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GUIDANCE ON INTEGRATED PEST MANAGEMENT FOR THE WORLD'S MAJOR CROP PESTS AND DISEASES



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Foreword

Across the globe, weeds, pests and pathogens (referred to here as "pests") lower agricultural productivity by a respective 34 percent, 18 percent and 16 percent. Pest issues are increasingly worsened by global warming, biodiversity loss and environmental degradation, while international commodity trade, tourism and passenger transport allow them to spread across the globe. In terrestrial settings, invasive invertebrates (mostly insects) cause over USD 165 billion in losses per year – primarily to the detriment of agriculture and forestry sectors. Impacts of invasive pests readily worsen those of endemic pests, and are exacerbated in food-deficit regions with rapidly growing human populations. In those settings, invasive and endemic pests alike jeopardize food security and human nutrition, hamper economic growth, deepen poverty and vulnerability, and compromise human wellbeing. Resolving these pests sustainably is central to Food and Agriculture Organization of the United Nations (FAO)'s Strategic Objective of achieving the four betters. Those are: better production, better nutrition, a better environment, and a better life, leaving no one behind. This work is also central to meeting the Sustainable Development Goals (SDGs).

Synthetic pesticides have become hallmark features of post-1950s agriculture, serving as frontline treatments for a diverse suite of endemic and invasive pests. Over the past decade, usage rates of synthetic pesticides rose by one-fifth globally and by 153 percent in low-income countries (Shattuck *et al.*, 2023). While synthetic pesticides are instrumental in securing copious food supplies and alleviating malnutrition, they also negatively impact biodiversity, undermine vital ecosystem services and raise the energy usage intensity (or carbon footprint) of agrifood production. Widely seen as drivers of global environmental change, the societal implications of pesticide-centered approaches cannot be disregarded. To alleviate this overreliance upon synthetic entrants and to resolve their social-environmental externalities, a myriad of alternatives have been developed, validated and promoted across the globe.

FAO has a long and rich history in promoting integrated pest management (IPM) approaches for plant health and in implementing ambitious input-reduction initiatives. During the 1980s to 1990s, FAO's Farmer Field Schools (FFS) trained millions of farmers on pest management tactics such as biological control, and curbed pesticide use by 50–80 percent over extensive areas. Such was achieved through the promotion of IPM, which is the tactical integration of all available control options including a conscious prioritization of biological, cultural and physical measures with a goal of reducing pest-induced losses at minimal (or zero) usage of synthetic pesticides. Indeed, under IPM, preventative non-chemical approaches are the 'first line of defence' while synthetic pesticides are treated as 'measures of last resort'.

This FAO volume on IPM guidelines for the world's major crop pests and diseases offers an exceptionally rich compilation of IPM strategies for eight priority pest threats. As per IPM principles, the authors consciously prioritize preventative measures, decision-support tools and non-chemical interventions such as biopesticides – offering concrete opportunities to resolve pest threats with minimal synthetic pesticide inputs for sustainable pest management. These guidelines now serve as a basis for coordinated interventions to protect plant health at national, regional and global scales. I invite all stakeholders, in particular governments, researchers, extension agents and the private sector, to draw upon these guidelines in their efforts to intensify agrifood production in an environmentally sound and socially responsible manner.

Chike Mba

Deputy Director, Plant Production and Protection Division (NSP)

Preface

Agriculture employs one-quarter of the world's labour force and covers nearly half of the habitable land. Agrifood production assumes a pivotal role in feeding the world's population, alleviating poverty, and lifting the living standards of billions of people across the globe. Yet, in modern times, it is becoming ever more challenging to sustainably grow food under climatic upheaval, defaunation, ecosystem degradation and chemical pollution. Crop pests and diseases, which often thrive under warmer climates and disrupted environments, reduce crop yields by roughly 40 percent and their impacts are bound to intensify. Meanwhile, today's food system emits one-third of the world's greenhouse gas (GHG) emissions and farmland intensification causes species loss in and beyond agricultural settings. Input-intensive agriculture in particular has become a core driver and victim of global change.

Pesticide-intensive crop protection finds itself at the core of these issues. Since the 1950s, synthetic pesticides have been widely used to resolve a broad suite of pests, pathogens and weeds on the world's farmland. While these synthetic pesticides have effectively curbed pest problems, fed a swelling world population and driven economic growth over more than half a century, they have also caused pervasive social-environmental problems. Indeed, chemical inputs now replace many of nature's ecosystem services and have given rise to ecologically brittle farming systems that require constant intervention in order to maintain their desirable states. Over the long run, pesticide-centered measures increase the vulnerability to pest or disease attack, pesticide resistance, pest resurgence, abiotic stressors and ultimate crop failure. In an ever-more interconnected world, these impacts are prone to cascade beyond local or national scales, proliferate through globe-spanning supply chains and raise societal susceptibility to major crises. Integrated pest management (IPM) poses a sound, universally valid approach to defuse pest threats, safeguard farmers' harvests and resolve their overreliance upon chemical inputs. As Food and Agriculture Organization of the United Nations (FAO)'s long-standing compass for plant health and sustainable crop protection, IPM has been effectively deployed in countless farming contexts across the globe. While IPM effectively cut chemical inputs by 50–80 percent on millions of Asian farms over the 1980s to 1990s, as demonstrated by the FAO Farmer Field School (FFS) IPM programme, an effective pairing of traditional approaches with modern technologies bodes well for its future. Indeed, modern-day IPM has cut pesticide use by 95 percent in horticultural crops in the Midwest region of the United States of America while enhancing yields by one-quarter and doubling the activity-density of native pollinators. Without doubt, when properly defined and judiciously deployed, IPM can spawn a cornucopia of societal benefits.

In this volume on IPM guidelines for the world's major crop pests and diseases, FAO with collaborators from the Chinese Academy of Agricultural Sciences (CAAS) and other specialized organizations, outline multifaceted IPM packages for eight different pest and disease threats of global reach. Each individual chapter offers a bundle of IPM solutions for the principal biotic threats of staple crops, such as cereal grains (maize, wheat, rice) and crops such as potato, fruits and vegetables. Each chapter makes for a captivating read that introduces traditional approaches,

such as crop sanitation or good agronomy, as well as modern DNA-based technologies, marker-assisted breeding or innovative tools such as robotics, biological control agents and biopesticides, or digital alert systems. By putting biodiversity-based and agroecological preventative measures front-and-center, and by listing innovative ways to combine action over different spatio-temporal scales, readers are presented with a bonanza of practical ways to establish climate-resilient, pest-suppressive cropping systems that are mutually beneficial to farmers, consumers and the environment. The practical IPM tactics should be specific to local scenario of pest management, while this volume on IPM guidelines also provides general principles and comment, and modern technology for sustainable integrated management of pests.

I personally believe that these IPM guidelines provide an exceptionally valuable resource for further coordinated action and investment on plant health globally. This volume is of immediate value to governments, plant health professionals, pest management practitioners, development partners, agro-industry actors and even individual farmers. It provides readers with a wide spectrum of tailored solutions and best-bet crop protection tactics. Their thoughtful on-farm implementation can safeguard crop production in the light of pest attack without compromising crop yield, farm profit or environmental sustainability.

I hope that you will not only enjoy reading the technical details in this volume, but also put your learnings into use within your own farming context, country and/or institution. Only by doing so can we take IPM to scale and make a difference in remediating the environmental footprint of global agriculture. The time for action is now.

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Abstract

Agricultural pests and pathogens lower agricultural productivity by 18 percent and 16 percent, respectively, jeopardizing food security and farmer livelihoods globally. To tackle pest- and pathogen-related issues in a sustainable, environmentally friendly manner, Food and Agriculture Organization of the United Nations (FAO) endorses the use of integrated pest management (IPM). In this volume, FAO builds upon an extensive compilation of "best-bet" IPM measures for multiple global priority pests and pathogens, based on research conducted by the Chinese Academy of Agricultural Sciences (CAAS) and other specialized organizations, many international. Threats were prioritized based upon their geographical distribution, severity and societal importance. Each chapter offers a 'bundle' of IPM solutions for the principal pest threats of cereal grains, potato, fruits and vegetables. It offers a wide spectrum of tailored solutions ranging from traditional approaches, such as crop sanitation and good agronomy, to modern DNA-based technologies, marker-assisted breeding, and innovative tools such as robotics, biological control and biopesticides, as well as digital alert systems. By putting biodiversity-based and agroecological preventative measures front-and-center, and by providing innovative ways to integrate stand-alone technologies, future readers are presented with practical ways to establish climate-resilient, pest-suppressive cropping systems. As such, this volume can be of immediate value for government decision-makers, pest management practitioners, development partners, agro-industry actors and individual farmers.

Abbreviations

ADHI	aphid hyperspectral vegetation index
AI	aphid index
BPH	brown planthopper
BYDV	barley yellow dwarf virus
CAAS	Chinese Academy of Agricultural Sciences
CBSD	cassava brown streak disease
CIMMYT	International Maize and Wheat Improvement Center
CLCV	cotton leaf curl virus
CMD	cassava mosaic disease
COI	cytochrome c oxidase subunit I
DNA	deoxyribonucleic acid
Dpi	days post inoculation
dsRNA	double-stranded RNA
DSS	decision support system
EBF	E-β-farnesene
EC	electrical conductivity
EIL	economic injury level
ELISA	enzyme-linked immunosorbent assay
Foc	<i>Fusarium oxysporum</i> f. sp. <i>cubense</i>
gRNA	genomic RNA
ICAR	Indian Council of Agricultural Research
IC-RT-PCR	immuno-capture reverse transcription-polymerase chain reaction
IDM	integrated disease management
IPM	integrated pest management
IPP	Institute for Plant Protection
IRRI	International Rice Research Institute
JGMV	Johnsongrass mosaic virus
FFS	Farmer Field School
GHG	greenhouse gas
HR	hypersensitive response
LAMP	loop-mediated isothermal amplification
LED	light-emitting diode
MARPLE	Mobile And Real-time PLant disEase
MCMV	maize Chlorotic Mottle Virus
MDMV	maize dwarf mosaic virus
ME	methyl eugenol



