台灣農業研究 (J. Taiwan Agric. Res.) 73(3):153–168 (2024)
https://doi.org/10.6156/JTAR.202409_73(3).0001

Feature Article

Challenges and Future Directions of Predatory Mites as Biological Control Agents under Climate Change

Jhih-Rong Liao[1,*], Chyi-Chen Ho[2,3], and Chiun-Cheng Ko[4,†]

Abstract

Liao, J. R., C. C. Ho, and C. C. Ko. 2024. Challenges and future directions of predatory mites as biological control agents under climate change. J. Taiwan Agric. Res. 73(3):153−168.

Climate change significantly challenges agricultural ecosystems, impacting pest and natural enemy dynamics and the effectiveness of biological control. Predatory mites (phytoseiid mites), crucial in the sustainable management of various agricultural pests, are particularly susceptible to these changing conditions. This review focuses on the influence of climate change on the biological control potential of predatory mites, identifying critical gaps in current knowledge that limit the development of climate-resilient biological control strategies. It examines how altered temperature regimes, precipitation patterns, and extreme weather events affect the physiology, distribution, and interactions of predatory mites with their prey. The review highlights the necessity for adaptive strategies to preserve and enhance the biological control efficacy of predatory mites against climate change. Through case studies, we illustrate practical implications and adaptive measures in managing predatory mites under changing climatic conditions. Urging dedicated research into species-specific climatic adaptability and the enhancement of predictive modeling for biological control outcomes, this analysis emphasizes the imperative for innovative management practices to tackle the challenges posed by climate change. A holistic approach, merging ecological, genetic, and technological insights, is crucial to sustain the functionality of biological control systems in a warming world.

Key words: Climate resilience, Pest management, Adaptation strategies, Ecosystem dynamics, Sustainable agriculture.

INTRODUCTION

The quest for sustainable pest management strategies has emphasized the critical role of natural enemies within agricultural ecosystems, with predatory mites from the Phytoseiidae family at the forefront. Controlling a broad spectrum of agricultural pests such as spider mites, thrips, and whiteflies have been a key focus of global research and application since the 1970s. This shift towards biological control methods was driven by concerns over the environmental and health impacts of chemical pesticides (Huffaker *et al*. 1970; McMurtry *et al*. 1970, 2013, 2015; Chant & McMurtry 2007). Phytoseiid mites are known for their remarkable adaptability and high rates of growth and reproduction under favorable conditions, transitioning rapidly through 4 immature stages and with mated females capable of producing several eggs per

Received: April 11, 2024; Accepted: June 16, 2024.
* Corresponding author, e-mail: k1107053@hotmail.com
1 JSPS International Fellow, Systematic Zoology Laboratory, Department of Biological Sciences, Tokyo Metropolitan University, Tokyo, Japan.
2 Former Research Fellow, Applied Zoology Division, Taiwan Agricultural Research Institute, Taichung City, Taiwan, ROC.
3 Research Fellow, Taiwan Acari Research Laboratory, Taichung City, Taiwan, ROC.
4 Professor, Department of Entomology, National Taiwan University, Taipei, Taiwan, ROC.
† Deceased, 29 October 2020. This paper is dedicated to the memory of the late Chiun-Cheng Ko.

day (McMurtry *et al*. 2013; Ghazy *et al*. 2018; Zhang *et al*. 2019). This biological potential facilitates their commercial mass production for biological control applications. Yet, in natural environments, large populations of phytoseiid mites are uncommon, suggesting that a complex interplay of environmental factors influences their abundance (Ghazy *et al*. 2016).

Globally, more than 2,700 phytoseiid species have been recorded, demonstrating significant biodiversity that is invaluable in combating a variety of agricultural pests (Demite *et al*. n.d.; Chant & McMurtry 2007). Severty phytoseiid species, including novel discoveries, and introduced species have been recorded in Taiwan, underscoring the country's critical role in phytoseiid research and global biodiversity contributions (Liao *et al*. 2020a, 2021b, 2023a, 2023b). Despite its small size, Taiwan's contribution is notable compared to the United States with 318 species and Japan with 101 species (Demite *et al*. n.d.). This underscores the need for further exploration of phytoseiid biodiversity, potentially revealing species with untapped biological control potential or enhanced climate resilience.

Climate change significantly impacts agricultural ecosystems by creating complex interactions among plants, herbivorous pests, natural enemies, and the environment. These tritrophic interactions become even more intricate when additional trophic levels such as pollinators and decomposers are considered. This leads to multifaceted effects, including direct impacts on species' physiology and behavior, as well as indirect effects through altered species interactions and ecosystem processes (Tylianakis *et al*. 2008; Thomson *et al*. 2010; Gerard *et al*. 2013; Welch & Harwood 2014; Han *et al*. 2019; Harvey *et al*. 2023). Temperature fluctuation, a key aspect of global climate change (Naz *et al*. 2022), poses significant challenges to the balance between phytoseiid mites and their prey (Ghazy *et al*. 2016). This creates a complex scenario, which both direct and indirect effects of climate change on natural enemies and their prey remain largely unpredictable (Fig. 1) (Nechols 2021). The behavioral and physiological parameters of these mites, central to their survival, development, and reproduction, are significantly influenced by the ambient temperature. Extreme temperatures can provoke stress, reducing survival and reproductive efficiency, or even leading to death under chronic conditions (Salt 1961; Denlinger 1991; Morewood 1992; Veerman 1992; Broufas & Koveos 2001; Ghazy *et al*. 2016; Zhang *et al*. 2016; Nakai *et al*. 2021). In addition, heat waves lead to differential responses between natural enemies and prey, with implications for biological control outcomes (Tscholl *et al*. 2023). Despite these challenges, phytoseiid mites exhibit remarkable adaptability, having evolved strategies like hibernation and reproductive diapause to survive harsh conditions. These adaptation measures underscore the need for in-depth research into species-specific responses to temperature extremes, which are becoming more unpredictable with climate change. This emphasizes the importance of strategic adaptation to maintain the efficacy of phytoseiid mites as biocontrol agents in the face of warming climates (Nechols 2021).

This article reviews the current researches on how climate change impacts the biological control potential of predatory mites and explores adaptation strategies to sustain their effectiveness. By identifying key research gaps and suggesting future directions, this review aims to enhance biological control practices amidst climatic uncertainties, supporting sustainable agricultural ecosystems through better understanding and adaptation to environmental stresses affecting phytoseiid mites.

