Biological Control Systems and Climate Change

CABI Ecostacking Series

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The ecostacking logo symbolizes the interconnectedness of all ecosystem processes. Affecting one of the processes invariably will affect all other ecosystem components. Conceptual design: Heikki Hokkanen and Ingeborg Menzler-Hokkanen, final design by CABI.

Biological Control Systems and Climate Change

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CABI is a trading name of CAB International

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A catalogue record for this book is available from the British Library, London, UK.

ISBN-13: 9781800625075 (hardback)
9781800625082 (ePDF)
9781800625099 (ePub)

DOI: 10.1079/9781800625099.0000

Commissioning Editor: Ward Cooper
Editorial Assistant: Emma McCann
Production Editor: James Bishop

Typeset by Exeter Premedia Services Pvt Ltd, Chennai, India
Printed and bound in the UK by CPI Group (UK) Ltd, Croydon, CR0 4YY

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Introduction

Biological communities typically maintain a dynamic balance that supports the coexistence of all their constituent species. Alterations in the system structure or in the density of a given species due to natural or artificial disturbances exceeding a certain threshold can tend towards the breakdown of the system, which will have to adapt to the new conditions, if it has not ceased to exist. During the First Agricultural Revolution, in the Neolithic period, humans started to alter the natural ecosystems to create the first croplands. Complex ecosystems, such as forests or meadows, were changed at a small scale around human settlements to fit the new production needs. Recent evidence suggests that farming did not bring a productivity advantage to the hunter-gatherers who initiated it, unless a previous possession-based private property structure existed, changing the traditional view of farming, because of technological improvements, to an 'institution-first' perspective (Bowles and Choi, 2019). These institutional changes may have predated and provided conditions for subsequent technical changes that allowed for agriculture's birth. Thus, premodern agrarian autocracies benefited most from the advent of agriculture, frequently requiring farmers to grow cereals – easier to harvest and store – rather than root crops, to sustain their dominance.

The Green Revolution (aka the Third Agricultural Revolution) implemented technological improvements to reduce or eliminate hunger. Improved irrigation systems, the use of synthetic pesticides and fertilizers and the selection of high-yielding strains of crops boosted the farmland productivity of a few selected staple crops to unprecedented levels (Soby, 2013). Scaling all these technologies globally was also linked to the birth of a multi-billion industry concentrated in a small number of multinational companies, with a global yearly market of $49 billion on pesticides alone in 2022, according to FAOSTAT (FAO, 2022). But has the Green Revolution proven itself a successful strategy for ending hunger? Increasing production cannot alleviate hunger if it fails to alter the tightly concentrated distribution of economic power, specifically the access to land and the necessary technological products (Rosset *et al.*, 2000). The modern intensification and technological advancement of agriculture have resulted in an agrochemical dependence that represents one of the most pressing challenges to global environmental sustainability and public health (Hu, 2020).

The shift to conventional agriculture, which includes the use of agrochemical pollutants, is the main driver of the decline in insect populations worldwide (Sánchez-Bayo and Wyckhuys, 2019). Agrochemicals have well-known effects on non-target taxa, including alterations in activity, physiology and diversity of terrestrial and aquatic faunal communities (Beringue *et al.*, 2024). The decline in bee populations due to the prevalence of neonicotinoids in farmland is probably one of the best known examples of the negative impact of pesticides on non-target species. This problem is particularly important as bees are a key species needed for the pollination of many crops worldwide (Sgolastra *et al.*, 2020). The detrimental effects of the Green Revolution reached further trophic networks; during the last decades, for instance, up to 70% decline in farmland insect populations and around 50% loss of farmland birds' abundance have been reported in European countries, where solid long-term monitoring schemes exist (Brühl and Zaller, 2019; Geiger *et al.*, 2010). Given the wealth of evidence on the detrimental effects of pesticides on biodiversity, Brühl and Zaller (2019) suggest that the environmental risk assessments enforced in the registration process of agrochemicals fail to measure the detrimental effects of these products on the environment and should therefore be upgraded to a higher level of exigence.