MEAM1	Middle East Asia Minor 1 biotype
MED	mediterranean biotype
MLND	maize lethal necrosis disease
mtCOI	mitochondrial COI
mtDNA	mitochondrial DNA
NGS	next-generation sequencing
NRL	nucleotide-binding domain and leucine-rich repeat domain-containing receptor
ORF	open reading frame
PCR	polymerase chain reaction
Pgt	<i>Puccinia graminis</i> f. sp. tritici
Pst	<i>Puccinia striiformis</i> f. sp. Tritici
PLB	potato late blight
Pt	<i>Puccinia triticina</i>
R&D	research and development
RGSV	rice grassy stunt virus
RNA	ribonucleic acid
RNAi	RNA interference
RRSV	rice ragged stunt virus
RT-LAMP	reverse transcription loop-mediated isothermal amplification
RT-PCR	reverse transcription PCR
RVI	ratio vegetation index
RWA	Russian wheat aphid
SCMV	sugarcane mosaic virus
SDG	Sustainable Development Goal
SIT	sterile insect technique
SMRT	single-molecule real-time
SR	Seedling resistance
TR4	banana Fusarium wilt Tropical race 4
TYLCV	tomato yellow leaf curl virus
UV	ultraviolet
VCG	vegetative compatibility group
VOC	volatile organic compounds
WSMV	wheat streak mosaic virus

Executive Summary

Integrated pest management (IPM) constitutes Food and Agriculture Organization of the United Nations (FAO) time-tested compass for plant health. Its judicious implementation – for instance, through the FAO-led Farmer Field Schools (FFS) campaign during the 1980s to 1990s – generated remarkable social-environmental benefits in Asia and other parts of the developing world. IPM has been implemented in various regions and countries that are different in terms of their natural and socio-economic conditions as well as their level of agricultural development, and the FFS campaigns continue up to today. These campaigns benefited millions of small-scale farmers in Asia, Africa, Latin America, Europe and Central Asia, and truly transformed pest management practice in countries such as Viet Nam, the Philippines and Indonesia. Across intervention sites and target crops, IPM through FFS reduced pesticide use by one-quarter (up to 82–92 percent in paddy rice in Viet Nam and Bangladesh) and lowered the environmental footprint of agriculture by 39 percent. This, while raising yields and farm profits by 13–19 percent and strengthening farmers' knowledge on sustainable forms of crop production and protection (Van den Berg and Jiggins, 2007; Waddington *et al.*, 2014). Given the major technoscientific advances in multiple sustainable agriculture domains over the past 20 to 30 years, these achievements only wait to be replicated and deepened.

Building upon the accomplishments of the 1980s to 1990s, this volume offers clear pointers and practicable means to resolve the social-environmental externalities of biotic stressors and their pesticide-intensive control. Indeed, these IPM guidelines – drafted by some of the world's leading crop protection experts – provide a comprehensive overview of the available options to mitigate pest or disease attack in globally important food crops. For eight major pests or diseases of cereal grains, potato, banana, fruits and horticulture crops, a multifaceted IPM toolbox is laid out in which emerging technologies and innovative opportunities are highlighted to resolve or actively prevent pest-related losses in a sustainable and economically sound manner.

Specifically, these IPM guidelines offer concrete guidance on how to uphold plant health in the face of attack by wheat aphid, wheat rust, oriental fruit fly, banana Fusarium wilt, maize lethal necrosis, potato late blight, rice brown planthopper and silverleaf whitefly. They provide guidance on how to put IPM into practice for each crop, aiming to bring pests or diseases below economically damaging levels while safeguarding food security and achieving such with minimal (if any) pesticidal inputs.

An in-depth understanding of the identity, biology and ecology of crop pests or diseases is sine qua non for the development of efficacious and cost-effective mitigation measures. As such, each of the following chapters covers the diagnostic features and taxonomic classification of a given pest, its geographical distribution and host range, and other key aspects of its bio-ecology, such as temperature-dependent development or life cycle. Further, for each target pest or disease, a quantitative description is given of its direct or indirect impacts in terms of reduced primary productivity, monetary losses or extent of pesticide usage intensity. This allows the reader to appreciate the myriad benefits for farmers and society at large that can be gained from proactive IPM.



Early detection is crucial for effectively addressing both endemic and invasive pest threats alike. It allows for a rapid response from national authorities or individual farmers. In the case of pests like wheat aphid, silverleaf whitefly or banana Fusarium wilt, these IPM guidelines dedicate ample attention to low-cost, practical ways for detecting pests or disease symptoms within the confines of single fields or over entire landscape matrices. Such can be achieved through time-tested approaches, such as sticky cards, transect walks or pheromone traps; and novel technologies, such as hand-held sequencers or phone apps that use computer vision, data-driven forecasting tools and remote sensing. Practical guidance is provided for individual farmers on how to scout their fields for specific pests or diseases and compare their incidence or infestation pressure to pre-established thresholds or injury levels, allowing them to take management decisions that are well-attuned and economically sound. As resource-poor farmers allocate significant financial resources on pesticides, regular field scouting thereby constitutes an essential first step to rationalize management action.

Under IPM, agroecological and biodiversity-based measures are the 'first line of defence' – and such is clearly reflected in the organization of each of the chapters. Non-chemical practices, such as crop sanitation, the use of clean seed or planting material, tolerant or resistant crop varieties, disinfection protocols and sound agricultural practices (e.g. proper fertilization, pruning and crop irrigation) are thus consciously prioritized for each single pest and disease threat. Where feasible, these are further complemented with epigenetic resistance priming and farm-level habitat management tactics such as inter- or intraspecific crop diversification; conservation agriculture practices, such as grass barrier strips or hedgerows; or the incorporation and active retention of soil organic matter. When deployed in an integrated fashion over space and time, these measures all help to bolster plants' immune responses, reduce their susceptibility to pest attack and minimize the need for pesticide-centered control. Even from a therapeutic control angle, chapters pay ample attention to non-chemical solutions, such as invertebrate or microbial biological control and phytochemicals or low-risk approaches such as insecticidal bait sprays. Synthetic pesticides are systematically treated as a "measure of last resort" – that is, deemed unnecessary when a wide array of IPM alternatives are adopted in their integrity.

These IPM guidelines have become a voluminous book of nearly 120 pages, which can become unwieldy for those seeking practical solutions to pressing pest or pesticide-related issues. Hence, for each crop pest or disease, the most salient aspects of the IPM strategy are distilled and summarized for policymakers and pest management practitioners alike. By doing so, actors on the ground have the necessary information at their fingertips to resolve pest threats in a way that benefits individual growers, consumers and the environment. By thus empowering end-users with first-hand insights into the newest technologies and the very best of crop protection science, the authors aim to deliver upon the promise of IPM. It offers yet another means to translate IPM science into practice and to achieve outcomes that are no less ambitious than those achieved during the 1980s and 1990s and with FFS on millions of farms across the globe.

FAO principles on integrated pest management

Integrated pest management (IPM) is identified as the operational approach of sustainable plant protection. IPM is the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations. IPM emphasizes the growth of a healthy crop with the least possible disruption to agroecosystems and encourages natural pest control mechanisms. It combines biological, chemical, physical and crop specific (cultural) management strategies and practices to grow healthy crops and minimize the use of pesticides, reducing or minimizing risks posed by pesticides to human health and the environment for sustainable pest management.

FAO promotes IPM as the preferred approach to crop protection and regards it as a pillar of both sustainable intensification of crop production and pesticide risk reduction. As such, IPM is being mainstreamed in FAO activities involving crop production and protection.

IPM was developed in response to an escalating rise in pesticide usage intensity that resulted in pest control crises (outbreaks of secondary pests and pest resurgence following development of pesticide resistance) and increasing evidence and awareness of the cost to health and the environment caused by the intensive use of pesticides.

Putting IPM into context

IPM has been implemented in various regions and countries that differ in terms of their natural and socioeconomic conditions as well as their level of agricultural development. However, progression in plant production and protection may be achieved in any existing situations by implementing IPM. The application of IPM is not a simple and strict compliance with rules and regulations; rather, it means actions are taken via an environmental approach that includes principles, strategies and tactics that contribute to the reduced use of chemicals as well as to sustainable production for higher food security. In order to make IPM as effective as possible, its core principles should be carefully followed while its technical aspects can be adapted to local/regional conditions.

IPM in a temporal scale: think of cropping systems instead of one single season

Cultivated annual and perennial plants host a wide variety of pest- and non-pest herbivores and diseases, and allow the emergence of non-crop plants or weeds in the field. In the case of arable crops, alternating plant species over time at the same site (crop rotation) may break the life cycle of pests, resulting in reduced pest pressure in the subsequent crop. In perennial crops, including orchards, the density



of pests in a given year is a major determining factor in the initial infestation level in the subsequent year. Both crop rotation and/or other pest management measures will thus have an impact on the occurrence of pests in any cultivated plants in a temporal scale. In this context, IPM is the rational regulation of pests, present at the same site, not only in one plant species grown in a given year but also in cropping systems over several years and of the agrilandscape. This approach is also valid and applicable for beneficial organisms. Therefore, IPM should be considered in a spatio-temporal context.