PHYTOSEIID MITES: PILLARS OF BIOLOGICAL CONTROL

Phytoseiid mites, belonging to the family Phytoseiidae, are paramount in the arsenal of biological control agents used in agricultural ecosystems. With over 2,700 species across 90 genera globally, these mites demonstrate signifi-

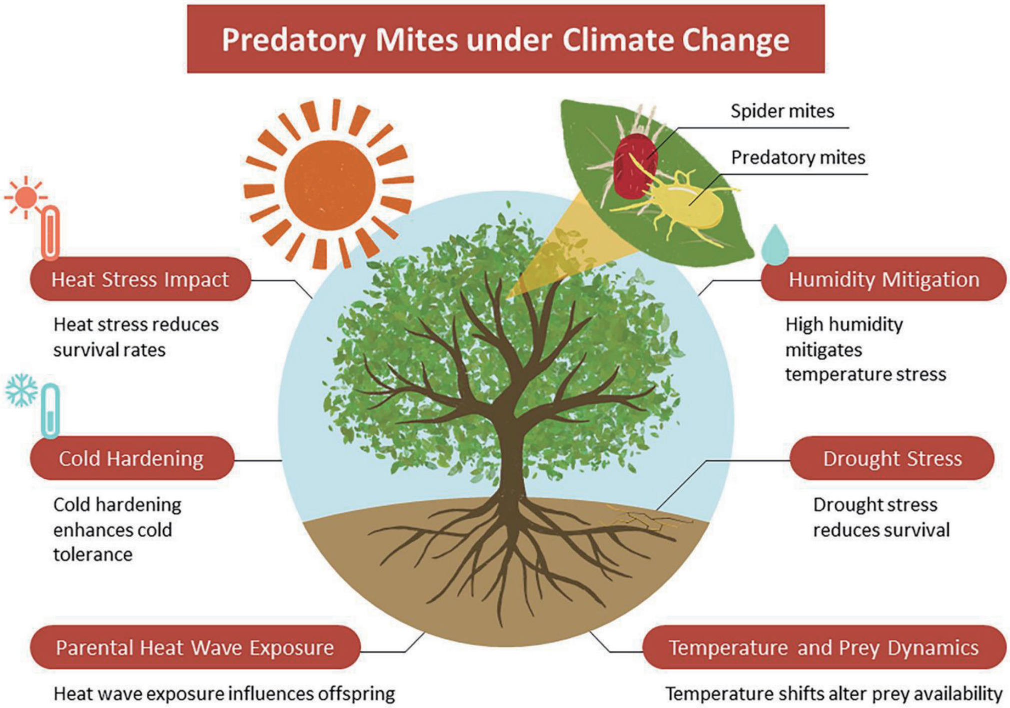

Fig. 1. Climate change affects predatory mites as biological control agents through multiple trophic levels, impacting their interactions with prey, host plants, and the environment.

cant diversity and adaptability—traits that make them formidable adversaries against a range of agricultural pests (Demite *et al*. n.d.; Chant & McMurtry 2007). The lifestyles are classified into 4 major types based on feeding habits, from specialized mite predators to pollen-feeding generalists, allowing for tailored biological control strategies to match specific pest scenarios (McMurtry & Croft 1997; McMurtry *et al*. 2013). Type I mites are efficient predators of *Tetranychus* spider mites, suitable for controlled agricultural environments where these pests are prevalent. Type II species are selective predators of tetranychid mites. Type III species are generalist predators that engage in a wide range of prey, while Type IV mites thrive in environments where pollen is readily available, demonstrating their utility as generalist predators in diversified crop systems. Subsequently, McMurtry *et al*. (2013) classified the major 4 lifestyles into more several substyles based on the diverse habitats, from plants to soils. This diversity ensures that phytoseiids can be effectively employed against a wide range of agricultural pests, including spider mites, thrips, and whiteflies, which are common threats to crops worldwide (Huffaker *et al*. 1970; McMurtry *et al*. 1970, 2013, 2015). This adaptability extends to their physiological resilience against environmental stressors such as temperature and humidity, crucial under the evolving threat of climate change (Ghazy *et al*. 2016; Harvey *et al*. 2023).

Taiwan and its affiliated islands, known for their rich biodiversity, have been reported to have 70 species of phytoseiids. This underscores the region's importance in phytoseiid research and potential in biological control applications (Liao *et al*. 2020a, 2023b). Taiwan has been at the forefront of phytoseiid mite research, significantly contributing to the understanding and application of these mites in biological control. Early researches by P. K. C. Lo and C. I. T. Shih on *Neoseiulus longispinosus* (Evans), later correctly identified as *N. womer-*

sleyi (Schicha), laid the foundation for innovative mass-rearing techniques and practical field applications (Schicha 1975; Lo & Ho 1979; Shih & Shieh 1979; Ho 2005). Their pioneering work facilitates the control of spider mites in various orchards, including strawberry fields and tea plantations, showcasing the practical application and adaptability of phytoseiids in Taiwan's unique agricultural landscape (Lo *et al*. 1984, 1986; Ho 1990). Continued efforts by Taiwanese researchers have further demonstrated the adaptability and effectiveness of local predatory mite species, such as *N. womersleyi* and *Euseius ovalis* (Evans), in sustainable pest management strategies (Shih *et al*. 1993; Shih & Wang 1997; Ho & Chen 2001, 2002a, 2002b; Ho 2005). Moreover, commercial endeavors by local companies, such as Good Farms, have illustrated the successful transition from research to market, developing products based on *N. barkeri* Hughes (Liao *et al*. 2020a), which offer higher adaptability in the field and a broader range of prey.

The growing impacts of climate change—temperature fluctuations, altered precipitation patterns, heat waves, and increased frequency of extreme weather events—underscore the need for continued research into the ecological roles and adaptability of phytoseiids (Ghazy *et al*. 2016; Tscholl *et al*. 2023). Recent discoveries of phytoseiid biodiversity in Taiwan (Liao *et al*. 2020a) enhance the arsenal of biological control agents, offering new avenues for pest management in the face of climate shifts. Optimizing the use of phytoseiids in agriculture through understanding their responses to environmental stressors and developing innovative strategies to enhance their effectiveness is essential for the sustainability of agricultural ecosystems and food security (Welch & Harwood 2014).

CLIMATE CHANGE IMPACTS ON AGRICULTURAL ECOSYSTEMS AND PREDATORY MITES

Climate change induces profound environmental alterations, affecting every component of agricultural ecosystems, from water availability to the dynamics of pests and their natural enemies (Loboguerrero *et al*. 2019; Skendžić *et al*. 2021; Naz *et al*. 2022). Extreme weather events, such as prolonged droughts, severe flooding, heatwaves, and heavy storms, exacerbate these impacts, causing direct harm to crops and altering the habitats of pests. These climatic changes can unpredictably shift the presence and abundance of pests, potentially diminishing the effectiveness of biological control strategies (Gillespie *et al*. 2012; Ghazy *et al*. 2016; Zhang *et al*. 2016; Nakai *et al*. 2021; Nechols 2021; Tscholl *et al*. 2023).

