resilience of agroecosystems. As a consequence, many conventional control strategies, largely based on chemical inputs or simplified production systems, are becoming less effective and increasingly unsustainable. Addressing these complex and evolving challenges requires the adoption of integrated, adaptive, and environmentally sustainable management approaches, grounded in a solid scientific understanding of ecological processes and climate-pest interactions. Such approaches must be supported by responsive and forward-looking policy frameworks capable of promoting innovation, risk prevention, and long-term resilience. Only through coordinated efforts across disciplines, sectors, and spatial scales, linking research, policy, and agricultural practice, can cropping systems remain productive, resilient, and capable of ensuring food security under conditions of ongoing climate change and increasing biological invasion pressures.

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