General principles for the implementation of IPM

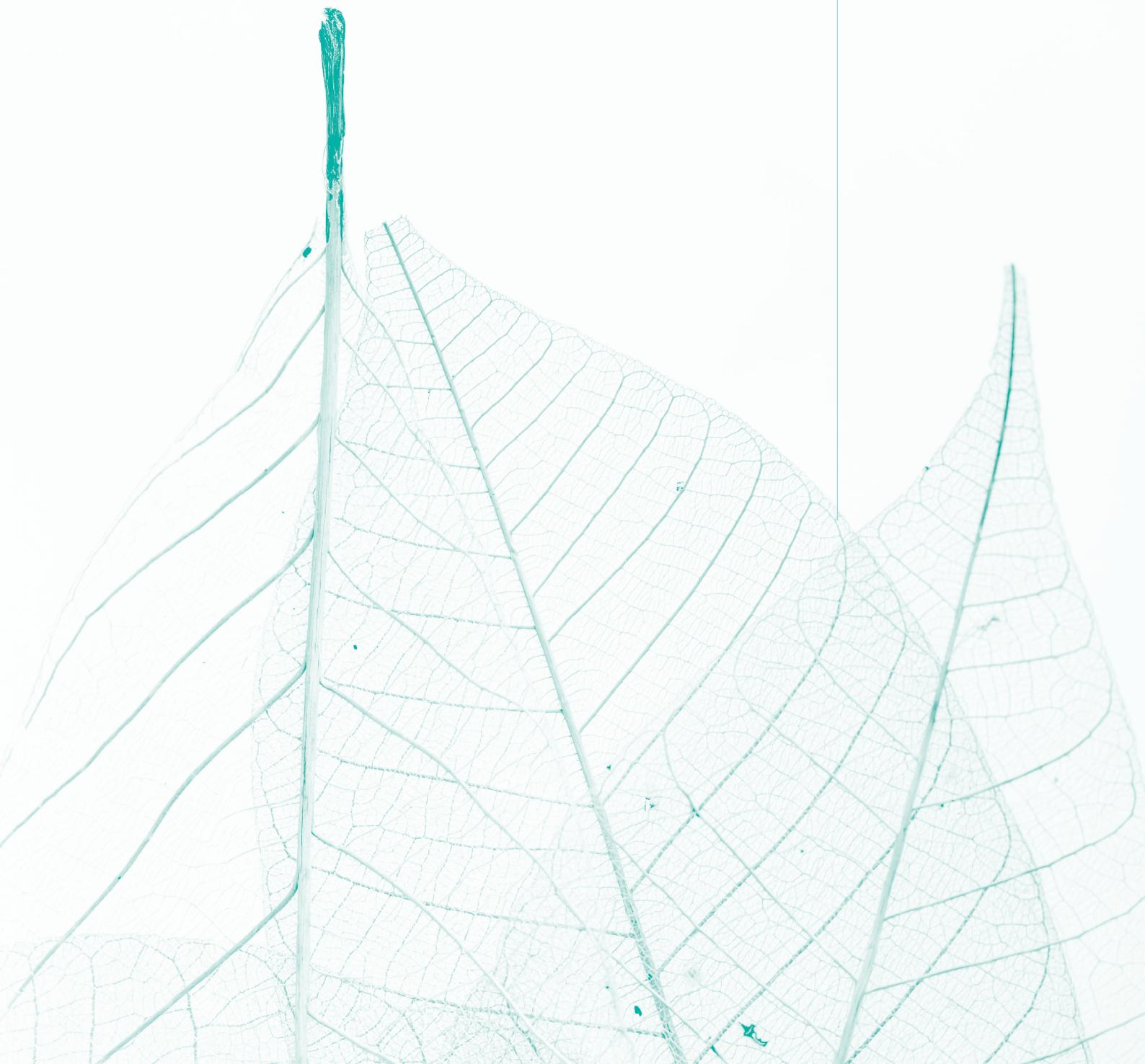
1. Surveillance and monitoring

- Harmful organisms should be monitored with adequate methods and tools, where available. These should include observations in the field, such as occurrence of pests, appearance of symptoms and, where feasible, scientifically sound warning, forecasting and early diagnosis systems (consisting of traps, weather stations, etc.). Next, by comparing field-collected infestation data with established, locally relevant injury or action thresholds, pest management decisions can be taken that are sound and economically justified. The regular consultation of professionally qualified advisors including government extension officers is also recommended.

2. Prevention and/or suppression of harmful organisms should be targeted and achieved by combining various options, such as:

- Biological control and agroecological measures as a first line of defense. The latter includes practices such as crop rotation and intercropping.
- Use of adequate cultivation techniques (e.g. seedbed sanitation, sowing/planting time and plant densities, under-sowing, conservation tillage, pruning and direct sowing).
- Where appropriate, the use of resistant/tolerant cultivars and standard/certified seed and planting material is encouraged.
- Balanced nutrient supply and optimal water management is provided.
- Spread of harmful organisms through field sanitation and hygiene measures is prevented (e.g. removal of infected plants, plant parts and plant debris and regular cleaning of machinery and equipment).
- Populations of resident beneficial organisms such as invertebrate predators, parasitoids or antagonistic fungi are actively conserved and enhanced through habitat management (e.g. flower strips or grass barrier strips) or periodic releases of laboratory-reared or -grown individuals.

3. Synthetic pesticides as a "measure of last resort", to be relied upon when none of the (locally) available non-chemical approaches prove practicable and effectively keep pest or disease populations below economic thresholds. When opting for synthetic pesticides, careful selection and adherence to guidelines in pesticide management are critical to reduce human and environmental health risks. Low-risk compounds that present limited or no harms for human or environmental health are to be consciously prioritized and their application is to be made in a targeted manner i.e. avoiding unguided "blanket" applications. Pesticide use ideally is limited to those compounds with high levels of selectivity for beneficial organisms such as (wild or managed) pollinators and (vertebrate, invertebrate or microbial) natural enemies.



Guidance on integrated pest management for the world's major crop pests and diseases



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1. Wheat aphid

1.1 Summary for policymakers

- ▶ Aphids are key pests of global wheat crops; they inflict direct feeding damage, hamper photosynthesis and act as vectors of disease agents.
- ▶ Climate change and agricultural intensification raise wheat aphid infestation pressure.
- ▶ Insecticides are increasingly favoured by small-scale wheat growers and their overuse causes a suite of social-environmental problems.
- ▶ Science-based decision tools are available to forecast aphid pest outbreaks, rationalize biopesticide spray applications and safeguard farm profitability.
- ▶ Non-chemical approaches such as intercropping, biological control or semiochemical use should be further refined, endorsed and promoted.
- ▶ Insecticidal seed treatment degrades ecological resilience and triggers pest resurgence, thus jeopardizing the long-term sustainability of wheat farming systems.

1.2 Take-home messages for practitioners

- ▶ In wheat systems, aphid feeding damage, virus disease transmission and insecticide applications lower farmer profits.
- ▶ Remote sensing, yellow pan traps and suction traps are key tools to anticipate aphid pest outbreaks at field, farm or agrolandscape scales.
- ▶ Resistant or tolerant varieties, in-field or landscape-level diversification, and biological control all help to prevent aphid population build-up.
- ▶ Legume integration improves natural pest control, partially replaces synthetic fertilizer, and enhances overall system performance.
- ▶ Agroecological and biodiversity-driven approaches constitute entirely practicable, cost-effective and efficacious alternatives to synthetic pesticides.
- ▶ Under integrated pest management (IPM), insecticides are to be used exclusively in a curative (versus preventative) manner and deployed as a "measure of last resort".

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1.3 Introduction

Wheat (*Triticum aestivum* L.) is one of the world's prime food staples and provides 20 percent of the calories consumed by humans. Several aphid species are key pests of wheat crops i.e. bird cherry-oat aphid *Rhopalosiphum padi* L., English grain aphid *Sitobion avenae* Fabricius, greenbug *Schizaphis graminum* Rondani, Indian grain aphid *Sitobion miscanthi* Takahashi, Russian wheat aphid *Diuraphis noxia* Kurdjumov, and the rose-grain aphid *Metopolophium dirhodum* Walker. In China, the dominant cereal aphid species is *S. miscanthi* although this has been often misnamed as *S. avenae*.

As phloem-feeding pests, wheat aphids reduce wheat yield by: (i) sucking sap from plants, which negatively affects grain filling; (ii) excreting honeydew which – as sooty mould on wheat leaves – reduces photosynthesis; and (iii) transmitting plant viruses. Wheat aphids mainly transmit barley yellow dwarf virus (BYDV), as well as other viruses, including the cereal yellow dwarf virus, filaree red leaf virus, maize leaf fleck virus, rice gallum virus, onion yellow dwarf virus, as well as oat yellow leaf disease by *R. padi*. Further, millet red leaf virus, sugarcane mosaic virus, maize dwarf mosaic virus is transmitted by *S. graminum*, while barley mosaic and sugarcane mosaic viruses are vectored by *D. noxia*.

1.4 Biology and ecology

Wheat aphid populations often fluctuate from one year to another with nearly ten to 20 generations per year. There are two life cycle forms of the wheat aphid: the anholocyclic form, which refers to a life cycle based on asexual reproduction, and the holocyclic form, which refers to sexual reproduction and allows the aphid to hibernate as eggs. Asexually reproducing females colonize on wheat plants and are mostly responsible for damage in aphid species. Environmental factors such as photoperiod and temperature, or host plants of lower food quantity or quality, cause parthenogenetic females to produce sexual females and males. The sexual forms usually mate and lay eggs in autumn, and in spring, the eggs hatch to begin new parthenogenetic lines. In the wheat aphids, the holocyclic populations have been found in *S. avenae*, *R. padi*, *S. graminum*, *M. dirhodum* and *D. noxia*.

Similar to other Aphidoidea, wheat aphid adults exist in winged or wingless morphisms in field, greenhouse and laboratory culture conditions. The mechanism of wing differentiation is complex. This phenotypic plasticity is caused by environmental cues, including poor nutrition of host plant, overcrowding, interspecific interactions, the presence of nature enemies; and abiotic factors, such as temperature, humidity, photoperiod, and alarm pheromone. Also, maternal and transgenerational effects, including grand-maternal phenotype, developmental stages and maternal phenotype can modulate wing dimorphism in aphids.

During the last decades, global climate warming has been demonstrated to have considerable effects on the population dynamics of insect pests. Temperatures have been proven to positively influence the occurrence of wheat aphids, following an analysis of the population of *S. avenae* and climatological data collected in China the using fuzzy cognitive maps (FCM) model. It was found that small increases in average temperatures led to a substantial increase in the frequency of high

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and extreme high temperature events and concurrent changes in the natural community structure of *S. avenae*, *S. graminum* and *R. padi*. Global warming also enhances the development and fecundity of *S. avenae*, while decreasing parasitism rates.