For phytoseiid mites, temperature stands out as a pivotal abiotic factor deeply influencing their behavior and physiological parameters (Ghazy *et al*. 2016). Temperature, largely dictated by ambient conditions, directly and indirectly influences their survival, development, and reproduction (Veerman 1992; Ghazy *et al*. 2016; Han *et al*. 2019). Extreme temperatures, either too high or too low, can provoke significant stress, reducing their survival rates, interrupting development and reproduction processes, or even leading to death under chronic exposure (Tscholl *et al*. 2023). Adaptation measures such as hibernation and reproductive diapause have evolved in phytoseiid mites to withstand these harsh temperature conditions, showcasing their resilience and the critical need for strategic adaptation to sustain their biological control potential amidst climate change (Salt 1961; Denlinger 1991; Veerman 1992; Teets & Denlinger 2013; Ghazy *et al*. 2016). Rising temperatures may facilitate the escape and establishment of introduced predators from greenhouses into the surrounding environment (Hart *et al*. 2002). In addition, Tscholl *et al*. (2023) highlighted that parental exposure to heat waves can influence the reproductive investment of subsequent generations of predatory mites. This transgenerational effect suggests that the biological control efficacy of phytoseiid mites could be shaped by the climatic experiences of their ancestors, adding a layer of complexity to predicting the performance of biological control agents under climate extremes.

Cold stress, manifesting through chilling or freezing, requires phytoseiid mites to employ mechanisms like cold hardening to enhance their cold tolerance—a genetic trait triggered by environmental stimuli such as decreasing temperature and shortening day length (Salt 1961; Denlinger 1991; Teets & Denlinger 2013). Conversely, high temperatures combined with limited access to prey can exacerbate drought stress, dehydrating mites, and potentially leading to their demise. Environments with high humidity may mitigate the severity of both temperature extremes and food shortages, underlining the complex interplay between temperature, humidity, and food availability in determining the biological control efficacy of phytoseiid mites under the rapidly changing climatic conditions (Morewood 1992; Broufas & Koveos 2001; Nakai *et al*. 2021). Amid these challenges, the adaptability of phytoseiid mites to changing climates, as demonstrated by classical biological control (CBC) of 3 exotic phytoseiids in Taiwan, offers valuable insights. These researches highlight the importance of ecological niche modeling in predicting biological control success under varied climatic conditions, emphasizing strategic species selection for future pest management scenarios (Liao *et al*. 2021a, 2023a).

As we advance, prioritizing research that anticipates the responses of both pest and predator populations to climate change is crucial. Designing effective, climate-resilient biological control programs hinges on our understanding of the adaptability and resilience of phytoseiid mites against climate change. This underscores the importance of continued innovation and adaptation in biological control strategies, ensuring the effectiveness of phytoseiid mites as biological control agents. To illustrate the practical implications of these challenges and adaptations, we discuss 2 case studies that highlight the impact of climate change on predatory mites. These examples demonstrate the complexities involved and offer insights into potential strategies for sustaining agricultural production and ecosystem health in a warming world.

CASE STUDY 1: CLASSICAL BIOLOGICAL CONTROL OF 3 EXOTIC PREDATORY MITES IN TAIWAN

Taiwan's innovative approach to agricultural pest management in the 1980s included the introduction of 3 exotic phytoseiid mite species: *Phytoseiulus persimilis* Athias-Henriot, *N. californicus* (McGregor) (Fig. 2), and *N. fallacis* (Garman). Lots of exotic predatory mites were released across diverse agricultural areas, from alpine orchards to tea plantations (Lo *et al*. 1986; Lee & Lo 1989; Ho 1990; Lo *et al*. 1990; Hao *et al*. 1996). This initiative aimed to leverage CBC program to combat spider mite infestations effectively. Initial post-release observations indicated an establishment only for *N. fallacis*, evidenced by its significant presence in the release fields (Lo *et al*. 1986). However, all 3 species were absent in subsequent long-term investigations (Liao *et al*. 2020a), suggesting a failure in its establishment. Liao *et al*. (2021a, 2023a) conducted comprehensive field investigations across Taiwan and applied ecological niche modeling to assess the establishment success of the 3 phytoseiid species. The results confirmed that only *N. californicus* successfully established in high mountain orchards (Fig. 2), while *P. persimilis* and *N. fallacis* failed to become sustainable parts of the agroecosystem. The modeling results matched the field observations, indicating that the unsuitable climatic conditions in Taiwan contributed to the unsuccessful establishment of *P. persimilis* and *N. fallacis*. This differential success among the introduced species illustrates the nuanced interaction between predatory mites and their new environments, emphasizing the critical role of selecting species with ecological compatibility for CBC programs. The contrasting outcomes

Fig. 2. *Neoseiulus californicus* established population on high mountain orchards. (A) Peach orchard in high mountain areas; and (B) adult female feeding on *Tetranychus urticae* on peach leaves.

of these introductions serve not only as a testament to the potential of CBC within specific ecosystems but also as a cautionary narrative about the complexities introduced by climate and environmental suitability. The success of *N. californicus*, in contrast to the failures of *N. fallacis* and *P. persimilis*, calls for a deeper exploration into how climatic conditions influence the establishment and efficacy of predatory mites as biological control agents.

Predictive models, particularly MaxEnt, have shown that current climatic conditions favor *N. californicus* over *N. fallacis*, explaining their differential establishment outcomes. Yet, the shadow of climate change looms large, threatening to contract the suitable habitats for both species within Taiwan. This potential contraction signifies a pressing need for adaptive management strategies within CBC programs to accommodate the shifting environmental thresholds dictated by climate change. To navigate these challenges, a standardized assessment procedure becomes paramount. Cédola *et al*. (2021) proposed a framework essential for gauging the environmental fit and impact of introducing exotic predators. Advancements in molecular tools, such as metabarcoding, pave the way for precise identification of predatory mites, simplifying community-level assessments (Ollivier *et al*. 2020). Additionally, the integration of machine learning into CBC offers a novel avenue for enhancing species identification with unprecedented speed and accuracy (Liao *et al*. 2020b).

The narrative of *N. californicus* in Taiwan not only celebrates the triumphs of CBC but also serves as a cautionary tale about the complexities introduced by climate change. The case underscores an urgent call for research dedicated to understanding the nuanced effects of climatic shifts on biological control agents. Future investigations should prioritize species-specific assessments, particularly focusing on how altered temperature ranges, precipitation patterns, and the frequency of extreme weather events influence predatory mite populations and their prey dynamics. This comprehensive approach, marrying cutting-edge identification techniques with environmental risk assessments, is key to fortifying the resilience of CBC programs against climate change. By addressing the differential impacts of these environmental shifts, researchers and practitioners can better tailor biological control strategies, ensuring the sustainability of agricultural productivity and ecosystem health for generations to come.

CASE STUDY 2: ADAPTATION OF PREDATORY MITES TO CLIMATE CHANGE WITH POLLENS

Pollen has always played a crucial role in the research of phytoseiid mites due to its importance as a food source. McMurtry & Croft (1997) and McMurtry *et al*. (2013) classify certain phytoseiids as phytophagous or generalist type IV feeders, noting their use of pollen as an alternative food source. The potential of pollen as a substitute food for mass rearing natural enemies has been a subject of research (Shih *et al*. 1993; Pina *et al*. 2012), highlighting its significance in the study of predatory mites. In the face of climate change, the role of alternative food sources, such as pollen, becomes increasingly vital in mitigating the competitive pressures intensified by the shifting climate. Pollen positively affects the biology of predatory mites to stable populations. For example, applying pollen to vineyards increased predatory mite egg and motile form densities, illustrating the importance of supplemental pollen in sustaining mite populations, particularly during periods when natural pollen is scarce (Malagnini *et al*. 2022).

