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4 Weed Biocontrol with Introduced Insects Under Climate Change

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Abstract

This chapter investigates the complex challenges of using introduced insects for weed biocontrol in the context of climate change. It explores how changing climatic factors, such as temperature, precipitation and CO_2 levels, affect the physiology, behaviour and ecological interactions of both invasive plants and their biological control agents (BCAs). These changes can greatly impact the effectiveness and safety of biocontrol efforts. This chapter emphasizes the need to integrate evolutionary biology with ecological modelling to accurately predict and manage these impacts. Additionally, it addresses the potential for non-target impacts resulting from altered habitats and phenological overlaps caused by climate change. By proposing interdisciplinary strategies, this chapter offers a framework for developing sustainable, eco-friendly biocontrol methods as traditional chemical approaches become less viable. This synthesis of current research is crucial for those seeking to improve weed management practices in the context of global climate change and the One Health concept.

4.1 Introduction

In this chapter, we delve into the intricate trophic interplay of plant–herbivore dynamics, a complexity climate change is anticipated to amplify. The profound effects of climate change, such as alterations in temperature, precipitation, CO_2 levels, insolation and the frequency of extreme climatic events, are shaping all stages of the plant invasion process, from introduction and establishment up to spread and impact. Concomitantly, they also affect growth and development of associated herbivores as well as antagonists at higher trophic levels. Together, these changes subsequently impact species interactions, ecosystem services and human livelihoods. The chapter asserts that classical biological control has historically been an effective and cost-efficient strategy to mitigate plant invasions (Müller-Schärer and Schaffner, 2008, 2020). However, understanding how climate change alters the dynamics between host plants and biocontrol agents (BCAs) remains largely unexplored.

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© CAB International 2025. *Biological Control Systems and Climate Change* (eds Joan van Baaren *et al.*)
DOI: 10.1079/9781800625099.0004

The complexity of interactions involving invasive plants, biotic and abiotic components under varying climatic scenarios presents policy and management challenges. These include assessing effectiveness and biosafety of biocontrol methods under different climate change scenarios. Specifically, climate change is expected to affect invasive weeds and BCAs through impacts on metabolism, phenology, physiology and their interactions, as well as effects on non-target attack of native plant species.

As we scrutinize the interplay between climate change and weed biocontrol, we observe that climate change may severely alter interactions of invasive weeds and BCAs by influencing phenotypic traits such as physiology, biochemistry, life history and phenology, or by changing the abiotic and/or biotic environments in which these interactions occur. This can modify the frequency, timing, intensity and duration of interactions between plant invaders and BCAs, thereby enhancing or reducing effects on plant invaders. Because plants differ in their susceptibility to damage at different life stages, changes in timing of insect and weed emergences under climate change could modify the consequences of insect feeding. Geographic distribution changes, especially with warming and more frequent extreme events, can impact interactions between BCAs and weeds as differential migration rates of insects, host plants, higher trophic level agents and other species create novel biotic interactions and new above- and below-ground communities. The net effect of climate change on weed biocontrol will depend on the relative strengths of these various responses to multiple climate change factors.

Understanding evolutionary aspects is also crucial as invaders and BCAs rapidly evolve in response to environmental shifts. Many cases of rapid adaptive evolution have been reported for invasive plants, including shifts in resource allocation from defence to growth, local adaptation to new habitats and climates, evolution of phenotypic clines along climatic gradients, evolution of greater dispersal ability,and increases in rates of population growth and expansion (Helliwell *et al.*, 2018; Sotka *et al.*, 2018). For instance, van Boheemen *et al.* (2019) found a shift to warmer and wetter climates in the introduced European and Australian ranges of the North American native *Ambrosia artemisiifolia* L. (Asteraceae). Despite the recent introductions into Australia and a bottleneck limiting genetic variation, their results indicate rapid and repeated adaptation to more productive environments, potentially contributing to trait divergence between the ranges.

Evolutionary adaptation is also expected for BCAs when they encounter novel environments or changes in climatic conditions, especially for species with short generation times. Integrating evolutionary studies into different stages of weed biocontrol programmes can help predict and adapt management strategies to these changes. For instance, using reciprocal transplants or common garden experiments coupled with population modelling, researchers could match climatically adapted BCA candidates with their target release environments or evaluate their potential evolvability under changing selection pressures (Müller-Schärer *et al.*, 2020). High genetic variance in life history and abiotic stress tolerance traits may allow researchers to screen for strains or populations that could adapt to future climates.

In conclusion, the intricate trophic relationships among plants, herbivores and their natural enemies under the lens of climate change reveal a complex, dynamic and challenging field of study, necessitating an interdisciplinary approach that integrates ecological, evolutionary and modelling perspectives to foresee and mitigate the impacts of climate change on weed biocontrol. Practitioners of classical biological control of invasive weeds are confronted with a dual expectation: successfully control plant invaders while avoiding damage to non-target plants and adverse indirect effects. In the following, we specifically address (1) effectiveness and (2) biosafety of weed biocontrol under climate change, and then (3) future opportunities for weed biocontrol in the light of increasing plant invasions due to global change and decreasing availability of alternative management tools (herbicide bans and absence of new molecules). Thus, eco-friendly management methods are becoming increasingly important as an integral part of the One Health concept that emphasizes biological control (Essack, 2018).

4.2 Classical Biological Control under Climate Change

Classical biological control involves intentional introductions of natural enemies from the invasive plant's native region to suppress its populations in the new environment (Müller-Schärer and Schaffner, 2008). Climate change introduces variables that can affect the biology and ecology of invasive plants and their BCAs. The complexity of these interactions under varying climatic conditions presents unique challenges for policy and management strategies in biocontrol programmes. Integrating considerations of climate change into biocontrol strategies is crucial for ensuring their effectiveness and environmental responsibility in the long term.

With growing concern about climate change effects and plant invasions, publications and their citations of plant invasions under climate change have sharply increased over the past 20 years. This is paralleled by increases in studies on climate change and weed biocontrol, highlighting the interest in exploring biological control measures as an integrated and adaptable tool to successfully manage plant invasions under climate change conditions (Fig. 4.1). However, our understanding of biocontrol outcomes under the full complement of climate-driven changes remains rudimentary (Fig. 4.2). Multiple reports suggest that climate change may promote plant invasions and increase their impact (Dukes and Mooney, 1999; Bradley *et al.*, 2010; Gioria *et al.*, 2023), while studies of climate change effects on performance and impact of BCAs report both positive and negative outcomes, with variable consequences for their efficacy and safety (Sun *et al.*, 2020a).