1.5 Economic and environmental impact

Wheat aphids are distributed in almost all wheat-growing regions of the world, with more than 30 aphid species able to colonize and damage individual wheat plants. Aphids either affect the cereal crops directly by feeding upon plant juice or by transmitting barley yellow dwarf virus (BYDV) diseases. Aphid feeding damage and disease vectoring can cause up to 47 percent yield losses in wheat. In China, *S. avenae* or *S. miscanthi* annually cause yield losses up to 40 percent. Among the world's principal cereal aphid species, the Russian wheat aphid (RWA) is one of the most destructive species. RWA was originally recorded in 1900 in the southern Russian Federation and has spread to Afghanistan, the Americas, China's northwest (occurring only in Xinjiang) Ethiopia, the Mediterranean, the Middle East and Pakistan. RWA infestation can cause obvious chlorosis and necrosis in crops, resulting in serious reduction in wheat production. This species is becoming an increasingly important cereal pests in both developing and developed areas in the world. Other species such as *S. miscanthi*, *R. padi*, *M. dirhodum* and *S. graminum* annually affect approximately 15 million hectares in China, causing a reduction of wheat yield by more than eight percent throughout the year, and as much as 20 percent to 30 percent in severely infested years.

1.6 Integrated pest management

Detection and inspection

While aphids reduce wheat production, they also greatly impact the nutritional quality of the harvested produce such as wheat kernels. Accurate and large-scale monitoring and forecasting of the occurrence of wheat aphid can help to manage this pest more effectively. Detection and inspection thus constitute an essential first step of a multi-faceted integrated pest management (IPM) strategy (see **Figure 1.1** on p. 8).

Field survey. The wheat aphid population is surveyed at the different developing stages of wheat in the field, including seedling, jointing, heading and flowering, and filling stages. Based on the long-term field survey data of wheat aphids and meteorological data, the change of population dynamics of wheat aphids with meteorological key factors can be predicted by establishing a meteorological forecast model with stepwise regression using a correlation analysis method.

Yellow sticky cards and yellow pan traps. Aphids are attracted by the colour yellow. Therefore, yellow sticky card traps and yellow pan traps are usually used to monitor the immigration and emergence of winged wheat aphids in the field. From the beginning of the wheat jointing stage, the yellow traps can be put in the wheat field, with 12 to 20 pieces/pans per 667 m². The size of common-used yellow sticky cards is 25 cm by 40 cm, which are placed 20 cm above the wheat

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canopy in east-west direction. Recording the aphid species and the number of aphids on both sides of the card/in the pans once a week is suggested.

Remote sensing. While remote sensing technology (RST) is increasingly used for the monitoring and forecasting of agricultural pests and diseases, limited progress has been made in applying it to assess wheat aphid occurrence and damage. Earlier research has recorded the spectral reflectance of wheat leaves damaged by the Russian wheat aphid, and determined two of the most sensitive leaf reflectance spectrum bands, 625 nm to 635 nm and 680 nm to 695 nm. Research has been carried out on wheat canopy reflectance, and an aphid index (AI) captures the relationship between spectral vegetation indices and aphid-related crop damage. By using RST to identify wheat affected by greenbugs and Russian wheat aphid, a vegetation index was constructed that uses 800/450 nm and 950/450 nm to distinguish damage symptoms of these two aphid species. In China, some researchers proposed the plant physiological basis for monitoring by remote sensing of winter wheat aphids outbreaks; proved the feasibility of monitoring wheat aphids by the reflectance spectrum index ratio vegetation index (RVI) value of winter wheat; and gave the determination of aphids control point in the winter wheat. The spectral characteristics of winter wheat infested with different density of aphids have been investigated, and a so-called aphid hyperspectral vegetation index (ADHI) has been computed by collecting canopy spectra using RST and regressing these indices with aphid damage levels. As such, field-level monitoring of aphid infestation pressure and crop damage can be done during the filling stage of winter wheat.

Suction traps. Suction traps are used for the long-term monitoring of small migratory insects. The suction trap was first invented by Johnson and Taylor of the Rothamsted Experimental Station in the United Kingdom of Great Britain and Northern Ireland and was first operated in the Lausanne Experimental Station in Switzerland in 1964. Subsequently, suction traps were established in Belgium, Denmark, France, Italy, the Kingdom of the Netherlands, Poland, Switzerland, the United Kingdom, and other countries in Europe. Scientists from these countries have collaborated and shared data to build an aphid early warning network covering large parts of Europe. Beginning in the 1980s, suction traps were established in the United States of America and successively expanded to ten central and northern states. This suction trap network covered the main soybean-producing areas in the United States and was used to monitor the occurrence of wheat aphids and soybean aphid *Aphis glycines*. In China, 21 suction traps were established in the main wheat and soybean production areas to monitor the occurrence and migration dynamics of wheat aphids and soybean aphids.

Simulation modelling. Germany, the Kingdom of the Netherlands, and the United Kingdom developed computer-based simulation model systems for population dynamics of *S. avenae* in the 1980s. Initial models were built and validated to predict the population dynamics of *S. avenae* or the rose grain aphid *M. dirhodum*. These models were either integrated with those of prevailing natural enemies – for example, the ladybeetle (*Coccinella septempunctata*) – to gauge the strength of natural biological control or facilitate the programming of in-field management practices, such as overhead sprays, chemical or biological pesticides. With the development of computers and artificial intelligence, new methods such as artificial neural networks, phase space reconstruction prediction methods, and wavelet analysis have been applied to forecast and monitor the occurrence of wheat aphids.

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Prevention and control

The wheat flowering to milking stage is a crucial time for implementation of prevention and control measures. During this phenological stage, wheat aphids often attain densities of more than eight individuals per wheat ear while the relative abundance of natural enemies is low – i.e. natural enemy/pest numbers below 1:150. Thus, this stage constitutes a suitable time for the deployment of preventative IPM measures such as invertebrate biological control, entomopathogens, semiochemical use or (environmentally compatible) pesticides. Because wheat aphids concur with several plant diseases such as wheat stripe rust, gibberellic disease, and powdery mildew at the middle and late wheat developing stages, crop protection interventions can be combined in order to simultaneously address multiple wheat disease and pest issues.

Aphid-resistant cultivars. Breeding resistance cultivars is an alternative tactic to control aphids, and is recognized as the most effective and economical pest control technology. Moreover, planting of cultivars with the resistance genes can reduce the use of pesticides and is safe for both the environment and human health. Consequently, there has been considerable effort made in recent decades to screen and characterize sources of plant resistance to wheat aphids. Russian wheat aphids can be controlled using resistance cultivars. Some resistance genes (R gene) characterized thus far include Dn1-Dn10 genes, based on chromosomal location or geographic origin. Among these characterized resistance genes, the Dn4 gene has been used most widely in the United States, for both spring and winter wheat cultivars. Under field conditions, resistance provided by the Dn4 gene helps to prevent yield loss due to Russian wheat aphid infestations of varying magnitude. Since the late 1950s, work has been conducted to identify aphid-resistant wheat varieties in China, establishing a set of standardized screening methods. Some resistant varieties have been successfully identified, such as Zhong 4 wumang, KOK1679, and Linuxuan207. However, most of these varieties were difficult for farmers to grow at a large scale because of low quality and yield. In addition, although plenty of research exists into screening aphid-resistant cereal crops, no wheat or barley varieties with high resistance against cereal aphids such as *S. avenae*, *M. dirhodum* and *R. padi* are widely planted in Europe. How to balance quality, yield and pest resistance is an important topic requiring joint efforts by agronomists, entomologists, geneticists, molecular biologists, and breeders to achieve a breakthrough.

Landscape management. Both crop and non-crop habitats in the agricultural landscape have an important impact on the occurrence of pests and natural enemies. Many studies to date have focused on the impacts of non-crop habitats around farmland on the occurrence of natural enemy populations. For example, non-crop habitats such as woodland and grassland can provide ladybirds with aphids, pollen, nectar as habitats and shelters, and promote the occurrence of the ladybirds. Ladybirds grown and developed in non-crop habitats can migrate to wheat fields to prey on aphids and trigger enhanced pest control. The non-crop habitat in farm landscapes can also provide a safe place for ladybirds to overwinter, thereby promoting an increase in their numbers. Furthermore, woodland and landscape diversity promote the occurrence of ladybirds in wheat crops. Therefore, changes of landscape patterns can be used effectively to control pest populations through habitat rearrangement and agricultural landscape patterns optimization.

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Also, the proportion of non-crop habitats within agricultural landscapes can greatly affect parasitoid abundance. While landscape complexity is directly related to primary parasitism, it can also promote the activity of hyperparasitoids and thus, disrupt aphid biological control. Actually, much remains to be investigated about the exact relationship among cereal aphids, primary parasitoids, hyperparasitoids, and landscape complexity.

Intercropping. Promoting biodiversity in field ecosystems benefits from various ecosystem services for pest control. One lucrative approach to improve the overall sustainability of wheat production is to employ intercropping to increase (in-field) plant and animal species diversity. The intercropping of winter wheat with rape, soybean, mung bean, garlic, and green manure (alfalfa) in northern China has consistently resulted in greater abundance and diversity of aphid predators and parasitoids. Also, integrating white clover *Trifolium repens* L. with wheat directly lowers *S. avenae* densities. Lasting wildflower margins or strips can also provide shelter and food resources such as nectar and pollen to resident natural enemies and thus, contribute to natural aphid biological control. Specific plant traits should be considered when formulating effective flower mixes. Aside from its benefits for biological control, diversification with legume intercrops, such as pea, can increase nitrogen fixation, boost plant nutrition and reduce synthetic fertilizer needs. As wheat intercropping thus generates a suite of ecosystem services, its farm-level adoption and diffusion should be actively promoted.

Semiochemical use. The field-level release of semiochemicals can simultaneously repel cereal aphid pests and attract their natural enemies. For example, application of methyl salicylate (MeSA), an herbivore-induced plant volatile, can repel wheat aphids and attract predatory ladybeetles, hoverflies, and parasitoids. Aphid alarm pheromones can be used in a similar fashion. Upon attack by natural enemies, aphids routinely secrete alarm pheromones from their cornicles. Low doses of (E)- β -farnesene (EBF), a major component of these alarm pheromones, repel aphids and attract their natural enemies. Slow-release formulations of these synthetic, non-toxic volatiles can be integrated with other tactics such as wheat-pea intercrops in so-called “push-pull” strategies to lower aphid settling while bolstering resident natural enemy communities. Work is underway to refine efficacious and cost-effective slow-release systems for behavioural manipulation in cereal crops.