Urbaneja-Bernat *et al*. (2019) and Urbaneja-Bernat & Jaques (2021, 2022) explored the nuanced effects of future climate conditions on key predatory mites, specifically *E. stipulatus* (Athias-Henriot), *N. californicus*, and *P. persimilis*, which are essential for managing *T. urticae* populations in citrus groves. A central theme in their investigations is the role of alternative food sources, such as pollen, in mitigating the competitive pressures exacerbated by climate change. Such pressures threaten to diminish the natural resilience of these predatory mites in their battle against pests in increasingly warmer futures. Urbaneja-Bernat *et al*. (2019) initially outlined the looming challenges predatory mites are likely to face under future climate scenarios, highlighting potential decreases in biological control efficacy due to harsher environmental conditions. Urbaneja-Bernat & Jaques (2021, 2022) subsequently provided empirical evidence that access to high-quality pollen sources can significantly enhance the resilience of *E. stipulatus* and *N. californicus*, evidenced by increased survival, oviposition rates, and predation capabilities amidst intensified competition and shifting climate conditions.

These findings underscore the complexity inherent in biological control systems and the need for a nuanced understanding of each species' dietary preferences and life histories. Moreover, the studies emphasize the importance of incorporating adaptive strategies, like providing alternative food sources and leveraging ecological niche modeling, to predict and enhance biological control success under varied climatic conditions. To navigate the complexities introduced by climate change, this case study underscores the necessity for continued research focused on understanding the specific impacts of temperature fluctuations, altered precipitation patterns, and the frequency of extreme weather events on predatory mite populations and their prey dynamics. By integrating these insights, the case study highlights the indispensable role of adaptive management strategies in maintaining the efficacy of biological control agents. It points towards the need for innovative measures, such as the provision of alternative food sources, to mitigate the impacts of climate change on biological control efforts, ensuring the sustainability of agricultural practices for the future.

IDENTIFIED KNOWLEDGE GAPS OF PREDATORY MITES IN CLIMATE CHANGE WORLD

The established utility of predatory mites in biological control, highlighted by the vast biodiversity and adaptability of phytoseiid species (Demite *et al*. n.d.; Chant & McMurtry 2007), stands in stark contrast to the accelerating challenges posed by climate change. This scenario unveils pivotal knowledge gaps, underscoring the need for a comprehensive understanding of climatic thresholds essential for the survival, reproduction, and efficacy of predatory mites.

Exploring indigenous phytoseiid species

Investigating the biodiversity of phytoseiid mites is not merely about cataloging species; it is crucial for uncovering potential indigenous predators with innate adaptability to local climates. Species such as *N. womersleyi* and *N. barkeri* are noted for their superior adaptability to their native climates (Ho 2005; Liao *et al*. 2020a). This adaptability suggests these species possess specific adaptive behaviors, habitat preferences, and stress responses that confer resilience to environmental pressures, including those induced by climate change. Döker *et al*. (2021) emphasize the importance of understanding interactions between indigenous and exotic phytoseiids for effective biological control. A focused examination of these indigenous species can enhance our understanding of their potential as biological control agents and guide the development of climate-resilient strategies. Leveraging the unique traits of indigenous phytoseiids can optimize biological control practices by aligning them with local ecosystem dynamics.

Climatic preferences and impacts on predatory mites

A primary knowledge gap lies in our understanding of the specific climatic preferences of predatory mites and how these preferences impact their role in biological control. While ecological niche modeling has shown potential in identifying regions climatically suitable for biological control agents (Liao *et al*. 2021a, 2023a), the contrasting success rates of species such as *N. californicus* and the challenges encountered by *N. fallacis* and *P. persimilis* in adapting to Taiwan's climate (Liao *et al*. 2021a, 2023a) underscore the need for detailed research into the climatic factors that favor or hinder these mites. This includes a deeper exploration into species-specific climate preferences, such as optimal temperature and humidity ranges, and how deviations from these conditions affect their survival, reproduction, and efficacy in pest control. Understanding these climatic impacts is crucial for predictive modeling and selecting the most effective mite species for biological control in varying climatic conditions (Thompson *et al*. 2010; Ghazy *et al*. 2016).

Uncovering the genetic foundations of adaptability

Investigating the genetic factors that enable predatory mites to adapt to diverse climatic conditions is essential. Research focused on the molecular responses of these mites to environmental stressors can uncover genetic variations that enhance resilience to climatic changes (Ghazy *et al*. 2016; Zhang *et al*. 2019; Cruz-Miralles *et al*. 2021). Identifying these traits allows for the strategic selection or genetic enhancement of predatory mites, equipping them to better withstand the challenges of climate change (Cruz-Miralles *et al*. 2021). This approach not only promises more effective biological control agents in the face of current climatic variability but also prepares these agents to meet future environmental conditions. By leveraging genetic insights, we can improve the adaptability of both indigenous and introduced species to ensure the long-term efficacy and resilience of biological control strategies.

Transgenerational responses to climate extremes

The impact of extreme climate events such as heat waves on predatory mites and their subsequent generations remains underexplored. Tscholl *et al*. (2023) revealed that exposure to such events can alter reproductive investments in these mites, suggesting a nuanced interaction between climate stressors and biological control effectiveness. How environmental stress impacts mites' physiological responses, which may extend to subsequent generations, remains to be explored (Veerman 1992; Ghazy *et al*. 2016). Additionally, Zhang *et al*. (2016) showed that heat stress affects reproductive success, underscoring the potential for transgenerational impacts. This highlights the need for further research into transgenerational adaptability and resilience of biological control agents to climate extremes. Understanding how these stressors affect not only the immediate generation but also subsequent ones is vital for refining biological control strategies to withstand the challenges posed by a changing climate.

RECOMMENDATIONS FOR FUTURE CLIMATE-ADAPTED BIOLOGICAL CONTROL WITH PREDATORY MITES

Adapting biological control strategies to the challenges posed by global climate change is critical for ensuring the sustainability of agricultural ecosystems. A key initial step involves exploring the diverse habitats of phytoseiid mites to identify potential natural enemies with high adaptability to future climate conditions. This exploration is essential not only for cataloging species but also for uncovering those with innate resilience to varying environmental conditions. Members within the genus *Euseius*, such as *E. stipulatus*, are exemplary in their versatility and resilience, capable of thriving on a range of food sources including pollen, which highlights their potential in climates altered by global warming (McMurtry *et al*. 2013; Cruz-Miralles *et al*. 2021). However, the identification of highly adaptable species is just the beginning. Creating supportive agricultural ecosystems that can sustain these selected biological control agents through every season and climatic challenge is equally important. This includes incorporating indigenous species like *N. womersleyi* and *N. barkeri* into biological control schemes, leveraging the natural biodiversity to address pest challenges effectively and environmentally sensitively (Ho 2005; Liao *et al*. 2020a). The local climatic adaptation of these species provides a foundation for deploying biological control agents that are most likely to succeed in environmental settings.