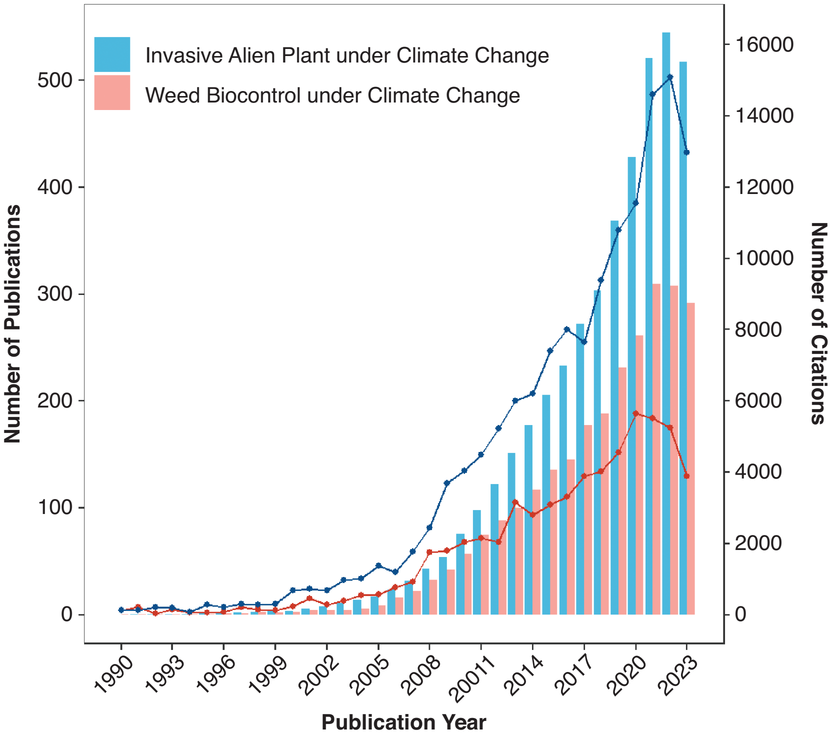

Fig. 4.1. Literature survey since 1990 on increase of publications on invasive weeds under climate change compared to increase of weed biocontrol under climate change. Bars represent the number of publications per year and the lines represent the sums of citations per year.

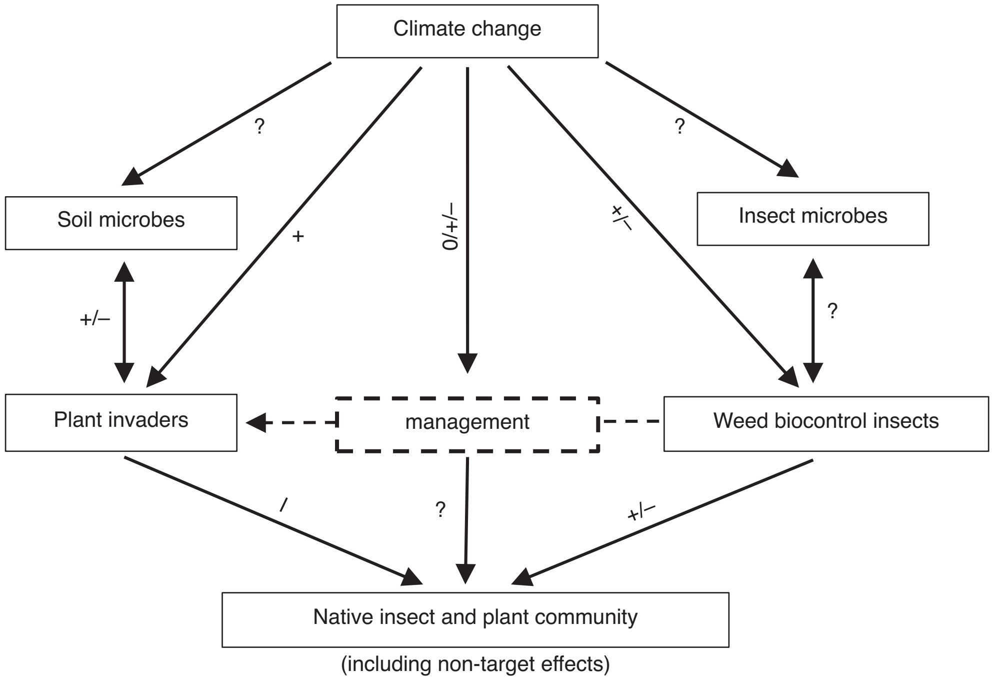

Fig. 4.2. Impact of climate change on plant invasions, weed biocontrol insects and their interactions (i.e. management; dashed lines) as evidenced from literature. 0/+/– represent no, positive and negative effects. Modified from Sun *et al*. (2020a).

4.3 Weed Biocontrol Efficiency and Impact under Climate Change

Climate change is expected to affect performance, population build-up and spread of both plant invaders and their BCAs independently, and therefore the frequency, timing, intensity and duration of their interactions. Thus, predicting agent impacts on plant invaders under climate change conditions is complex and highly demanding and net effects of climate change on weed biocontrol will depend on relative strengths of responses to multiple climate change factors (see Fig. 4.2).

In the following, we address sharp declines in insects worldwide under climate change vs increases in insect pests and ask: (i) are weed biocontrol insect impacts like natural insects (decreasing) or crop pests (increasing) under climate change? (ii) How will various climate change factors affect BCA impacts? (iii) Climate change will affect invader demography and population genetics, thus how to best match genotypes and phenotypes of invaders and BCA to optimize biocontrol effectiveness. (iv) Will recent advances in predictive modelling tools including life-history traits and climate-dependent vital rates allow spatially explicit long-term forecasts of BCA success and impacts?

4.3.1 Are weed biological control agents winners or losers under climate change?

A recent review reported dramatic declines of insect species worldwide that may lead to extinction of 40% of insect species over the next few decades, with Lepidoptera, Hymenoptera and Coleoptera being most affected in terrestrial ecosystems (Sánchez-Bayo and Wyckhuys, 2019). Coleoptera and Lepidoptera are also the taxa most often used in weed biological control projects (Schwarzländer *et al*., 2018). The main drivers of species decline in order of importance appear to be habitat change, pollution (mainly synthetic pesticides and fertilizers), biological traits and climate change, with climate warming accounting for 12.6% of the decline, mainly in tropical areas. Concurrently, a small number of species are becoming more abundant; these are adaptable, mobile generalist species occupying newly vacant niches (Thomas *et al.*, 2004; Sánchez-Bayo and Wyckhuys, 2019).

In contrast, a recent report released by the Intergovernmental Panel on Climate Change (IPCC, the UN's authority on climate change) (Legg, 2021) addressed how climate changes will affect crop losses worldwide, especially from insects. For instance, Deutsch *et al.* (2018) estimate grain (rice, maize and wheat) yield losses of 10–25% per 1°C of global warming, especially in temperate regions that produce most grain. This reflects rising temperatures boosting insect digestion rates and warming temperatures in temperate regions increasing insect activity and reproduction. Furthermore, warming is expected to increase crop losses to insect pests through geographic range expansions, human-assisted introductions, biological invasions of pest species, effects on natural enemies of pests and changes in plant nutrient content and defence. Some responses may be compounded by interactive effects of warming with other factors, such as changing rainfall patterns and increasing atmospheric CO_2 concentrations. Thus, how will insect BCAs influence invasions from establishment, performance and population build-up, up to spread and impact?