Invertebrate biological control. A diverse set of natural enemies – for example, parasitic wasps, ladybirds, lacewing and hoverfly larvae – contribute to the biological control of wheat aphids, and their role is particularly important in early season and at the onset of aphid population outbreaks. In large fields, under chemically intensified management regimes, or in less diverse systems, these natural enemies routinely fail to keep aphid populations below levels causing economic damage. However, research has shown that even modest reductions in aphid population growth, for example, through the release or in-field conservation of natural enemies, can help to sustain crop yields. Yet, at present, biological

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control of wheat aphids receives little research attention and as a result, its field-level implementation encounters multiple challenges. Nevertheless, multiple successes in wheat systems in China, Europe, and the United States underscores the immense potential of this non-chemical management solution. In systems in the United States combining inoculative releases of predatory lacewings with varietal tolerance has resulted in synergistic effects on crop yields.

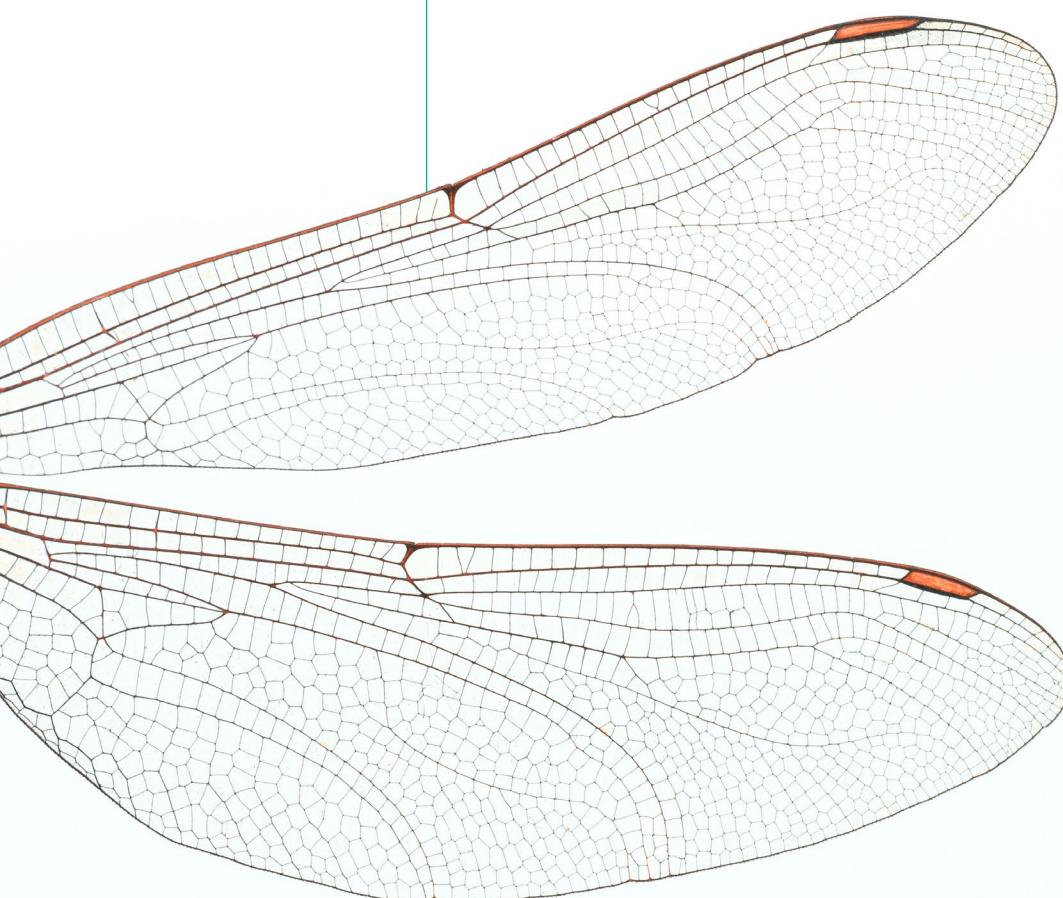
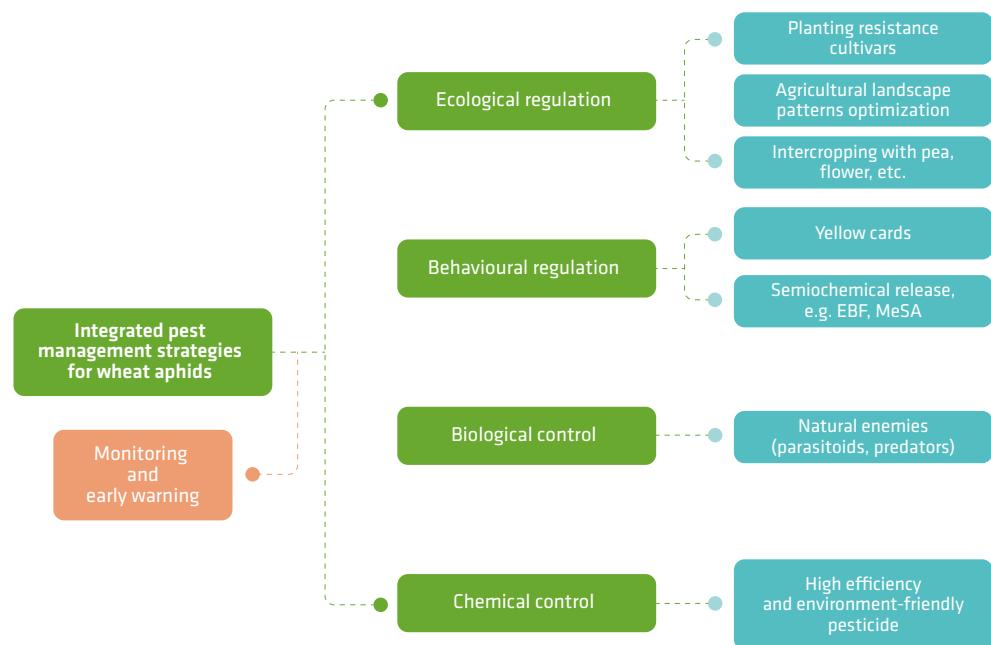
Releases of 20 000 *Aphidius rhopalosiphi* parasitoids per hectare at weekly intervals kept the wheat aphid *Sitobion avenae* below an economic threshold; improved mass-rearing systems or its integration with microbials could make this approach economically competitive with chemical control. During the mid-1990s, classical biological control – the scientifically guided introduction of natural enemies from the region of origin of an invasive aphid species – resulted in considerable and long-lasting reductions in *D. noxia* population levels in North America. Field-, farm- or landscape-scale diversification can enhance resident, released or introduced natural enemy populations and thus, bolster wheat aphid biological control. In China and Europe, wheat-alfalfa strip cropping, or the establishment of ryegrass strips, promote biological control and slow aphid population build-up. Yet, to fully tap the potential of biological control, applied research, development and commercialization must be actively encouraged and incentivized.

Chemical pesticides. Synthetic insecticides are commonly used for insect pest control. Neonicotinoid, pyrethroid, carbamate and organophosphate insecticides are widely used to control wheat aphids, which has favoured the development of resistance to multiple active ingredients. Although some insecticides provide good aphid control, their usage often interferes with natural biological control. Neonicotinoids are increasingly put forward for aphid management. Despite their comparatively low mammalian toxicity, these products negatively affect pollinators and soil and aquatic invertebrates. Due to their systemic nature, neonicotinoids such as imidacloprid or dinotefuran are taken up by the plant and translocated to floral or extra-floral nectar, guttation fluid or pollen of the treated crop and nearby wildflowers. As such, they can inflict considerable levels of mortality on foraging wild or managed pollinators, natural enemies and various other farm-dwelling biota. Neonicotinoids are increasingly applied in a prophylactic fashion – for example, through seed coating. This mode of application, however conflicts with globally valid IPM principles in which pesticides are to be used as a last resort and not as a first line of defence. As such, insecticidal seed treatment degrades the resilience of agroecosystems and triggers pest resurgence, often at no or minimal yield gains, thus constituting an unnecessary cost component especially for resource-poor smallholders. Given their potential to engender social-environmental problems, systemic neonicotinoids do not belong within wheat aphid IPM packages. Instead, synthetic insecticides must be carefully chosen based upon their multidimensional One Health risks including compatibility with biological control, and should exclusively be used in a curative (instead of preventative) fashion.

Figure 1.1

Components of an integrated pest management strategy for wheat aphids

Source: Haan, N. L., Zhang, Y. J. & Landis, D. A. 2020. Predicting landscape configuration effects on agricultural pest suppression. *Trends in Ecology & Evolution*, 35.



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2. Wheat rust

2.1 Summary for policymakers

- Since the earliest human civilizations, rust diseases have impacted wheat crops, caused devastating epidemics, and compromised food security and human wellbeing.
- The scientific understanding of rust biology, ecology and epidemiology, as gained over the span of a century, enables sustainable management of wheat rust.
- Diagnostic platforms and monitoring systems in prime wheat cropping areas are key to detect new virulence, anticipate rust outbreaks, and guide resistance breeding.
- To prevent rust epidemics, a coordinated implementation of agroecological measures, such as crop rotation, removal of volunteer wheat, or alternative host plants at field and landscape scales is essential.
- Varietal resistance, including multilines and varietal mixtures, can constitute a user-friendly, cost-effective and environmentally sound way to manage wheat rust.
- Resistant varieties are not a silver bullet, but need to be consciously paired with systems-level interventions and diversification tactics.

2.2 Take-home messages for practitioners

- Rust diseases attain recurrent epidemics in wheat production systems, compromising primary productivity, profitability, and farmer livelihoods.
- Monitoring tools such as RustMapper and RustTracker visualize rust occurrence in key production regions and help to anticipate future disease epidemics.
- Artificial intelligence (AI) powered applications such as Leaf Doctor facilitate estimates of disease severity and thus, inform the need and timing of curative interventions.
- Crop rotation, removal of volunteer plants or alternative hosts, adjusted sowing time, and rust-resistant varieties provide a first line of defence.
- By accounting for the dynamic host-pathogen interplay, the yin-yang concept helps to anticipate emergence of virulence and strategize both preventative and curative wheat rust management.
- When preventative measures, some low-cost, are judiciously implemented, fungicidal sprays are rarely warranted.