It is crucial to consider their potential impact on non-target species and the overall ecosystem when developing biological control strategy (Nechols 2021). This comprehensive approach to biological control underlines the importance of not only enhancing the adaptability and efficacy of biological control agents but also ensuring that these interventions do not adversely affect the biodiversity and ecological balance of agricultural landscapes. Moving forward demands a synergy of research and practical approaches to ensure biological control agents not only survive but thrive under the stress of climate change (Thomson *et al*. 2010; Nechols 2021; Liao *et al*. 2023a). This involves delving into ecological and genetic research to discover how predatory mites adapt to different climates and environmental pressures (Ghazy *et al*. 2016; Cruz-Miralles *et al*. 2021). Utilizing ecological niche modeling is crucial in this context (Liao *et al*. 2023a), refining our predictions about the regional suitability for biological control agents and the changing dynamics of pest populations in response to climate change.

Developing agricultural landscapes that can withstand climate extremes is foundational to this strategy, including the incorporation of domatia, small structures on the undersides of leaves that provide shelter for beneficial organisms like predatory mites (Fig. 3) (Walter 1996). Implementing diversified planting schemes, windbreaks, and shade structures can create microclimates that shelter biological control agents from severe conditions. Moreover, ensuring consistent availability of alternative food sources (Shih *et al*. 1993; Pina *et al*. 2012; Urbaneja-Bernat *et al*. 2019; Urbaneja-Bernat & Jaques 2021, 2022), such as pollen, during periods of low pest activity is vital for maintaining predator populations and extending their biological control effectiveness. Innovations like slow-release sachets further reinforce the presence and impact of biological control agents in the field, contributing to their prolonged effectiveness (Shimoda *et al*. 2017, 2023; Urbaneja-Bernat & Jaques 2022). Backing these practical strategies with collaborative research and policy support for sustainable agriculture practices is crucial for a comprehensive approach to climate-adapted biological control. Integrating research insights with advanced, proactive strategies enables the agricultural sector to adeptly manage the intricacies introduced by climate change, ensuring the continuity of biological control practices. This integrated approach is vital for preserving the balance between agricultural productivity and ecosystem health in an era of significant environmental transformation.

CONCLUSION

This review has underscored the significance of predatory mites in agricultural ecosystems amid the challenges of climate change. It highlights the necessity for adaptive biological control strategies that align with the specific resilience characteristics of predatory mites and the overarching health of ecosystems. The intricate relationships between climate factors and the biological control potential of predatory mites demand a nuanced understanding and strategic ecosystem modifications to enhance their survival and effectiveness (McMurtry *et al*. 2013; Nechols 2021; Liao *et al*. 2023a).

As climate change continues to reshape the dynamics of agricultural pests and their natural enemies, this study advocates for a proactive approach in biological control practices. This entails a dual focus on selecting inherently resilient mite species and implementing ecosystem enhancements to buffer against extreme climatic conditions (Ghazy *et al*. 2016; Urbaneja-Bernat *et al*. 2019). Moreover, the evolving nature of climate change compels ongoing research to refine biological control strategies, ensuring they remain effec-

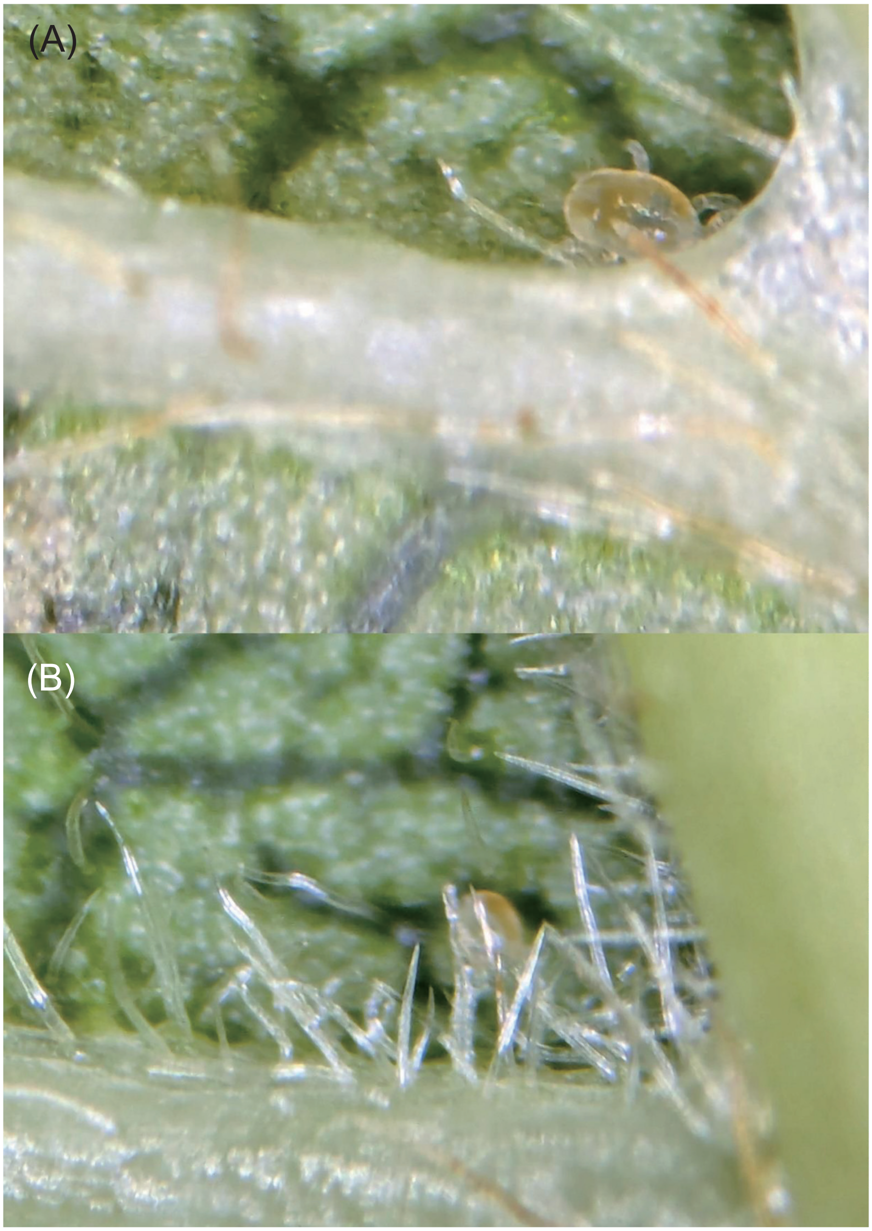

Fig. 3. Predatory mites on domatia on cherry tree leaves. (A) Larva of *Amblyseius* species; and (B) egg of predatory mite.

tive under changing environmental conditions (Thomson *et al*. 2010). The future of biological control in agriculture hinges on our ability to innovate and adapt. By prioritizing research and practices that enhance the adaptability of predatory mites, we can ensure the sustainability of biological control as a fundamental component of integrated pest management in the face of global climate change.