First, BCAs must be host plant specific and reared free of antagonists. They often originate from one or few populations from a limited eco-geographic range (Sun *et al.*, 2017). Habitat loss and conversion to intensive agriculture and urbanization will favour the target host and so the BCA. Biological factors, including pathogens and introduced species, are not expected to negatively impact BCAs, at least in the short term. Pollution (mainly synthetic pesticides and fertilizers) will only negatively affect BCAs targeted on crop weeds, but not the 90% of BCAs that are used against environmental weeds (Müller-Schärer *et al.*, 2018). Like many insect pests, BCAs rely on a single host plant in a given area, but crops, noxious weeds and plant invaders are abundant and predictable, and thus less affected by the main drivers of insect decline. Based on this, BCAs are rather like insect pests and thus their performance and impacts are expected to increase under rising temperatures and CO_2 levels, especially in temperate regions. In biological control against insect pests, the BCAs are predators and parasitoids, i.e. at the top of the trophic chains, while in the control of invasive plants, the BCAs are phytophagous insects, so at a lower level of the trophic chain. Based on this, the weed BCAs should be less affected by climate change than the BCAs of insect pests, with either positive or negative outcomes for the population increase of the weed BCA and thus for the impacts on the plant invaders.

4.3.2 Drivers of climate change affecting herbivorous insects

Insects are poikilotherms so temperature is probably the critical environmental factor affecting their behaviour, distribution, development and reproduction (Damos and Savopoulou-Soultani, 2012; see also Chapter 1 of this book). Warming is expected to increase overwintering survival, increasing the number of generations but with lower body weight and thus fecundity, although with overall increasing abundance. Postintroduction expansion to newly suitable areas under climate change is expected, but impacts will greatly depend on parallel spread and phenological synchrony with the target host, which remains difficult to predict.

Theoretically, in temperate regions, temperature increase is expected to result in optimal metabolic activity and thus population increase and range expansion, but not in the tropics, where temperatures are already optimal for many insects for rapid growth (Deutsch *et al.*, 2018; Skendžić *et al.*, 2021). As outlined above, this response to climate warming has been well documented for insects in general (population decline mainly in the tropics) and insect pests in particular (increasing crop losses due to insects mainly in temperate regions). Unfortunately, based on our bibliographic review (see Fig. 4.1), this has not yet been explored for outcomes of weed BCAs.

Effects of elevated CO_2 on insect performance are mainly mediated through changes in host plant quality. For instance, Baso *et al.* (2021) investigated the effects of elevated atmospheric CO_2 on the biological control of four invasive aquatic weeds, *Azolla filiculoides* Lam. (Salviniaceae), *Salvinia molesta* Mitch. (Salviniaceae), *Pistia stratiotes* L. (Araceae) and *Myriophyllum aquaticum* (Vell.) Verdc. (Haloragaceae), which presently are under successful control by their respective BCAs *Stenopelmus rufinasus* Gyllenhal (Coleoptera: Curculionidae), *Cyrtobagous salviniae* Calder and Sands (Coleoptera: Curculionidae), *Neohydronomus affinis* Hustache (Coleoptera: Curculionidae) and *Lysathia sp.* (Coleoptera: Chrysomelidae), respectively, in South Africa. At elevated CO_2, the authors found a general overall increase in biomass production across all weed species, and a reduced insect feeding damage, except for *S. molesta*. They conclude that although plants will respond differently to CO_2 increase, the general trend suggests that these species will become more challenging to manage through biological control in future. In another experimental study, Paper *et al.* (2023) examined the interaction between water hyacinth *Pontederia crassipes* Mart. (Pontederiaceae), one of the world's worst aquatic weeds and a target for biological control, and two insect biocontrol agents, the leaf-chewing *Cornops aquaticum* Brüner (Orthoptera: Acrididae) and the phloem-feeding *Megamelus scutellaris* Berg (Hemiptera: Delphacidae) under elevated CO_2. *Pontederia crassipes* (Mart.) Solms (Pontederiaceae) growth responses increased when exposed to insect herbivory, with chewing herbivory by *C. aquaticum* being consistent across CO_2 conditions, whereas the feeding by *M. scutellaris* increased substantially at elevated CO_2. This indicates that successful biological control of water hyacinth under elevated CO_2 conditions might rely on phloem-feeding insects, with chewers playing a lesser role.

Similarly, changing precipitation patterns may result in more frequent and intense drought and flooding. On the one hand, heavy rainfall can wash away insect larvae and eggs from plants and decrease overwintering probability through flooding and prolonged stagnation of water, while drought-stressed plants may become more susceptible to insect attack because of decreased chemical defences. Henrikson *et al.* (2018) studied the interaction between the plant invader *Alternanthera philoxeroides* (Mart.) Griseb. (Amaranthaceae) and the introduced biocontrol beetle *Agasicles hygrophila* Selman and Vogt (Coleoptera: Chrysomelidae: Halticinae) in terrestrial (well-watered) and flooded environments in Texas. They found that the hydrological environment may affect invasive plant performance by altering herbivore oviposition and feeding preferences. Under controlled conditions, flooding increased leaf toughness and decreased beetle consumption, and beetles preferred to feed and oviposit on terrestrial plants in choice trials.

In summary, a multitude of direct and indirect host plant-mediated effects of various climate change factors can alter the frequency, timing, intensity and duration of interactions between plant invaders and BCAs and, as the above examples show, impacts of BCAs on plant invaders may be enhanced or reduced. Furthermore, changes in geographic distributions, especially as the climate continues to warm and extreme events become more common, can impact interactions between BCAs and weeds as differential migration rates of insects, host plants, higher trophic levels and other species create novel biotic interactions. Sun *et al.* (2017) used a biogeographic approach and species distribution models to select among six BCA candidates and their combinations to potentially cover a large European range of the North American invader *A. artemisiifolia*, under both current and future bioclimatic conditions. Besides a considerable discrepancy in geographic range overlap between Europe (31.4%) and North America (83.3%), which might be partially due to the expansion of ragweed in Europe and the fact that habitats with high ragweed occurrences in Europe are rare in North America, and predicted to be unsuitable for the candidates, they found total geographic range of all candidates combined to decrease under climate change in both ranges, but that the species will respond differently. Complex modelling tools are therefore urgently needed to make realistic predictions of biological control outcomes under future climate conditions (see below).

4.3.3 How to best match genotypes and phenotypes between plant invaders and BCAs to optimize biocontrol effectiveness

Many cases of rapid adaptive evolution have been reported for invasive plants, including shifts in resource allocation from defence to growth (Coley, *et al.*, 1985; Orians and Ward, 2010), local adaptation to new habitats (Colautti and Barrett, 2013) and climates such as by the evolution of phenotypic clines along climatic gradients (Yang *et al*., 2021), evolution of greater dispersal ability (Alex Perkins *et al*., 2013) and increases in rates of population growth and expansion (Lee, 2010; Hodgins *et al*., 2018). According to the evolution of increased competitive ability (EICA) hypothesis (Blossey and Nötzold, 1995), mechanical and/or chemical defensive characters may be adaptive in the presence of enemies, but they become unnecessary and costly when these enemies are absent, such as when introduced into new areas. This has been widely tested, for instance in *Silene latifolia* Poiret (Caryophyllaceae), which was introduced from Europe to North America c.200 years ago. A common garden experiment in Europe revealed that plants from North America have evolved a two-to-threefold higher reproductive potential, at the expense of higher susceptibility to fungal infection, fruit predation and aphid infestation, compared to plants from Europe (Wolfe *et al*., 2004). Rapid evolutionary change can also occur in BCAs post introduction in response to new climatic and environmental conditions (Suarez and Tsutsui, 2008; Roderick *et al*., 2012), especially for species with short generation times (Van Asch *et al*., 2013; Szűcs *et al*., 2017; Wright and Bennett, 2018). A recent review of experiments and theory suggests BCA changes following introduction may be larger than previously considered (Szűcs *et al*., 2019). As outlined above (see Fig. 4.2), *a priori* predictions of interactions between a plant invader and its BCAs are difficult, even more so when including a parallel change in climate conditions for both a plant invader and BCA has an ecological and evolutionary dimension.