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2.3 Introduction

Wheat suffers from various diseases including three devastating rusts: stripe (yellow) rust, leaf (brown) rust, and stem (black) rust. Wheat rust likely already occurred at the time of wheat domestication around 12 000 years ago. Archeologists have found 3 300-year-old stem rust-infected wheat lemma fragments from the Late Bronze Age II (1 400 to 1 200 BCE), demonstrating that early human civilization had endured wheat rust. Since the establishment of the science of plant pathology around the mid-1800s, extensive efforts have been made to study wheat rust diseases, including pathogen biology, disease epidemiology, genetics and breeding to select resistant varieties. Several programmes have contributed to the management of wheat rust, such as the green revolution worldwide and the barberry eradication programme in the United States of America and in Europe. Rust fungi, however, can quickly evolve and migrate, with several newly emerged strains threatening global wheat supply. For example, Ug99, a wheat stem rust race that was initially detected in Africa in 1999, affected most commercial wheat cultivars and quickly spread throughout the world's prime wheat-growing regions. All three wheat rusts have been reported in almost every country with significant wheat production, where their incidence and impact is mediated by local cultivars, environmental conditions, and pathogen virulence. Norman Borlaug, Nobel laureate and father of the green revolution, even summarized the issue with the quote: "Rust never sleeps." Hence, in order to prevent devastating rust epidemics, we require long-term efforts on surveillance and monitoring for rust fungi, genetics and resistance breeding, and both applied and fundamental research.

2.4 Disease symptoms

Wheat stripe rust. Rust infections mainly occur on the above-ground parts of wheat, such as leaves, leaf sheaths, glumes and awns from wheat emergence to maturity, given plants are still green and environmental conditions are suitable for disease occurrence. On seedlings, uredinia produced by the infection of a single urediniospore progressively emerge from the infection site to eventually cover the entire leaf surface. Individual uredinal pustules are oblong and yellow or orange in colour. As the plants grow, generally after stem elongation, infections can be observed as uredinia, chlorosis or necrosis in long stripes on leaves between the leaf veins. Depending on the level of the plant's resistance and environmental conditions, various degrees of chlorosis or necrosis appear, with or without sporulation. At higher temperatures, or at later host phenological stages, black, oblong telia are produced. Generally, telia of stripe rust are covered by host epidermis in the wheat sheath and occasionally erupt in the blade under natural conditions.

Wheat stem rust. Infections mainly occur on stems, leaf sheaths, leaf blades, and glumes. Early infection produces small chlorotic flecks. Later, a pustule several millimeters long and a few millimeters wide is formed by the rupture of the host epidermis from pressure of a mass of urediniospores (see [Figure 2.2](#) on p. 18). These uredinal pustules are orange to dark red in colour, tend to be linear or diamond-shaped, and may grow up to 10 mm long. Stem rust pustules are more elongated than those of stripe and leaf rusts. Late in the season or at higher temperatures, the infection ceases production of dark urediniospores and yields a layer of black teliospores instead. This turns the stems of infected plants black. Usually, telia of stem rust erupt from the host epidermis under natural conditions.

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Wheat leaf rust. Infections mainly occur on the leaf blades and occasionally on the sheath, awns, and glumes. Wheat varieties that are fully susceptible to leaf rust pathogens produce large uredinia without causing tissue chlorosis or necrosis. Resistant wheat varieties exhibit various responses to infection, ranging from small hypersensitive flecks to small- or moderate-sized uredinia that are often surrounded by chlorotic and/or necrotic zones. Uredinal pustules of leaf rust are brown in colour and generally circular in shape. They are more scattered on leaves compared to pustules of stripe and stem rusts.

2.5 Taxonomy, biology and ecology

The three wheat rust fungi belong to the same genus. The stripe rust pathogen is *Puccinia striiformis* f. sp. *tritici* Westend (*Pst*); the stem rust pathogen is *P. graminis* f. sp. *tritici* (*Pgt*); and the leaf rust is *P. triticina* (*Pt*). They are all classified in kingdom Fungi, phylum Basidiomycota, class Urediniomycetes, order Uredinales, family Pucciniaceae, genus *Puccinia*. All three rusts produce urediniospores and teliospores during infection of wheat. All three fungi have heteroecious macrocyclic life cycles, meaning that two taxonomically distant host plants are required to complete the different sporulating stages. All three fungi, thus, have both primary and alternate hosts. For *Pst*, common primary hosts include: *Triticum aestivum* L. (common wheat), *T. turgidum* var. *durum* L. (durum wheat), *T. dicoccum* Schrank (cultivated emmer wheat), *Triticosecale* (triticale), *Hordeum vulgare* L. (barley), *Secale cereale* L. (rye), *Aegilops* spp., *Agropyron* spp., *Bromus* spp., *Elymus* spp., etc.; common alternate hosts include: *Berberis* spp. (barberry) and *Mahonia aquifolium* (Oregon grape). For *Pgt*, common primary hosts include: common wheat, durum wheat, barley, rye, etc.; common alternate hosts include: *Berberis* spp., *Mahonia* spp., and *Mahoberberis* (*Berberis* x *Mahonia*). For *Pt*, common primary hosts include: common wheat, durum wheat, cultivated emmer wheat, wild emmer wheat, *Aegilops speltoides*, *A. cylindrica* (goat grass), and *Triticosecale* (triticale); common alternate hosts include: *Thalictrum speciosissimum* (synonym *T. flavum glaucum*) and *Isopyrum fumaroides*. While detailed sequential events and the molecular basis of each sporulating stage has been reviewed, we outline several aspects related closely to epidemiology of wheat stripe and stem rust. The disease cycle of wheat leaf rust is similar to that of stem rust.

Wheat stripe rust. Urediniospores are the most important initial inoculum for epidemics in most regions. Over-summering is a bottleneck for the disease cycle. A mean temperature of 22.3 °C or a mean maximum temperature of 32.4 °C is considered as the threshold for wheat stripe rust pathogen to over-summer. Urediniospores that over-summer in cool regions serve as initial inoculum for autumn-sown wheat regions. Urediniospores germinate and infect wheat. Normally, no sporulation occurs before and during winter, unless the temperature is favourable. Infection by *Pst* is restricted to a narrow temperature ranging from 5 °C to 12 °C. The infection ceases during harsh winter conditions, with mycelium surviving in infected seedlings. Compared to stem or leaf rust pathogens, stripe rust withstands cold temperatures relatively well. In areas where *Pst* successfully over-winters, the disease usually starts early in spring with dormant mycelium reviving. After sporulation, the urediniospores are dispersed locally as well as long-distance by wind and serve as inoculum sources for other regions. After landing

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on surface of a wheat leaf, urediniospores germinate when dew is present and the temperature is within the range from 1 °C to 23 °C (optimal range of 7 °C to 12 °C). The germ tube of germinated urediniospores penetrates wheat tissue through stoma. Infectious hyphae continue growing within the plant tissue, and sporulation (when uredinia appear and release urediniospores) starts about 12 to 14 days after infection under favourable temperature conditions. The released urediniospores can re-infect wheat, and the infection cycle is carried on during the crop season up to the time the plant reaches maturity. At high temperatures or late in the crop season, production of urediniospores ceases, and black telia containing teliospores are produced. Germination of teliospore initiates the sexual life-cycle of *Pst* by producing basidiospores and later pycniospores and aeciospores. Unlike stem and leaf rust fungi, for which telia are important for survival during the hot summer and cold winter, teliospores of the stripe rust fungus generally do not play a role in the pathogen survival or disease epidemics.

Wheat stem rust. *Pgt* has similar asexual cycles as *Pst*. Moreover, the telial stage and infection of alternate hosts by basidiospores can cause epidemics of stem rust in some regions. The teliospores of *Pgt*, after over-wintering in cooler regions, germinate in the spring, and produce basidiospores. After they are ejected into the air and land on young and tender barberry, basidiospores germinate and penetrate directly through the host epidermis and form mycelium. A few days after basidiospore infection, the pycnia (also called spermatia) are formed on the adaxial leaf surface. The pycniospores with liquid nectar are spread by insects or by rainwater to fertilize compatible receptive hyphae. Following the fertilization, the elongated, cylindrical aecia are formed on the abaxial leaf surface and the aeciospores released from aecium and infected wheat complete the sexual life cycle. Although the sexual cycle produces limited inoculum for epidemics, genes can recombine in the meiosis process, which increases pathogen genetic diversity and produces new virulent races. Indeed, high numbers of urediniospores from aeciospore-infected wheat could result in severe epidemics through multiple reinfection cycles during a single cropping season if susceptible varieties are grown in the vicinity of the alternate hosts.

2.6 Impact

For all three wheat rusts, yield losses depend on the host resistance of the variety and on how early the disease starts in the crop season. In general, yield losses are greatest in susceptible varieties and with early infections. Infections at seedling stage under favourable environmental conditions could result in the death of tillers or entire plants, causing 100 percent yield loss. Severe disease on the foliage reduces the photosynthetic areas, causing a loss of nutrients and water and disrupting the plant transport system. Yield loss results from reduced kernel number per spike, grain weight, and kernel quality, or combinations of all of these.

2.7 Integrated disease management (IDM)

Detection and inspection

Wheat fields can be inspected for all three wheat rusts at any stage of growth; however, a continuous monitoring of fields in disease-prone areas is highly recommended for early detection of disease in order to implement control strategies. Wheat rust diagnosis is primarily based on symptoms. All rust fungi produce uredinia from chlorotic areas after infection on susceptible varieties. The pustules are elongated and yellow to orange, or orange to dark-red in colour. These typical symptoms and signs make wheat rust diseases easily distinguishable from other wheat diseases. The three rusts can be distinguished from each other by the size, shape, colour, and arrangement of uredinia.