ACKNOWLEDGMENTS

This study was made possible thanks to the great assistance of our colleagues in the plant protection community, who shared their valuable experience and knowledge. We thank to Gilberto José de Moraes (University of São Paulo, Brazil), İsmail Döker (Çukurova University, Turkey), Tetsuo Gotoh (Ryutsu Keizai University, Japan), Yu-Fang Tseng (Good Farms, Taiwan), Katsuyuki Eguchi and Francesco Ballarin (Tokyo Metropolitan University, Japan), Sheng-Feng Lin (National Museum of Natural Science, Taiwan), Yun Hsiao (National Taiwan University, Taiwan), and Po-An Lin (National Taiwan University, Taiwan) for their advice. The first author was supported by a grant from the Japan Society for the Promotion of Science (JSPS KAKENHI n°22P22380).

REFERENCES

Broufas, G. D. and D. S. Koveos. 2001. Cold hardiness characteristics in a strain of the predatory mite *Euseius* (*Amblyseius*) *finlandicus* (Acari: Phytoseiidae) from northern Greece. Ann. Entomol. Soc. Am. 94:82–90. doi:10.1603/0013-8746(2001)094[0082:CHCIAS]2.0.CO;2

Cédola, C., M. G. Luna, M. F. Achinelly, and N. E. Sánchez. 2021. Contributions to improve current environmental risk assessment procedures of generalist arthropod biological control agents (GABCAs) in Argentina. BioControl 66:153–166. doi:10.1007/s10526-020-10063-6

Chant, D. A. and J. A. McMurtry. 2007. Illustrated Keysand Diagnoses for the Genera and Subgenera of the Phytoseiidae of the World (Acari: Mesostigmata). Indira Publication House. West Bloomfield, MI. 220 pp.

Cruz-Miralles, J., M. Cabedo-López, M. Guzzo, M. Pérez-Hedo, V. Flos, and J. A. Jaques. 2021. Plant defense responses triggered by phytoseiid predatory mites (Mesostigmata: Phytoseiidae) are species-specific, depend on plant genotype and may not be related to direct plant feeding. BioControl 66:381–394. doi:10.1007/s10526-021-10077-8

Demite, P. R., G. J. de Moraes, J. A. McMurtry, H. A. Denmark, and R. C. Castilho. n.d. Phytoseiidae Database. http://www.lea.esalq.usp.br/phytoseiidae/ (visit on 10/4/2024)

Denlinger, D. L. 1991. Relationship between cold hardiness and diapause. p.174–198. *in*: Insects at Low Temperature. (Lee, R. E. and D. L. Denlinger, eds.) Chapman and Hall. New York, NY. 404 pp.

Döker, İ., A. M. Revynthi, C. Kazak, and D. Carrillo. 2021. Interactions among exotic and native phytoseiids (Acari: Phytoseiidae) affect biocontrol of two-spotted spider mite on papaya. Biol. Control 163:104758. doi:10.1016/j.biocontrol.2021.104758

Gerard, P. J., J. R. F. Barringer, J. G. Charles, S. V. Fowler, J. M. Kean, C. B. Phillips, ... G. P. Walker. 2013. Potential effects of climate change on biological control systems: case studies from New Zealand. Biocontrol 58:149–162. doi:10.1007/s10526-012-9480-0

Ghazy, N. A., M. Osakabe, M. W. Negm, P. Schausberger, T. Gotoh, and H. Amano. 2016. Phytoseiid mites under environmental stress. Biol. Control 96:120–134. doi:10.1016/j.biocontrol.2016.02.017

Ghazy, N. A., T. Suzuki, and H. Amano. 2018. Development and reproduction of *Neoseiulus californicus* (Acari: Phytoseiidae) and *Tetranychus urticae* (Acari: Tetranychidae) under simulated natural temperature. Environ. Entomol. 47:1005–1012. doi:10.1093/ee/nvy067

Gillespie, D. R., A. Nasreen, C. E. Moffat, P. Clarke, and B. D. Roitberg. 2012. Effects of simulated heat waves on an experimental community of pepper plants, green peach aphids and two parasitoid species. Oikos 121:149–159. doi:10.1111/j.1600-0706.2011.19512.x

Han, P., C. Becker, A. Sentis, M. Rostás, N. Desneux, and A. V. Lavoir. 2019. Global change-driven modulation of bottom–up forces and cascading effects on biocontrol services. Curr. Opin. Insect Sci. 35:27−33. doi:10.1016/j.cois.2019.05.005

Hao, H. H., H. L. Wang, W. T. Lee, and K. C. Lo. 1996. Studies on biological control of spider mites on papaya. J. Agric. Res. China 45:411–421. (in Chinese with English abstract) doi:10.29951/JARC.199612.0009

Hart, A. J., J. S. Bale, A. G. Tullett, M. R. Morland, and K. F. A. Walters. 2002. Effects of temperature on the establishment potential of the predatory mite *Amblyseius californicus* McGregor (Acari: Phytoseiidae) in the UK. J. Insect Physiol. 48:593−599. doi:10.1016/s0022-1910(02)00087-2

Harvey, J. A., K. Tougeron, R. Gols, R. Heinen, M. Abarca, P. K. Abram, ... S. L. Chown. 2023. Scientists' warning on climate change and insects. Ecol. Monogr. 93:e1553. doi:10.1002/ecm.1553

Ho, C. C. 1990. A preliminary study on the biological control of *Tetranychus kanzawai* in tea field by *Amblyseius fallacis* and *Phytoseiulus persimilis* (Acarina: Tetranychidae, Phytoseiidae). J. Agric. Res. China 39:133−140. (in Chinese with English abstract) doi:10.29951/JARC.199006.0007

Ho, C. C. 2005. Re-evaluation of *Neoseiulus womersleyi* as a natural enemy of the spider mite. Formosan Entomol. Spec. Public. 7:167–188. (in Chinese with English abstract)

Ho, C. C. and W. H. Chen. 2001. Life history and feeding amount of *Amblyseius asetus* and *A. maai* (Acari: Phytoseiidae) on *Thrips palmi* (Thysanoptera: Thripidae). Formosan Entomol. 21:321−328. (in Chinese with English abstract) doi:10.6661/TESFE.2001026

Ho, C. C. and W. H. Chen. 2002a. Evaluation of feeding and ovipositing responses of *Feltiella minuta* (Diptera: Ceccidomyiidae) to different amounts of Kanzawa spider mite eggs (Acari: Tetranychidae). Formosan Entomol. 22:19–26. (in Chinese with English abstract) doi:10.6661/TESFE.2002002

Ho, C. C. and W. H. Chen. 2002b. Evaluation of feeding and ovipositing responses of *Oligota flavicornis* (Coleoptera: Staphylinidae) to different amounts of Kanzawa spider. Plant Prot. Bull. 44:15–20. (in Chinese with English abstract)

Huffaker, C. B., M. van der Vrie, and J. A. McMurtry. 1970. Ecology of tetranychid mites and their natural enemies: A review: II. Tetranychid populations and their possible control by predators: An evaluation. Hilgardia 40:391–458. doi:10.3733/hilg.v40n11p391

Lee, W. T. and K. C. Lo. 1989. Integrated control of two-spotted spider mite on strawberry in Taiwan. Chinese J. Entomol. Spec. Public. 3:125–137. (in Chinese with English abstract)