Populations of both a plant invader in the introduced range and its potential BCAs in the native range may be genetically differentiated among geographically distinct regions. A first pragmatic approach to test the outcome of their interaction when brought together has recently been tested by Sun *et al*. (2020b) by challenging various plant genotypes of the target invader *A. artemisiifolia* with genotypes of the accidentally introduced and now successful BCA in China, the ragweed leaf beetle *Ophraella communa* L. (Coleoptera: Chrysomelidae). Both the invader and its antagonist were collected over three continents, i.e. in their native North American and introduced European and Chinese ranges and across large environmental amplitudes. The authors found the BCA genotype to be the critical factor, as some were effective against most plant genotypes, indicating the potential for at least short-term control efficacy. This approach will also indicate where to find the most efficient BCA genotypes, and it could be extended to set up these genotype-by-genotype interactions under different temperatures mimicking climate warming. An alternative approach for understanding and predicting population dynamics under climate change is the incorporation of climate-dependent vital rates of the BCA into species distribution models (cf. below).

4.3.4 Recent advances in predictive demographic modelling tools

In addressing the escalating complexities of weed biocontrol under climate change, it becomes evident that traditional modelling approaches may not suffice. To effectively predict and manage the future interplay of plants and herbivores, we must develop more sophisticated predictive modelling tools that incorporate a detailed understanding of life-history traits and climate-dependent vital rates (Sun *et al*., 2020a). Life-history traits, including reproduction, growth and survival rates, are fundamental to understanding how species respond to environmental changes. These traits are shaped by evolutionary forces and current environmental conditions and can provide insights into resilience and adaptability of both invasive plants and their BCAs. Models incorporating these traits can help predict how species will respond to various climate scenarios, including changes in temperature, precipitation patterns and the frequency of extreme events (Kearney and Porter, 2009), such as integral projection models (IPMs) (Easterling *et al*., 2000) and DYMEX (Hearne Scientific Software) (Maywald *et al*., 2007). For example, a process-based population dynamics model predicted that invasive *Buddleja davidii* Franchet (Buddlejaceae) would succumb rapidly to damage by its biocontrol weevil *Cleopus japonicus* Wingelmüller

(Coleoptera: Curculionidae) under warming conditions (Kriticos *et al.*, 2009).

Incorporating these factors into predictive models requires a detailed understanding of the species in question, including their physiology, behaviour and interactions with other species and the environment. It also requires sophisticated modelling techniques capable of capturing the complexity of biological systems and their responses to a changing climate. This might include mechanistic models based on underlying biological processes that can make detailed predictions about how species will respond to specific environmental changes. Moreover, these models must be dynamic, capable of adapting to new information and changing conditions. This requires ongoing research and data collection, as well as a willingness to revise and improve models as new information becomes available. Combining species distribution models (SDMs) and mechanistic (process-based) models by integrating physiological models of insect development into SDMs based on habitat suitability may enable more robust predictions of both range shifts (Kearney and Porter, 2009) and population abundances (Keith *et al.*, 2008; Gallien *et al.*, 2010). Such a combined approach identified climatic factors limiting populations of *O. communa*, a biocontrol candidate of invasive *A. artemisiifolia*, and predicted its potential population density across its suitable European range and the relative importance of those climatic factors on the population growth (Augustinus *et al.*, 2020).

In conclusion, as the interplay among plants and herbivores becomes increasingly complex under climate change, we need more detailed predictive modelling tools. These tools must incorporate life-history traits and climate-dependent vital rates to provide accurate predictions about weed biocontrol. Further studies would benefit from integrating theoretical modelling, physiological/behavioural experiments and experimental population studies under climate change conditions into a biocontrol programme. By embracing complexity and striving for a deeper understanding of the systems we seek to manage, we can develop models that not only predict the future but also guide our actions.

4.4 Non-target Effects under Climate Change

Climate change can modify non-target plant effects of insect BCAs via ecological mechanisms by increasing geographical or phenological overlap of a BCA and a plant in its potential host range (examples for alligator weed flea beetle detailed below) or by changing the realized host range (Acacia bud-galling wasp example below). Evolution can enhance these ecological mechanisms through evolved expansions in climatic niches or fundamental host ranges. In the short term, ecological effects are likely to be more important despite the potentially rapid evolutionary rates of herbivorous insects.

Non-target effects can increase if plants potentially within the BCA's host range that formerly had ranges distinct from the agent become sympatric with it. For instance, alligator weed flea beetle *A. hygrophila*, a BCA introduced in 1986 to China (from USA populations originally sourced from South America) to control alligator weed *A. philoxeroides*, has shifted its distribution to overlap with the non-target native plant *Alternanthera sessilis* (L.) R. Br. ex DC. (Amaranthaceae) and is now damaging this plant (up to 40% leaf area removal) (Lu *et al.*, 2015). Because, on average, insects shift their elevational and latitudinal range limits more rapidly than plants do (Lenoir *et al.*, 2020), potential increases in non-target effects with climate change are likely to be driven primarily by BCAs expanding their ranges to overlap those of non-target plants rather than non-target plants expanding their ranges to overlap with BCAs. Evolved increases in climatic niches of BCAs could magnify their range overlap with non-target plants but insects appear to have little evolutionary response to warming (Weaving *et al.*, 2022).

Non-target effects can increase if plants potentially within the BCA's host range that formerly had phenologies distinct from the agent begin to have overlap of the non-target plant's vulnerable stages with a period of active feeding by the BCA. For instance, *A. hygrophila* increased its non-target effects on *A. sessilis* in China in part through a shift in the plant's life history from perennial to annual with increasing latitude around 26°N (and from no emergence holes to ~10/0.25 m^2 of cover) (Lu *et al.*, 2015). Because both insects (Bale *et al.*, 2002) and plants (Parmesan and Hanley, 2015) change their phenology with climate, non-target effects may either increase or decrease depending on their relative changes (Forkner *et al.*, 2008). The net impact of climate change on non-target effects depends on phenology of plant defences and plant nutrition but these also respond directly to climate change (Pincebourde *et al.*, 2017) which makes it difficult to predict the overall contributions of phenology. Insects have been shown to evolve new phenologies in response to climate change, such as *Rhinocyllus conicus* (Froel.) (Coleoptera: Curculionidae) introduced to control invasive thistles (especially *Carduus nutans* L., Asteraceae) in North America (Russell and Louda, 2004), which indicates that evolved changes in the phenology of non-target plants and/or BCAs could magnify or dampen impacts of climate change.