Generally, the three wheat rust fungi are highly adapted to wheat, and pathogens of stripe and stem rusts on wheat have *formae speciales* (*P. striiformis* f. sp. *tritici* and *P. graminis* f. sp. *tritici*, respectively). That means that the rust isolates collected from wheat are generally wheat rusts. However, the barley stripe rust fungus (*P. striiformis* f. sp. *hordei*) can sometimes also infect wheat varieties. In such cases, the observed symptoms and collected isolates from wheat could be either wheat stripe rust or barley stripe rust, or both. This is even more complex for isolates collected from alternate hosts. For this situation, the collected isolates must be inoculated on a range of host species for *formae speciales* identification. Isolates within a *forma specialis* may have differences in avirulence/virulence profile, and isolates with the same avirulence/virulence profile are often called a race. The avirulence/virulence profile must be identified by testing the isolate on a set of wheat cultivars/lines called differentials. In practice, the differentials exhibit geographical variation based on the local importance of certain resistance genes. Due to rapidly evolving virulence, one thus needs to constantly survey pathogen populations to identify new virulence and monitor its dynamics. Hence, coordinated surveillance is needed across wheat cropping areas to reliably detect, predict and mitigate emerging rust diseases. In addition, long-term monitoring of virulence composition of fungal populations is needed to trace the dynamics of races. This information ultimately informs local and global breeding programmes.

Detection of wheat rusts has also benefitted from new genomic approaches, such as field pathogenomics. This approach uses transcriptome sequencing of rust-infected wheat leaves directly from the field, can detect changes in the pathogen population, and anticipate an emerging epidemic. The Mobile And Real-time PLant diSEase (MARPLE) diagnostics is another monitoring approach. This near real-time genomics-based point-of-care diagnostic platform has been applied to forecast wheat rust disease risk in Ethiopia. These technologies can help to reduce the impact of wheat rust diseases, but still require conventional avirulence/virulence analyses to update the molecular data.

After detection of the presence of the rust diseases, their intensity (for example, severity and incidence) should be quantified for spatiotemporal modeling or for making proper management decisions. This was traditionally done by experts or well-trained local farmers, which is time-consuming, costly and subject to human error. To overcome these limitations, advanced digital vision tools have been developed such as Leaf Doctor and the Estimate application. By uploading



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photographs of diseased wheat plants, these platforms that can quantify disease severity semi-automatically and thus, inform the need for, and exact timing of, a curative intervention, for example, a biological or other pesticide application.

Wheat rust monitoring systems have primarily been initiated by tracking and assessing the threat of the stem rust race lineage Ug99. A fully operational monitoring system should include several key components, such as the compilation of key datasets from trap nurseries, the mapping of confirmed diseased sites, the use of wind and rain models to understand potential movements, and the ability to deliver timely and targeted information to a range of end users. Currently, two publicly available monitoring tools are RustTracker and RustMapper, the latter a Google Earth-based application created and hosted by the Geographic Information System (GIS), Unit of the International Maize and Wheat Improvement Center (CIMMYT). It not only displays current rust survey sites, near real-time wind trajectories from sites reporting all races of stem rust, but also provides detailed information on major wheat growing areas and their production statistics. RustTracker.org was developed by CIMMYT and other partners to mitigate the wheat-rust threat. In India, more elaborate monitoring and prediction systems have been developed and used for stem rust.

Prevention and control

Varietal resistance. Growing resistant cultivars is a most effective, economic, practicable and environmentally friendly approach for wheat-rust management. When adequate genetic resistance to wheat rusts is achieved, no other control methods are necessary. Seeds of resistant cultivars may not be more expensive, and can avoid the cost of fungicides and eliminate their adverse impacts on human and environmental health. Growing resistant cultivars also does not require additional farming techniques, equipment and practices, and can be applied across geographies and management systems. Resistance to one rust is generally independent of resistance to other rusts, with only a few exceptions. For wheat stripe rust, there are a total of 83 sequentially designated resistance genes, i.e. Yr1 up to Yr83, at the time of writing. For stem rust, there are more than 85 resistance genes (*Sr*) that have been catalogued. For leaf rust, around 118 resistance genes are designated. While only a few resistance genes have been cloned and functionally characterized as up to date, advanced biotechnology offers the prospect of cloning many genes at a scale and thus, can facilitate breeding programmes.

Until present, only a few of these resistance genes had been incorporated into commercial cultivars. Developing resistant cultivars takes many years, even though marker-assisted selection and doubled-haploid techniques speed up the breeding process. Also, not all genes provide durable resistance given that new, more virulent races naturally develop and break down local resistance. It was estimated that race-specific resistance, which is easy to use and commonly used by many breeding programmes, has an effectiveness lifespan of about 3.5 years. Most severe epidemics of wheat rusts can be directly ascribed to rapid shifts in pathogen virulence.

This can be avoided by pyramiding multiple, suitable, resistance genes, or by focusing breeding on slow rusting, minor genes-based resistance. In the latter, one combines four to five genes with additive effects to attain durable resistance.

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CIMMYT's breeding programme has successfully utilized this strategy to develop resistant wheat varieties that are currently grown by millions of smallholder farmers worldwide. Another way is to develop and use multiline cultivars that are isogenic but differ in the resistance genes in each cultivar. While diversifying resistance genes could decrease the selection pressure from hosts exerted to plant pathogens, multiline cultivars need to ensure uniformity in maturity and grain quality. Multilines and varietal mixtures are currently not used to control wheat rusts even though the strategy has been known for more than 50 years. To guide resistance breeding efforts, a wheat resistance gene atlas has been developed consisting of an online directory that reports sources of resistance. While the ultimate goal of this atlas is to "turn wheat into a nonhost for its major pathogens," its practicality needs to be determined.

Chemical control. Chemical control assumes a minor role in stem rust management for the following three reasons: (i) high effectiveness of host resistance, (ii) remarkably rapid disease proliferation under optimum environmental conditions, and (iii) relatively low economic value of wheat as compared to the cost of fungicide applications. Notwithstanding the above, chemical control sometimes constitutes the only option to reduce yield losses during rust epidemics – provided their application is made at the onset of the epidemic. A wide range of fungicide active ingredients or formulations are available for the management of stripe rust. For wheat leaf rust, some older generations of fungicides prove effective and are often applied as seed dressings, although the latter increase the odds of resistance development, exacerbate environmental pollution and negatively impact soil biota. For these reasons, fungicidal seed treatment does not pose a sustainable solution and its usage is not endorsed. As rust fungi rapidly develop fungicide resistance, different active ingredients should be rotated and more importantly, non-chemical preventative strategies need to be deliberately prioritized.

Cultural control. To prevent rust disease problems, cultural control is to become a frontline management approach. Indeed, several cultural methods reduce the intensity of wheat rust epidemics. First, rust epidemics can be effectively reduced by changing the overall cropping system. This can include rotation with non-host crops, or growing only winter or spring wheat, if possible. This reduces the amount of infection inoculum, especially for regions where inoculum is endogenous. Second, break the "green bridges" that carry inoculum from one crop to the next. These green bridges generally consist of volunteer plants, crops that are year-after-year cultivated in the same area, or wild accessory hosts. Removal or avoidance of green bridges can prove highly effective, especially where the inoculum is endogenous. In this regard, it is important to gain sufficient in-depth knowledge of the *formae speciales* of endemic rusts, their host ranges, and movement of inoculum e.g. between cereals and nearby forage crops. Third, appropriate timing of planting could delay or even avoid the wheat rust onset. For all three rusts, appropriate late planting in the autumn under conditions that do not reduce yield potential can shorten the time of crop exposure to the rust pathogens. Yet, the effects of planting time for spring wheat differ between the three rusts and depend on local environmental conditions. For stripe rust, late planting in spring may shorten the period of time during which crops are vulnerable to disease. However, this would increase the chance of stem and leaf rust epidemics, since weather and environment in late season are generally favourable for these rusts. Fourth, eradication of the alternate hosts can be highly effective by preventing sexual



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stages of the rust fungi. All three wheat rust fungi have proven to be heteroecious, with asexual stages on wheat and sexual stages on alternate hosts. Programmes to eradicate alternate hosts such as *Berberis* sp. have been instrumental in limiting stem rust epidemics in North America and in Europe. Barberry eradication affects stem rust epidemics through four modalities: (i) delayed disease onset, (ii) reduced initial inoculum level, (iii) fewer pathogen races, and (iv) more stable pathogen phenotypes. However, its effectiveness is limited for other wheat rusts, such as stripe rust. Some other cultural control approaches include planting cultivar mixtures or a mixture of crops, avoiding excessive irrigation and defining fertilization schemes in line with the needs of the crop.

Biological control. The effectiveness of biological control of wheat rusts is limited, and therefore not commonly used in fields. One parasitic fungus that can infect multiple rust fungi is *Darluca filum*. Also, some *Alternaria alternata* strains, *Aphanocladium album*, *Verticillium niveostratum*, *V. fungicola*, and *Cephalosporium acremonium* can hyperparasitize wheat stripe rust fungi. However, the biological control potential of many of the above microorganisms is limited because of the rapid dispersion of rusts and the comparatively slow in-field population build-up of these antagonistic fungi.

Yin-yang concept. To comprehensively understand the integrated management of wheat rusts, we propose a 'yin-yang' concept incorporating all above strategies (see **Figure 2.3** on p. 18). This model presents the co-existence and co-evolution of pathogen population (coloured orange) and host population (coloured green). The first layer of management involves cultural practices and environmental conditions which provide an isolation between host and pathogen. In this layer, management strategies include, but are not limited to, cultural control. The second layer of management is to apply wheat resistance after the exclusion of disease is impossible. One needs to account for the emergence or re-emergence of virulence in the host population with high resistance (the solid orange circle surrounded by green in **Figure 2.3** on p. 18), as this newly emerged virulence could become prevalent and eventually break down host resistance (the solid green circle surrounded by orange). The final layer of management involves chemical and biological control to minimize the virulent pathogen population and protect the susceptible host population.