Despite the astounding results in terms of crop yield achieved by modern agricultural intensification, its environmental consequences extend beyond the problems of pest resistance or loss of biodiversity. In what seems to be a Faustian bargain that compromises the sustainability and viability of future human generations, issues linked to agricultural modernisation encompass other key aspects like pollution of critical resources in the face of climate change such as surface and groundwater; dependence on fossil fuels and derivatives corresponding to greenhouse gas emissions; loss of soil fertility and increased soil erosion (Badgley *et al.*, 2007). According to the FAO (2019), 90% of the world's topsoil is likely to be at risk by 2050, partially due to the intensification of agriculture.

Proponents of modern technological agricultural practices argue that no other productive strategy can ensure sufficiently high yields to satisfy the needs of the global food supply chain, even claiming that questioning the technological approach runs counter to scientific evidence (Borlaug, 2000). From this perspective, the assumed lower yield of organic crops would need more land to fulfil the supply needs, thus offsetting any possible environmental benefits of such practices. Badgley *et al.* (2007), using a global dataset from 293 studies on the yield of organic and conventional crops, estimated the viability of organic food production worldwide. Using FAO statistics on global food production and the daily caloric intake of the human population, they conclude that turning global production into organic would yield a ratio between 0.92 and 1.80 times the yield currently achieved by conventional (or Green Revolution) methods. They have also shown that it is also possible to fertilize such organic production using non-synthetic sources, such as crop residues, animal manures, compost and biologically fixed nitrogen from leguminous plants. These results suggest that organic options could play an important role in feeding the current and future human population without increasing the cultivated land, thus alleviating the heavy environmental trade-offs of today's dominant Green Revolution methods and stagnation of some yield crops (Schauberger *et al.*, 2018). Besides striving to improve production, it is generally accepted that the reduction of food losses, mainly attributable to the technological advances in agricultural practices and the food market globalisation boosted by the Green Revolution, would play a significant role in addressing world hunger and inequity (Soria-Lopez *et al.*, 2023).

Novel efficient food systems are required to meet environmental and consumer demands (Soria-Lopez *et al.*, 2023). The Millennium Ecosystem Assessment of 2005 recommended promoting methods that increase food production without harmful trade-offs due to excessive water usage, nutrients or pesticides. For instance, evidence shows that the correct management of the trophic levels of the agroecosystems, either above or below the target pests, can alter the pest population dynamics and reduce crop damage to acceptable thresholds, avoiding the use of pesticides (Matson *et al.*, 1997). Given the current situation, ecological interactions that reinforce biological pest control should become the first option and chemical approaches should only be encouraged when natural solutions prove inefficient in controlling pests.

However, to implement biocontrol instead of chemical pesticides, it is necessary to take into account the major changes of the last 50 years qualified by the term 'global environmental changes', which include changes in both land use (intensification of agriculture mentioned above) and climate change.

Regarding climate change, the main driver is the increase in greenhouse gases emitted into the atmosphere associated with anthropogenic activity such as the extraction and burning of fossil fuels, deforestation and corporate agricultural practices (IPCC, 2023). For example, the International

Panel on Climate Change (IPCC) 6th Assessment Report (AR6) stated that atmospheric carbon dioxide levels have increased to the current level of 410 ppm and will increase to between 730 and 1000 ppm by the end of this century. Rising mean global temperatures as well as changes in precipitation patterns are the direct result of this inexorable rise in concentrations of greenhouse gases, particularly carbon dioxide (CO_2), ozone (O_3) and methane (CH_4). The increase in temperatures has been observed since 1850. The global surface temperature was 1.09°C higher in 2011–2020 than in 1850–1900, with greater increases on land (1.59°C) than over the ocean (0.88°C) (IPCC, 2023) and is projected to increase further as global CO_2 levels are expected to double by the end of the 21st century (IPCC, 2023). Climate change affects both high- and low-income countries, with repercussions for food safety, resulting in fewer opportunities to overcome the crisis for low-income countries, due to the scarcity of resources (FAO, 2020).