Climate change can impact realized host ranges of BCAs through a phenotypic response (i.e. plants that already co-occur geographically and phenologically with the agent are fed upon). Non-target effects of BCAs may increase or decrease as their population densities vary in response to changing climate conditions. For instance, one study with *Trichilogaster acaciaelongifoliae* (Frogatt) (Hymenoptera: Pteromalidae) introduced to control *Acacia longifolia* (Andrews) Willd. (Fabaceae) in South Africa found that a greater number of exotic woody plants were attacked when its population densities were higher (Dennill *et al.*, 1993). Although insect populations and herbivory increase when temperatures increase (Currano *et al.*, 2008; Lemoine *et al.*, 2013), which would be expected to increase non-target effects by spillover, such increases may be offset by direct effects of temperature on insect diet breadth. For example, *Popillia japonica* (Coleoptera: Scarabaeidae; not a BCA) has a narrower diet breadth at higher temperatures (Lemoine *et al.*, 2013). So, the net impact of climate change on non-target effects via phenotypic changes in host ranges will depend on agent densities together with the indirect and direct effects of warming on agent diet breadth.

Biological control agents could also evolve a broader fundamental host range, putting additional non-target plants at risk of attack. However, reviews have found little evidence of such expansions of fundamental host ranges (van Klinken and Edwards, 2002; Wright and Bennett, 2018). More common, though still rare, is evolved higher performance of a BCA on a non-target plant but there does not appear to be a role of climate change in this evolved higher performance (van Klinken and Edwards, 2002). Even more commonly observed are evolved changes in quantitative traits that enhance performance of insects on their new hosts (van Klinken and Edwards, 2002). Such changes may increase non-target effects if an expansion of fundamental host range occurs.

A special case is accidental introductions of potential biological weed control agents, i.e. unintentionally introduced natural enemies, which are already used for biological control of plant invaders in another part of the invaded range (Müller-Schärer *et al.*, 2020). As for all non-native species, such introductions have increased with global exchange of goods and human travel. They offer opportunities to assess host use of agents with a potentially broader fundamental host range than those approved for field release directly in target areas, allowing comparison with records from literature surveys or, if available, with predictions from pre-release studies that rejected their introduction (Müller-Schärer *et al.*, 2020). An example, presently well studied by an international consortium, is the accidental introduction of *O. communa* into Europe as a potential BCA against ragweed. It was first recorded in 2013 in southern Switzerland and northern Italy, from where it has subsequently spread eastward up to Romania and recently also westwards to France (Müller-Schärer *et al.*, 2018; Müller-Schärer *et al.*, 2024; Sun *et al.*, 2022). Insights gained from detailed postintroduction studies of such accidentally introduced species will help to critically review and extend pre-release studies and thus re-evaluate the presently strict release criteria, as they might exclude safe and efficient agents. Müller-Schärer *et al.* (2020) proposed full development on non-target species under no-choice laboratory conditions should indicate only which test plant species should be used in further studies on biosafety. The focus should be on population growth rate rather than on survival on individual non-target plants, as a negative population growth rate on a non-target plant would indicate no sustainable population on this non-target plant, although spillover effects may occur (Hinz *et al.*, 2019).

4.5 Biological Control Opportunities Will Increase

4.5.1 Continued plant invasions under climate change

The introduction of alien species in new regions is an old phenomenon and their accumulation shows no signs of saturation (Seebens *et al.*, 2017). In 2020, ~ 14,000 plant species with established alien populations in at least one region were known, representing 4% of the world flora (Pyšek *et al.*, 2020). The first stages of biological invasion (transport, introduction) are mainly driven by economic activities, and vascular plants will continue to be spread to new areas through increased air travel (main vector for low-income countries) and trade of cultivated plants (main vector for high-income countries) (Early *et al.*, 2016). A global model projects an average increase of new vascular plant species of 18% in 2050, with a maximum of 41% in temperate Asia, and most new species in Australasia (1065), followed by Europe (997) (Seebens *et al.*, 2021).

Climate change is proportionally more important in facilitating later stages of biological invasion (establishment, spread). Interacting with land and sea use change, climate change is predicted to amplify the future threat from invasive species, especially in disturbed habitats and in nearby natural habitats (IPBES, 2023; AQ1 www.ipbes.net). A global analysis of climate change effects on invading taxa and receptivity of habitats showed overall increased performance of invasive species amongst plants, and in terrestrial habitats. Specifically, altered precipitation and CO_2 levels would enhance invasive woody plants and forbs in outcompeting native plant species (Stephens *et al.*, 2019). Severe plant invasions are expected in coastal and high-latitude ecoregions, such as coastal rivers, temperate forests and alpine vegetation (Wang *et al.*, 2019). In line with these global predictions, local studies forecasted northward range expansion of tropical invasive plants in the south-eastern USA due to future winter warming (Osland *et al.*, 2023) and increased chances of establishment for invasive plants in Poland (Solarz *et al.*, 2023).

In agriculture, climate change is generally expected to aggravate weed problems by positively impacting weed growth, but imposing more biotic and abiotic stress on crops (Varanasi *et al.*, 2016). Invasive plants have been identified as an increased risk for agro-ecosystems under climate change, for example in Sri Lanka (Marambe and Wijesundara, 2021). In addition, climate change will probably decrease the current efficacy of most herbicides, making weed management an even greater challenge for sustainable crop production (Varanasi *et al.*, 2016). As addressed earlier in this chapter, adaptation of invasive plants to climate change may exacerbate problems. As climate change and invasive species are drivers influencing each other, policy and management should thus consider their combined threats (Bradley *et al.*, 2022).

4.5.2 Political landscape – chances and threats for weed biocontrol

In recent decades, the need to take action globally against invasive species to protect biodiversity has been widely recognized, as reflected in several global agreements. In 2015, the United Nations' 2030 Agenda for Sustainable Development set 17 goals, including ecosystem conservation and measures against invasive alien species. The CBD 2022 (Convention on Biological Diversity, www.cbd.int) urges action against invasive species. The 2022 Kunming-Montreal Global Biodiversity Framework (www.cbd.int/gbf) aims to stimulate national efforts on biodiversity goals, including invasive species prevention and control. A 2023 IPBES report highlights that, with sufficient resources, political will and long-term commitment, preventing and controlling invasive species are achievable and beneficial for people and nature. This need for action can enhance development and/or adoption of (sustainable) methods like biological control.