Liao, J. R., M. C. Chiu, and M. H. Kuo. 2023a. Reassessing the presence of alien predatory mites and their prospects in the face of future climate change. Pest Manag. Sci. 79:5186−5196. doi:10.1002/ps.7722

Liao, J. R., C. C. Ho, M. C. Chiu, and C. C. Ko. 2021a. Niche modeling may explain the historical population failure of *Phytoseiulus persimilis* in Taiwan: Implications of biocontrol strategies. Insects 12:418. doi:10.3390/insects12050418

Liao, J. R., C. C. Ho, and C. C. Ko. 2021b. Survey of phytoseiid mites (Acari: Mesostigmata) in the Penghu Islands with two new records and descriptions of two new species. Syst. Appl. Acarol. 26:641−671. doi:10.11158/saa.26.4.1

Liao, J. R., C. C. Ho, and C. C. Ko. 2023b. Milestones and future directions in the taxonomy of mites (Acari: Mesostigmata) in Taiwan. Formosan Entomol. 43:15−23 doi:10.6662/TESFE.202302_43(1).002

Liao, J. R., C. C. Ho, H. C. Lee, and C. C. Ko. 2020a. Phytoseiidae of Taiwan (Acari: Mesostigmata). National Taiwan University Press. Taipei. 538 pp.

Liao, J. R., H. C. Lee, M. C. Chiu, and C. C. Ko. 2020b. Semi-automated identification of biological control agent using artificial intelligence. Sci. Rep. 10:14632. doi:10.1038/s41598-020-71798-x

Lo, K. C. and C. C. Ho. 1979. Influence of temperature on life history, predation and population parameters of *Amblyseius longispinosus* (Acari: Phytoseiidae). J. Agric. Res. China 28:237–250. (in Chinese with English abstract) doi:10.29951/JARC.197912.0003

Lo, K. C., C. C. Ho, T. K. Wu, and S. R. Lin. 1986. Studies on population dynamics and integrated control of spider mites on pear in temperate zone of Taiwan. Ann. Conv. Agric. Assoc. China Special Publ. 1986:98−111. (in Chinese)

Lo, K. C., W. T. Lee, T. K. Wu, and C. C. Ho. 1990. Use of predators to control spider mites (Acarina: Tetranychidae) in the Republic of China on Taiwan. p.166–178. *in*: The Use of Natural Enemies to Control Agricultural Pests: International Seminar "The Use of Parasitoids and Predators to Control Agricultural Pests." FFTC Book Series No. 40. (Mochida, O., K. Kiritani, and J. Bay-Peterson, eds). Food and Fertilizer Technology Center. Taipei, Taiwan. 254 pp.

Lo, K. C., H. K. Tseng, and C. C. Ho. 1984. Biological control of spider mites on strawberry in Taiwan (I). J. Agric. Res. China 33:406–417. (in Chinese with English abstract) doi:10.29951/JARC.198412.0008

Loboguerrero, A. M., B. M. Campbell, P. J. M. Cooper, J. W. Hansen, T. Rosenstock, and E. Wollenberg. 2019. Food and earth systems: Priorities for climate change adaptation and mitigation for agriculture and food systems. Sustainability 11:1372. doi:10.3390/su11051372

Malagnini, V., A. Pozzebon, P. Facchin, A. Paganelli, and C. Duso. 2022. Airborne pollen can affect the abundance of predatory mites in vineyards: Implications for conservation biological control strategies. Pest Manag. Sci. 78:1963−1975. doi:10.1002/ps.6815

McMurtry, J. A. and B. A. Croft. 1997. Life-styles of phytoseiid mites and their roles in biological control. Annu. Rev. Entomol. 42:291−321. doi:10.1146/annurev.ento.42.1.291

McMurtry, J. A., G. J. de Moraes, and N. F. Sourassou. 2013. Revision of the lifestyles of phytoseiid mites (Acari: Phytoseiidae) and implications for biological control strategies. Syst. Appl. Acarol. 18:297−320. doi:10.11158/saa.18.4.1

McMurtry, J. A., N. Famah-Sourassou, and P. R. Demite. 2015. The Phytoseiidae (Acari: Mesostigmata) as biological control agents. p.133–149. *in*: Prospects for Biological Control of Plant Feeding Mites and Other Harmful Organisms. (Carrillo, D., G. J. de Moraes, and J. Peña, eds.) Springer. Cham, Switzerland. 328 pp. doi:10.1007/978-3-319-15042-0_5

McMurtry, J. A., C. B. Huffaker, and M. van der Vrie. 1970. Ecology of tetranychid mites and their natural enemies: A review: I. Tetranychid enemies: Their biological characters and the impact of spray practices. Hilgardia 40:331−390. doi:10.3733/hilg.v40n11p331

Morewood, W. D. 1992. Cold hardiness of *Phytoseiulus persimilis* Athias-Henriot and *Amblyseius cucumeris* (Oudemans) (Acarina: Phytoseiidae). Can. Entomol. 124:1015–1025. doi:10.4039/Ent1241015-6

Nakai, Z., K. Shimizu, H. Oida, and S. Sonoda. 2021. Host plant and humidity effects on phytoseiid mite, *Gynaeseius liturivorus* (Acari: Phytoseiidae) egg hatchability. Exp. Appl. Acarol. 84:135–147. doi:10.1007/s10493-021-00617-3

Naz, S., Z. Fatima, P. Iqbal, A. Khan, I. Zakir, H. Ullah, ... S. Ahmad. 2022. An introduction to climate change phenomenon. p.3–16. *in*: Building Climate Resilience in Agriculture. (Jatoi, W. N., M. Mubeen, A. Ahmad, M. A. Cheema, Z. Lin, and M. Z. Hashmi, eds.) Springer. Cham, Switzerland. 413 pp. doi:10.1007/978-3-030-79408-8_1

Nechols, J. R. 2021. The potential impact of climate change on non-target risks from imported generalist natural enemies and on biological control. BioControl 66:37–44. doi:10.1007/s10526-020-10032-z

Ollivier, M., V. Lesieur, S. Raghu, and J. F. Martin. 2020. Characterizing ecological interaction networks to support risk assessment in classical biological control of weeds. Curr. Opin. Insect Sci. 38:40–47. doi:10.1016/j.cois.2019.12.002

Pina, T., P. S. Argolo, A. Urbaneja, and J. A. Jacas. 2012. Effect of pollen quality on the efficacy of two different life-style predatory mites against *Tetranychus urticae* in citrus. Biol. Control 61:176–183. doi:10.1016/j.biocontrol.2012.02.003

Salt, R. W. 1961. Principles of insect cold-hardiness. Annu. Rev. Entomol. 6:55–74. doi:10.1146/annurev.en.06.010161.000415

Schicha, E. 1975. A new predacious species of *Amblyseius* Berlese from strawberry in Australia, and *A. longispinosus* (Evans) redescribed (Acari: Phytoseiidae). J. Austral. Entomol. Soc. 14:101–106. doi:10.1111/j.1440-6055.1975.tb02010.x