At the UN Climate Change Conference in Paris in 2015, the participating countries agreed to limit the temperature increase below 2°C by the end of this century. However, this limit currently seems unachievable, as in practice political decisions have not been followed by the concrete implementation of plans to drastically reduce emissions (Nordhaus, 2018). In this framework, participating countries were required to submit their climate action plans, called nationally determined contributions (NDCs), by 2020. However, these NDCs present a substantial gap in greenhouse gas emissions compared to what would have been necessary to limit warming to 1.5°C or even 2°C assuming immediate action. As a result, a median global warming rate of 2.8 (2.1–3.4) °C is to be expected by 2100. It could even reach 4.4°C for a very high greenhouse gas emissions scenario (IPCC, 2023). This average increase masks significant changes in the frequency, intensity, spatial extent, duration and timing of weather and climate extremes such as droughts or major floods, storms, heat waves or unpredictable cold snaps (Seneviratne *et al.*, 2012). Extreme climate events can be defined as the occurrence of a value of a weather or climate variable above or below a threshold close to the upper or lower end of the range of observed values of the variable (for a discussion of these concepts and the use of extreme indices, see Seneviratne *et al.*, 2012). An increase in extreme temperatures can therefore be expected, especially during summer (Lelieveld *et al.*, 2016), these changes being greater in the northernmost countries. In addition, winters will be milder and vegetation will resume earlier in the spring.

Climate extremes are part of the environmental variability that the living world normally experiences and have therefore always been a selective pressure. Since the industrial era, however, two new elements have emerged: the rapid increase in the amplitude of these extremes and their frequency over time. This raises two questions: how do organisms respond to these increases in amplitude, which go beyond the usual range of conditions they encounter, and what are the consequences of the rapid repetition of these fluctuations for the adaptability of the living world?

For living organisms, a growing number of studies have been able to demonstrate that the modification of abiotic conditions, from the global scale to the local scale, is responsible for changes in the physiology and in all the life-history traits (e.g. fecundity, growth, longevity), in phenology (i.e. periodic events of biological activity determined by seasonal variations), in the relative abundances of individuals of different species, in species geographic distributions and the diversity of communities. As most of the pests (mainly insect herbivores) and most of the biological control agents (BCA) are ectothermic organisms, they are strongly affected by both rises in global temperatures and extremes in temperature and precipitation (Bale *et al.*, 2002; Harvey *et al.*, 2022). These abiotic and biotic changes also alter the interactions between species and trophic levels, leading to modifications in the functioning of these ecosystems and thus in the associated ecosystem services, such as the biological control of crop pests in agroecosystems. This service, supported by biodiversity, has been altered by pesticides as described above, but is also threatened by climate change when a change in practices becomes crucial for both human and environmental health.

The term 'biological control' is generally used to define any suppression or reduction of abundance below an ecological or economical threshold of an organism harmful to humans (pests, such as insects, mites, weeds and pathogens) by another living organism, called a biological control agent or BCA, which includes predators, parasitoids, pathogens, fungi, bacteria, virus etc. Some biocontrol methods rely on active substances or preparations containing one or more active substances of natural origin. This definition includes 'biocontrol products' that use natural mechanisms to combat pests as part of integrated pest management (IPM), such as micro-organisms (bacteria, viruses, fungi but also their extracts), plant defence stimulators and chemical mediators (pheromones, kairomones) and products of natural origin (extracts of plants, animals or minerals). Biological control always involves an active human management role and can be an important component of IPM programmes, even if pesticide application is still possible in IPM.

There are different basic strategies for biological pest control: classical, where a natural enemy of a pest is introduced into its new range; inoculative, when a small number of individuals are introduced in an area (often glasshouses) to establish themselves in this environment and to reproduce before the arrival of the pests; and augmented, in which large numbers of natural enemies are released for rapid pest control; conservational, involving habitat management to favour natural enemy populations against pest populations. The main objective of this book is to synthesize the effects (positive or negative) of climate change on these different methods of biocontrol.