In an agricultural context, recent policies are also promoting herbicide-free alternatives for weed control. The EU Environmental Agency acknowledges that widely used chemical pesticides in food production systems are a major source of pollution and biodiversity loss (www.eea.europa.eu/publications/how-pesticides-impact-human-health). In the context of the mission-driven European Green Deal to achieve a climate-neutral continent by 2025 (Boix-Fayos and de Vente, 2023), the Farm2Fork strategy includes a specific goal to reduce the use and risk of chemical pesticides by 50% by 2030 compared to the (EC, 2020). Herbicides made up 34% of the mass of chemical pesticides used in the EU from 2010 to 2019 (Triantafyllidis *et al*., 2023). In the past few decades several important and commonly used hazardous chemical herbicides have already been banned, including atrazine in 2004 and paraquat in 2007. Currently, a ban on glyphosate is being debated (but rejected by the European Commission in 2023). In addition, the EU's mission 'A Soil Deal for Europe' stimulates research into innovative solutions contributing to healthier soils. Together, these policies and strategies favour the inclusion of non-chemical alternatives for integrated weed management, including the use of biological control agents (Tataridas *et al*., 2022).

Although it is suggested that reducing herbicides may be more challenging than other groups (e.g. fungicides, insecticides), integrated weed control is feasible (Triantafyllidis *et al*., 2023). Indeed, eliminating paraquat has saved lives without reducing agricultural productivity, thanks to the use of less hazardous and more sustainable alternatives (Stuart *et al*., 2023). As farmers are often confronted with a multitude of weed species, it is unlikely that classical weed control will be the solution for all of these species. Agriculture may nevertheless benefit greatly from classical weed biocontrol programmes. Examples include cases where specific exotic weed species were widespread and very dominant in specific agricultural sectors or landscapes, such as the very cost-effective control of common ragwort on dairy farms in New Zealand using flea beetles (Fowler *et al*., 2016). In other cases, invasive plant species are weeds in both crop and non-crop land (Müller-Schärer *et al*., 2018) and are not exclusively targeted for agricultural purposes. Finally, classical BCAs may be augmented by mass releases to accelerate spread or increase local densities, as is being practised with the leaf beetle *O. communa* in China to control the highly allergenic common ragweed that is both an environmental and a crop weed (Müller-Schärer *et al*., 2018).

Implementation of these (global) policies that support integrated weed control and biological weed control can be challenging. Implementation of the CBD recommendations to act against invasive alien plants is limited by resources, capacity, a lack of legal frameworks and uncertainties associated with future trajectories of societies and global change (Early *et al*., 2016; Pyšek *et al*., 2020; Roura-Pascual *et al*., 2024). In the context of the EU Green Deal, scientists recently warned that EU member states should improve their National Action Plans to realise integrated pest management goals (Helepciuc and Todor, 2022a; 2022b). The EEA (2023) also acknowledges that more action is needed to achieve the goals.

Biological control is a critical tool to realise these environmental goals. It is an important method for controlling invasive plants in terrestrial and closed water systems as, next to adaptive management, it is most effective in the long term (IPBES, 2023). Impact has been demonstrated for a large majority of invasive plant species targeted, and for a substantial part of these, need for other control methods was greatly reduced or eliminated (Hinz *et al*., 2020; Sun *et al*., 2022). Compared to adaptive management, biological control is currently more available and easier to use. Scientists warn, however, that recent global (e.g. Nagoya protocol), continental and national regulations that restrict or lengthen the sourcing, importation or use of exotics may slow down or limit possibilities for biological weed control, even though this method is critical for the management of invasive alien plants (Paynter *et al*., 2020; Sun *et al*., 2022: Müller-Schärer *et al*., 2024).

References

Alex Perkins, T., Phillips, B.L., Baskett, M.L. and Hastings, A. (2013) Evolution of dispersal and life history interact to drive accelerating spread of an invasive species. *Ecology Letters* 16(8), 1079–1087.

Augustinus, B., Sun, Y., Beuchat, C. and Schaffner, U. (2020) Predicting impact of a biocontrol agent: Integrating distribution modelling with climate-dependent vital rates. *Ecological Applications* 30(1), e02003.

Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M. *et al*. (2002) Herbivory in global climate change research: Direct effects of rising temperature on insect herbivores. *Global Change Biology* 8(1), 1–16.

Baso, N.C., Coetzee, J.A., Ripley, B.S. and Hill, M.P. (2021) The effects of elevated atmospheric CO2 concentration on the biological control of invasive aquatic weeds. *Aquatic Botany* 170, 103348.

Blossey, B. and Nötzold, R. (1995) Evolution of increased competitive ability in invasive nonindigenous plants: A hypothesis. *Journal of Ecology* 83, 887.

Boix-Fayos, C. and de Vente, J. (2023) Challenges and potential pathways towards sustainable agriculture within the European Green Deal. *Agricultural Systems* 207, 103634.

Bradley, B.A., Blumenthal, D.M., Wilcove, D.S. and Ziska, L.H. (2010) Predicting plant invasions in an era of global change. *Trends in Ecology & Evolution* 25(5), 310–318.

Bradley, B.A., Beaury, E.M., Fusco, E.J. and Lopez, B.E. (2022) Invasive species policy must embrace a changing climate. *Bioscience* 73(2), 124–133.

Colautti, R.I. and Barrett, S.C. (2013) Rapid adaptation to climate facilitates range expansion of an invasive plant. *Science* 342(6156), 364–366.

Coley, P.D., Bryant, J.P. and Chapin III, F.S. (1985) Resource availability and plant antiherbivore defense. *Science* 230(4728), 895–899.

Currano, E.D., Wilf, P., Wing, S.L., Labandeira, C.C., Lovelock, E.C. *et al*. (2008) Sharply increased insect herbivory during the Paleocene-Eocene thermal maximum. *Proceedings of the National Academy of Sciences USA* 105(6), 1960–1964.

Damos, P. and Savopoulou-Soultani, M. (2012) Temperature-driven models for insect development and vital thermal requirements. *Psyche* 2012(1), 123405.

Dennill, G.B., Donnelly, D. and Chown, S.L. (1993) Expansion of host-plant range of a biocontrol agent *Trichilogaster acaciaelongifoliae* (Pteromalidae) released against the weed *Acacia longifolia* in South Africa. *Agriculture, Ecosystems & Environment* 43(1), 1–10.

Deutsch, C.A., Tewksbury, J.J., Tigchelaar, M., Battisti, D.S., Merrill, S.C. *et al*. (2018) Increase in crop losses to insect pests in a warming climate. *Science* 361(6405), 916–919.

Dukes, J.S. and Mooney, H.A. (1999) Does global change increase the success of biological invaders? *Trends in Ecology & Evolution* 14(4), 135–139.

Early, R., Bradley, B.A., Dukes, J.S., Lawler, J.J., Olden, J.D. *et al*. (2016) Global threats from invasive alien species in the twenty-first century and national response capacities. *Nature Communications* 7(1), 12485.

Easterling, M.R., Ellner, S.P. and Dixon, P.M. (2000) Size-specific sensitivity: Applying a new structured population model. *Ecology* 81(3), 694–708.

EC (2020) Farm to Fork targets – Progress. Available at: https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/farm-fork-targets-progress_en#:~:text=Further%20information-,About%20the%20targets,use%20of%20more%20hazardous%20pesticides (accessed 5 June 2025).

EEA (2023) Environmental statement. Available at: www.eea.europa.eu/en/analysis/publications/environmental-statement-2023#:~:text=The%20EEA's%20environmental%20performance%20in,an%20increase%20compared%20to%202022 (accessed 5 June 2025).