Shih, C. I. T., H. Y. Chang, P. H. Hsu, and Y. F. Hwang. 1993. Responses of *Amblyseius ovalis* (Evans) (Acarina, Phytoseiidae) to natural food resources and two artificial diets. Exp. Appl. Acarol. 17:503–519. doi:10.1007/bf00058894

Shih, C. I. T. and J. N. Shieh. 1979. Biology, life table, predation potential and intrinsic rate of increase of *Amblyseius longispinosus* (Evans). Plant Prot. Bull. 21:175–183. (in Chinese)

Shih, C. I. T. and C. J. Wang. 1997. Spatial dynamics of an acarine predator-prey system: Responses of *Amblyseius ovalis* (Evans) to its egg-laying behavior and density and aggregation of *Tetranychus urticae* Koch (Acarina: Phytoseiidae: Tetranychidae). Chinese J. Entomol. 17:100–118. doi:10.6660/TESFE.1997011

Shimoda, T., Y. Kagawa, K. Mori, N. Hinomoto, T. Hiraoka, and T. Nakajima. 2017. A novel method for protecting slow-release sachets of predatory mites against environmental stresses and increasing predator release to crops. BioControl 62:495–503. doi:10.1007/s10526-017-9800-5

Shimoda, T., Y. Kagawa, K. Yara, and R. Uesugi. 2023. Influence of temperature on the release of predatory mites from breeding and sheltered sachets. BioControl 68:591–601. doi:10.1007/s10526-023-10223-4

Skendžić, S., M. Zovko, I. P. Živković, V. Lešić, and D. Lemić. 2021. The impact of climate change on agricultural insect pests. Insects 12:440. doi:10.3390/insects12050440

Teets, M. M. and D. L. Denlinger. 2013. Physiological mechanisms of seasonal and rapid cold-hardening in insects. Physiol. Entomol. 38:105-116. doi:10.1111/phen.12019

Thomson, L. J., S. Macfadyen, and A. A. Hoffmann. 2010. Predicting the effects of climate change on natural enemies of agricultural pests. Biol. Control 52:296–306. doi:10.1016/j.biocontrol.2009.01.022

Tscholl, T., G. Nachman, B. Spangl, I. Scalmai, and A. Walzer. 2023. Parental exposure to heat waves improves offspring reproductive investment in *Tetranychus urticae* (Acari: Tetranychidae), but not in its predator, *Phytoseiulus persimilis* (Acari: Phytoseiidae). Ecol. Evol. 13:e10748. doi:10.1002/ece3.10748

Tylianakis, J. M., R. K. Didham, J. Bascompte, and D. A. Wardle. 2008. Global change and species interactions in terrestrial ecosystems. Ecol. Lett. 11:1351–1363. doi:10.1111/j.1461-0248.2008.01250.x

Urbaneja-Bernat, P., V. Ibáñez-Gual, M. Montserrat, E. Aguilar-Fenollosa, and J. A. Jaques. 2019. Can interactions among predators alter the natural regulation of an herbivore in a climate change scenario? The case of *Tetranychus urticae* and its predators in citrus. J. Pest Sci. 92:1149–1164. doi:10.1007/s10340-019-01114-8

Urbaneja-Bernat, P. and J. A. Jaques. 2021. Effect of pollen provision on life-history parameters of phytoseiid predators under hot and dry environmental conditions. J. Appl. Entomol. 145:191–205. doi:10.1111/jen.12845

Urbaneja-Bernat, P. and J. A. Jaques. 2022. Can pollen provision mitigate competition interactions between three phytoseiid predators of *Tetranychus urticae* under future climate change conditions? Biol. Control 165:104789. doi:10.1016/j.biocontrol.2021.104789

Veerman, A. 1992. Diapause in phytoseiid mites: A review. Exp. Appl. Acarol. 14:1–60. doi:10.1007/BF01205351

Walter, D. E. 1996. Living on leaves: Mites, tomenta, and leaf domatia. Annu. Rev. Entomol. 41:101–114. doi:10.1146/annurev.en.41.010196.000533

Welch, K. D. and J. D. Harwood. 2014. Temporal dynamics of natural enemy- Pest interactions in a changing environment. Biol. Control 75:18–27. doi:10.1016/j.biocontrol.2014.01.004

Zhang, G. H., Y. Y. Li, K. J. Zhang, J. J. Wang, Y. Q. Liu, and H. Liu. 2016. Effects of heat stress on copulation, fecundity and longevity of newly emerged adults of the predatory mite, *Neoseiulus barkeri* (Acari: Phytoseiidae). Syst. Appl. Acarol. 21:295–306. doi:10.11158/saa.21.3.5

Zhang, Y. X., X. Chen, J. P. Wang, Z. Q. Zhang, H. Wei, H. Y. Yu, ... M. Liu. 2019. Genomic insights into mite phylogeny, fitness, development, and reproduction. BMC Genomics 20:954. doi:10.1186/s12864-019-6281-1

氣候變遷下捕植蟎生物防治的挑戰與未來方向

廖治榮 [1,*]　何琦琛 [2,3]　柯俊成 [4,†]

摘要

廖治榮、何琦琛、柯俊成。2024。氣候變遷下捕植蟎生物防治的挑戰與未來方向。台灣農業研究 73(3):153−168。

氣候變遷對農業生態系統造成了重大的挑戰，尤其是在害蟲、天敵動態及生物防治的有效性方面。捕植蟎 (植綏蟎) 作為捕食多種農業害蟲的重要捕食性天敵，面臨著氣候變遷帶來的威脅。本文回顧了氣候變遷對捕植蟎生物防治潛力的影響，並指出了目前研究中存在的關鍵知識缺口，這些缺口制約了發展出適應氣候變遷的生物防治策略。文中深入探討了氣候變遷，如溫度波動、降水模式變化及極端氣候事件，對捕植蟎的生理狀態、分布及其與害蟎互動的影響。透過案例研究，本文展示了在變化氣候條件下管理捕植蟎具體實踐與適應措施。本文強調了針對物種特定氣候適應性進行深入研究的必要性，並呼籲加強生物防治結果的預測模型。為應對氣候變遷帶來的挑戰，創新的管理實踐至關重要。本綜述強調，需要結合生態學、遺傳學及技術見解的綜合方法，來維持全球氣候變遷下生物防治系統的功能。

關鍵詞：氣候韌性、害蟲管理、適應策略、生態系統動態、可持續農業。

投稿日期：2024 年 4 月 11 日；接受日期：2024 年 6 月 16 日。
[*] 通訊作者：k1107053@hotmail.com
[1] 東京都立大學生命科學專攻動物系統分類學研究室日本學術振興會外國人特別研究員。日本 東京都。
[2] 農業部農業試驗所應用動物組前研究員。臺灣 臺中市。
[3] 臺灣蟎蜱研究室研究員。臺灣 臺中市。
[4] 國立臺灣大學昆蟲學系教授。臺灣 臺北市。
[†] 已故，逝世日期：2020 年 10 月 29 日。以此文紀念故柯俊成教授。