The first part features nine chapters summarizing the impact of climate change on macro-organisms involved in biocontrol strategies (i.e. phytophagous insects against weeds, predators and parasitoids, bats, birds against pest herbivores, etc.). It includes both general concepts and applied studies and details the various impacts of climate change on the life-history traits of macro-organisms and how they vary according to species, inducing phenological modifications and the difference of vulnerability between organisms from temperate and equatorial-tropical areas (Chapters 1 and 2). Chapters of this first section also detail why an increase in pest outbreaks and plant diseases transmitted by vectors is expected following climate change (Chapter 3), and question the relative impacts of climate change on weeds and phytophagous insects to understand if and when the biocontrol will work better or decrease (Chapter 4). They explore the mechanisms of the role of climate change on plant defences and how they are modified by climate change (Chapter 5). Specific chapters present the importance of lesser known but also very important BCAs such as spiders (Chapter 6), birds (Chapter 7) and bats (Chapter 8). Finally, the last chapter of this part (Chapter 9) highlights a case study of community changes and genetic differentiation in parasitoids at a small scale induced by climate change and this knowledge can become a tool to produce BCAs adapted to particular climatic conditions.

The second part of this book focuses on the impact of climate change on pathogens such as fungi, oomycetes, bacteria and viruses, and on the micro-organisms involved in biocontrol strategies (fungi, oomycetes, bacteria and viruses) (Chapters 10 and 11). Chapter 12 deals with the impact of climate change on bacterial–insect symbiosis and the implications for parasitoidism and biological control.

The third part (13 chapters) includes chapters presenting either results of case studies in different continents or agricultural systems or potential future solutions (from the first proof of concept to techniques that still need to be developed). Chapter 13 presents the importance of adapting the biocontrol of aflatoxins in maize under a scenario of climate change, Chapter 14 details a potential adaptation of IPM strategy against the codling moth *Cydia pomonella* to climate change, and Chapter 15 explains how both biocontrol and IPM strategy could be adapted to the effects of climate change in the specific conditions of greenhouses. Chapter 16 provides a tool to determine the threshold of temperature at which the present biocontrol methods will not be efficient any more through a case study with acarine species. Chapter 17 explores how new biocontrol tools could be deployed against plant disease using plant growth-promoting endophytes (specific case of rhizobacteria). Chapter 18 presents how conservation biological control can take opportunities of climate change in some situations in which plant and insect phenology were modified, by developing the management of semi-natural elements as flowering strips or hedges around the fields, to intensify natural enemy pressure on pest populations. Chapter 19 focuses on a tool for early detection of invaders which can become new pests, to determine in advance the future invasive species and control them before invasion and avoid new pest outbreaks. Chapter 20 exposes how microclimate impacts biocontrol, and how managing microclimates can become a tool to improve biocontrol. Chapter 21 introduces a detailed list of new tools, recently used or which can be developed in the future in the area of biocontrol, and Chapter 22 details some case studies in Latin American crops. Chapter 23 reviews the different types of companies involved in biocontrol and the new tools that they could develop to adapt their products to climate change. Chapters 24 and 25 highlight the interest of economic and societal approaches to increase the adoption of biocontrol strategies in the future, either by valuating the ecosystem services using economic tools and methods or by innovation management using living technologies.

The main message of this book is that biocontrol can be improved or adversely affected by climate change, and that the resulting situation is specific to each case (both the system and the localization), with very little possibility of generalization, due to the complexity and the number of effects of climate change both on the pests/diseases and on the biocontrol agents (micro- or macro-organisms).

In this context, this book is timely as over 6000 publications have now provided valuable data on this subject, supplying enough material to produce a synthesis of the current challenges in this research area. This book is intended to provide students, teachers, stakeholders and managers of companies producing BCA or macro-organisms involved in biocontrol with the keys to understanding the impact of climate change on the different biocontrol methods, in order to be able to adapt them to new environmental conditions. Most studies on climate change are focused on the impact of climate change on individual species, whereas biological control methods involve interactions between species at different trophic levels and therefore the necessity to develop an understanding at a large scale. Climate change is a challenge that will require the development of flexible strategies capable of responding to changes in pest distribution and/or food web structure. Biocontrol strategies fit perfectly with Agenda 2030 contributing to the 'zero hunger' goal and particularly to food safety. Likewise, it is in line with the concept of One Health, which is an approach that aims to balance, protect and optimise the health of people, other living organisms such as plants and animals, and ecosystems (Sarrocco, 2023).

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