Essack, S. (2018) Antibiotic resistance and One Health: A mapping project. *Lancet Global Health* 6, S27.

Forkner, R.E., Marquis, R.J., Lill, J.T. and Le Corff, J. (2008) Timing is everything: Phenological synchrony and population variability in leaf-chewing herbivores of *Quercus*. *Ecological Entomology* 33(2), 276–285.

Fowler, S., Gourlay, A. and Hill, R. (2016) Biological control of ragwort in the New Zealand dairy sector: An ex-post economic analysis. *New Zealand Journal of Agricultural Research* 59(3), 205–215.

Gallien, L., Münkemüller, T., Albert, C.H., Boulangeat, I. and Thuiller, W. (2010) Predicting potential distributions of invasive species: Where to go from here? *Diversity and Distributions* 16(3), 331–342.

Gioria, M., Hulme, P.E., Richardson, D.M. and Pyšek, P. (2023) Why are invasive plants successful? *Annual Review of Plant Biology* 74, 635–670.

Helepciuc, F.-E. and Todor, A. (2022a) Evaluating the EU's efforts to improve resilience to health and environmental risks associated with pesticide use by analyzing the national action plans of EU Member States from 2009 to 2019. *International Journal of Environmental Research and Public Health* 19(9), 5446.

Helepciuc, F.-E. and Todor, A. (2022b) Greener European agriculture? Evaluating EU Member States' transition efforts to integrated pest management through their national action plans. *Agronomy* 12(10), 2438.

Helliwell, E.E., Faber-Hammond, J., Lopez, Z.C., Garoutte, A., von Wettberg, E. *et al*. (2018) Rapid establishment of a flowering cline in Medicago polymorpha after invasion of North America. *Molecular Ecolog* 27, 4758–4774.

Henrikson, J.W., Lim, D.S., Lu, X., Ding, J. and Siemann, E. (2018) Strong effects of hydrologic environment and weak effects of elevated CO2 on the invasive weed *Alternanthera philoxeroides* and the biocontrol beetle *Agasicles hygrophila*. *Arthropod Plant Interaction* 12, 691–700.

Hinz, H.L., Winston, R.L. and Schwarzländer, M. (2019) How safe is weed biological control? A global review of direct nontarget attack. *Quarterly Review of Biology 94*(1), 1–27.

Hinz, H.L., Winston, R.L. and Schwarzländer, M. (2020) A global review of target impact and direct nontarget effects of classical weed biological control. *Current Opinion in insect Science* 38, 48–54.

Hodgins, K.A., Bock, D.G. and Rieseberg, L.H. (2018) Trait evolution in invasive species. *Annual Plant Reviews Online* 459–496.

Kearney, M. and Porter, W. (2009) Mechanistic niche modelling: Combining physiological and spatial data to predict species' ranges. *Ecology Letters* 12(4), 334–350.

Keith, D.A., Akçakaya, H.R., Thuiller, W., Midgley, G.F., Pearson, R.G. *et al*. (2008) Predicting extinction risks under climate change: Coupling stochastic population models with dynamic bioclimatic habitat models. *Biology Letters* 4(5), 560–563.

Kriticos, D.J., Watt, M.S., Withers, T.M., Leriche, A. and Watson, M.C. (2009) A process-based population dynamics model to explore target and non-target impacts of a biological control agent. *Ecological Modelling* 220(17), 2035–2050.

Lee, C.E. (2010) Evolution of invasive populations. In: *Proceedings of the National Academy of Sciences USA*, pp. 15793–15798 (Vol. 104).

Legg, S. (2021) IPCC, 2021: Climate change 2021 – The physical science basis. *International Panel on Climate Change* 49, 44–45.

Lemoine, N.P., Drews, W., Burkepile, D.E. and Parker, J.D. (2013) Increased temperature alters feeding behavior of a generalist herbivore. *Oikos* 122(12), 1669–1678.

Lenoir, J., Bertrand, R., Comte, L., Bourgeaud, L., Hattab, T. *et al*. (2020) Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution* 4(8), 1044–1059.

Lu, X.M., Siemann, E., He, M.Y., Wei, H., Shao, X. *et al*. (2015) Climate warming increases biological control agent impact on a non-target species. *Ecology Letters* 18(1), 48–56.

Marambe, B. and Wijesundara, S. (2021) Effects of climate change on weeds and invasive alien plants in Sri Lankan agro-ecosystems: Policy and management implications. *Frontiers in Agronomy* 3, 641006.

Maywald, G., Kriticos, D., Sutherst, R. and Bottomley, W. (2007) *DYMEX Model Builder Version 3: User's Guide*. Hearne Scientific Software, Melbourne, Australia, p. 172.

Müller-Schärer, H., Sun, Y. and Schaffner, U. (2024) When a plant invader meets its old enemy abroad: What can be learnt from accidental introductions of biological control agents. *Pest Management Science* 80(1), 19–27.

Müller-Schärer, H. and Schaffner, U. (2008) Classical biological control: Exploiting enemy escape to manage plant invasions. *Biological Invasions* 10(6), 859–874.

Müller-Schärer, H. and Schaffner, U. (2020) Editorial overview: Biological control of plant invaders: A continued stimulus and yet untapped potential to link and advance applied and basic research. *Current Opinion in Insect Science* 38, v–viii.

Müller-Schärer, H., Sun, Y., Chauvel, B., Karrer, G., Kazinczi, G. *et al*. (2018) Cross-fertilizing weed science and plant invasion science to improve efficient management: A European challenge. *Basic and Applied Ecology* 33, 1–13.

Müller-Schärer, H., Bouchemousse, S., Litto, M., McEvoy, P.B., Roderick, G.K. *et al*. (2020) How to better predict long-term benefits and risks in weed biocontrol: An evolutionary perspective. *Current Opinion in Insect Science* 38, 84–91.

Orians, C.M. and Ward, D. (2010) Evolution of plant defenses in nonindigenous environments. *Annual Review of Entomology* 55, 439–459.

Osland, M.J., Chivoiu, B., Feher, L.C., Dale, L.L., Lieurance, D. *et al*. (2023) Plant migration due to winter climate change: Range expansion of tropical invasive plants in response to warming winters. *Biological Invasions* 25(9), 2813–2830.

Paper, M.K., Righetti, T., Raubenheimer, S.L., Coetzee, J.A., Sosa, A.J. *et al*. (2023) Effects of elevated CO_2 on feeding responses of biological control agents of Pontederia crassipes. *Entomologia Experimentalis et Applicata* 171(12), 998–1008.

Parmesan, C. and Hanley, M.E. (2015) Plants and climate change: Complexities and surprises. Review, *Annals of Botany* 116(6), 849–864.

Paynter, Q., Paterson, I.D. and Kwong, R.M. (2020) Predicting non-target impacts. *Current Opinion in Insect Science* 38, 79–83.

Pincebourde, S., van Baaren, J., Rasmann, S., Rasmont, P., Rodet, G. *et al*. (2017) Plant–insect interactions in a changing world. In: Sauvion, N., Thiéry, D. and P.A, Calatayud. (eds) *Advances in Botanical Research*, Vol. 81. Academic Press, New York, pp. 289–332.

Pyšek, P., Hulme, P.E., Simberloff, D., Bacher, S., Blackburn, T.M. *et al*. (2020) Scientists' warning on invasive alien species. *Biological Reviews* 95(6), 1511–1534.

Roderick, G.K., Hufbauer, R. and Navajas, M. (2012) Evolution and biological control. *Evolutionary Applications* 5(5), 419–423.

Roura-Pascual, N., Saul, W.C., Pérez-Granados, C., Rutting, L., Peterson, G.D. *et al*. (2024) A scenario-guided strategy for the future management of biological invasions. *Frontiers in Ecology and the Environment* 22(4), e2725.

Russell, F.L. and Louda, S.M. (2004) Phenological synchrony affects interaction strength of an exotic weevil with *Platte thistle*, a native host plant. *Oecologia* 139, 525–534.

Sánchez-Bayo, F. and Wyckhuys, K.A. (2019) Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation* 232, 8–27.

Schwarzländer, M., Hinz, H.L., Winston, R. and Day, M. (2018) Biological control of weeds: An analysis of introductions, rates of establishment and estimates of success, worldwide. *BioControl* 63(3), 319–331.

Seebens, H., Blackburn, T.M., Dyer, E.E., Genovesi, P., Hulme, P.E. *et al*. (2017) No saturation in the accumulation of alien species worldwide. *Nature Communications* 8, 14435.

Seebens, H., Bacher, S., Blackburn, T.M., Capinha, C., Dawson, W. *et al*. (2021) Projecting the continental accumulation of alien species through to 2050. *Global Change Biology* 27(5), 970–982.

Skendžić, S., Zovko, M., Živković, I.P., Lešić, V. and Lemić, D. (2021) The impact of climate change on agricultural insect pests. *Insects* 12(5), 440.

Solarz, W., Najberek, K., Tokarska-Guzik, B. and Pietrzyk-Kaszyńska, A. (2023) Climate change as a factor enhancing the invasiveness of alien species. *Environmental & Socio-Economic Studies* 11(4), 36–48.

Sotka, E.E., Baumgardner, A.W., Bippus, P.M., Destombe, C., Duermit, E.A. *et al*. (2018) Combining niche shift and population genetic analyses predicts rapid phenotypic evolution during invasion. *Evolutionary Applications* 11, 781–793.

Stephens, K.L., Dantzler-Kyer, M.E., Patten, M.A. and Souza, L. (2019) Differential responses to global change of aquatic and terrestrial invasive species: Evidences from a meta-analysis. *Ecosphere* 10(4), e02680.

Stuart, A.M., Merfield, C.N., Horgan, F.G., Willis, S., Watts, M.A. *et al*. (2023) Agriculture without paraquat is feasible without loss of productivity – lessons learned from phasing out a highly hazardous herbicide. *Environmental Science and Pollution Research* 30(7), 16984–17008.

Suarez, A.V. and Tsutsui, N.D. (2008) The evolutionary consequences of biological invasions. *Molecular Ecology* 17(1), 351–360.

Sun, Y., Brönnimann, O., Roderick, G.K., Poltavsky, A., Lommen, S.T. and Müller-Schärer, H. (2017) Climatic suitability ranking of biological control candidates: A biogeographic approach for ragweed management in Europe. *Ecosphere* 8(4), e01731.

Sun, Y., Ding, J., Siemann, E. and Keller, S.R. (2020a) Biocontrol of invasive weeds under climate change: Progress, challenges and management implications. *Current Opinion in Insect Science* 38, 72–78.

Sun, Y., Beuchat, C. and Müller-Schärer, H. (2020b) Is biocontrol efficacy rather driven by the plant or the antagonist genotypes? A conceptual bioassay approach. *NeoBiota* 63, 81–100.

Sun, Y., Müller-Schärer, H. and Schaffner, U. (2022) Fighting neobiota with neobiota: Consider it more often and do it more rigorously. *Biological Conservation* 268, 109506.

Szűcs, M., Vahsen, M., Melbourne, B., Hoover, C., Weiss-Lehman, C. and Hufbauer, R. (2017) Rapid adaptive evolution in novel environments acts as an architect of population range expansion. *Proceedings of the National Academy of Sciences USA* 114(51), 13501–13506.

Szűcs, M., Vercken, E., Bitume, E.V. and Hufbauer, R.A. (2019) The implications of rapid eco-evolutionary processes for biological control-A review. *Entomologia Experimentalis et Applicata* 167(7), 598–615.

Tataridas, A., Kanatas, P., Chatzigeorgiou, A., Zannopoulos, S. and Travlos, I. (2022) Sustainable crop and weed management in the era of the EU Green Deal: A survival guide. *Agronomy* 12(3), 589.

Thomas, J.A., Telfer, M.G., Roy, D.B., Preston, C.D., Greenwood, J.J.D. *et al*. (2004) Comparative losses of British butterflies, birds, and plants and the global extinction crisis. *Science* 303(5665), 1879–1881.

Triantafyllidis, V., Mavroeidis, A., Kosma, C., Karabagias, I.K., Zotos, A. *et al*. (2023) Herbicide use in the era of farm to fork: Strengths, weaknesses, and future implications. *Water, Air and Soil Pollution* 234(2), 94.

Van Asch, M., Salis, L., Holleman, L.J., Van Lith, B. and Visser, M.E. (2013) Evolutionary response of the egg hatching date of a herbivorous insect under climate change. *Nature Climate Change* 3(3), 244.

van Boheemen, L.A., Atwater, D.Z. and Hodgins, K.A. (2019) Rapid and repeated local adaptation to climate in an invasive plant. *New Phytologist* 222, 614–627.

van Klinken, R.D. and Edwards, O.R. (2002) Is host-specificity of weed biological control agents likely to evolve rapidly following establishment? *Ecology Letters* 5(4), 590–596.

Varanasi, A., Prasad, P.V. and Jugulam, M. (2016) Impact of climate change factors on weeds and herbicide efficacy. *Advances in Agronomy* 135, 107–146.

Wang, C.-J., Li, Q.-F. and Wan, J.-Z. (2019) Potential invasive plant expansion in global ecoregions under climate change. *PeerJ* 7, e6479.

Weaving, H., Terblanche, J.S., Pottier, P. and English, S. (2022) Meta-analysis reveals weak but pervasive plasticity in insect thermal limits. *Nature Communications* 13(1), 5292.

Wolfe, L.M., Elzinga, J.A. and Biere, A. (2004), Increased susceptibility to enemies following introduction in the invasive plant Silene latifolia. *Ecology Letter*s 7, 813–820.

Wright, M.G. and Bennett, G.M. (2018) Evolution of biological control agents following introduction to new environments [Review]. *Biocontrol* 63(1), 105–116.

Yang, Y., Liu, M., Pan, Y., Huang, H., Pan, X. *et al*. (2021) Rapid evolution of latitudinal clines in growth and defence of an invasive weed. *New Phytologist* 230(2), 845–856.