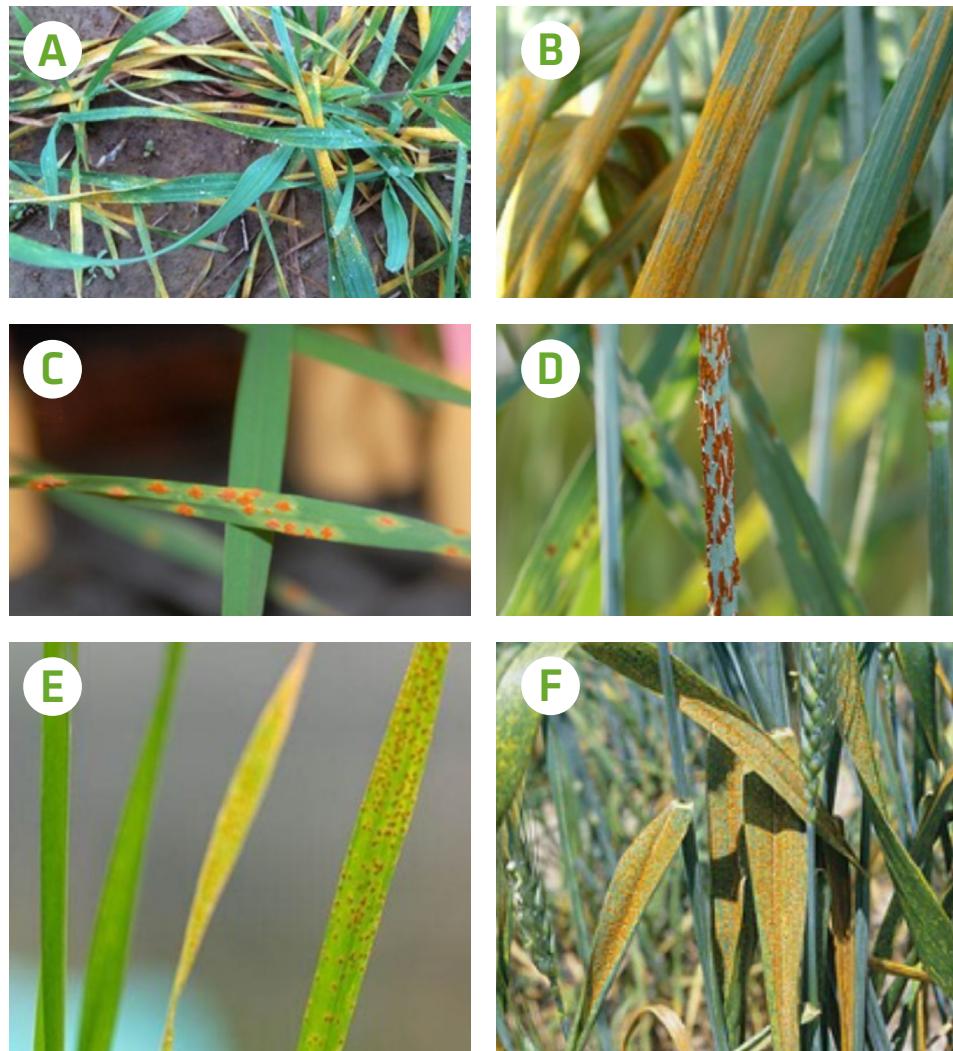


Figure 2.1

Disease symptoms
of three wheat rusts

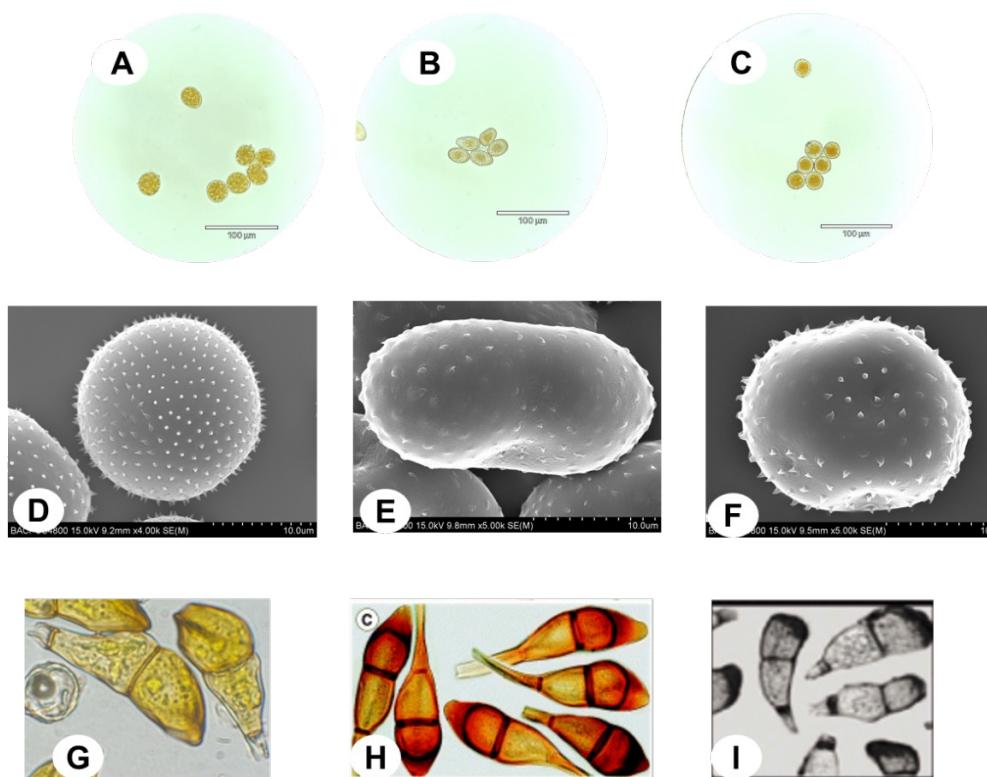
- A: Seedling
- B: Adult wheat stripe rust
- C: Seedling
- D: Adult wheat stem rust
- E: Seedling
- F: Adult wheat leaf rust

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**Figure 2.2**

Urediniospores, teliospores of wheat rusts
A-C: Urediniospores of *Pst*, *Pgt*, *Pt*
D-F: Scanning electron microscope view of urediniospores of *Pst*, *Pgt*, *Pt*
G-I: Teliospores of *Pst*, *Pgt*, *Pt*

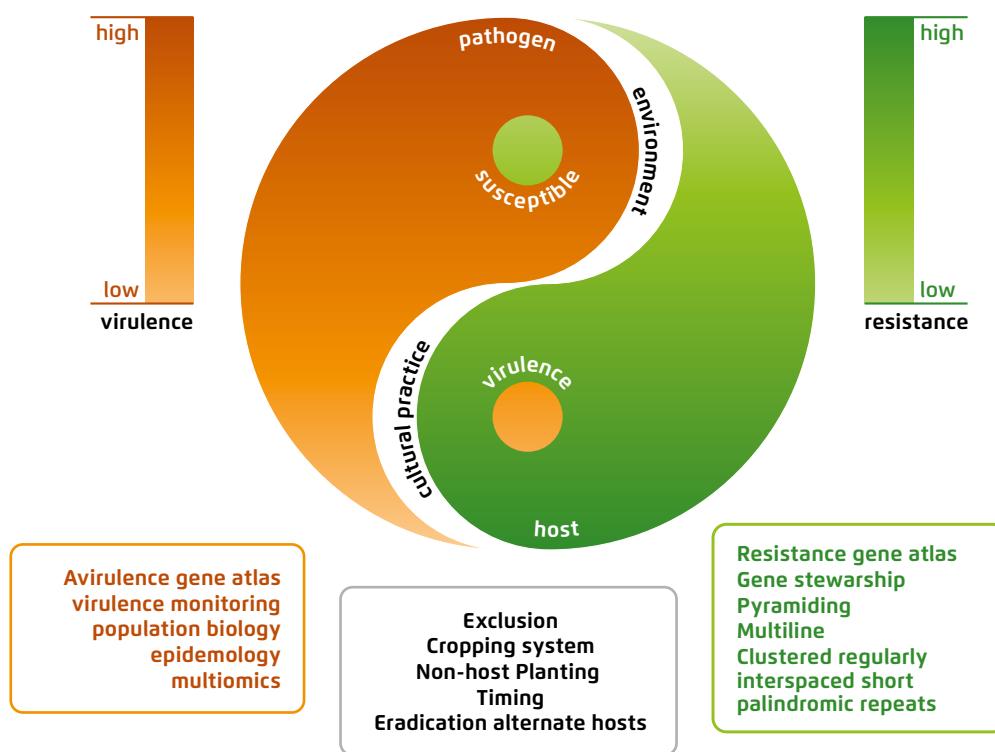
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**Figure 2.3**

Proposed yin-yang concept of integrated management of wheat rust diseases

This model illustrates the dynamics and co-evolution of host and pathogen population. Host and pathogen population are colored by green and orange, respectively. The solid green circle surrounded by orange represents host resistance overcome by pathogen; solid orange circle surrounded by green represents emergence of new virulence under the selection pressure exerted by host resistance. Strategies of the integrated management are listed in frame alongside the yin-yang cartoon

Source: Li, Z. Q. & Zeng, S. M. 2002. *Wheat rusts in China*. Beijing, Chinese Agricultural Press.



3. *Bactrocera dorsalis* fruit fly

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3.1 Summary for policymakers

- As a major horticultural pest, the oriental fruit fly affects crop yield, harvest quality and market access.
- As *Bactrocera dorsalis* (*B. dorsalis*) spreads through traded horticultural produce, quarantine measures can prevent its introduction into new areas.
- Overhead insecticide sprays have limited effectiveness against *B. dorsalis* and pose considerable human and environmental health hazards.
- Participatory training methods can familiarize farmers with trap-based monitoring, natural enemy conservation and bait sprays.
- In fly-affected production areas, the necessary infrastructure can be set up for sterile insect technique (SIT) and parasitoid mass rearing.
- Area-wide pest management can be attained by integrating bait sprays, biological control, mass trapping and sterile insect releases.

3.2 Take-home messages for practitioners

- The oriental fruit fly *Bactrocera dorsalis* is a key pest of fruits and vegetables in the Asia-Pacific, North America and Africa.
- In uninfected areas, great care should be taken to avoid introducing fly-infested agricultural produce, such as traded fruits.
- Traps with methyl eugenol (ME) or food-based lures can be used to monitor population levels and to lower overall infestation pressure.
- Insecticidal baits (as applied on bait stations, deployed throughout the orchard) provide first-rate control of oriental fruit fly adults.
- Fruit bagging and orchard sanitation constitute a highly effective way to prevent fly-induced yield or quality losses, with the former particularly suitable for high-value crops.
- Avoidance of insecticidal sprays and perennial cover crops favour resident natural enemy communities, and thus help to manage *B. dorsalis* preventatively.

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3.3 Introduction

Tephritid fruit flies are key pests of commercially grown fruit and vegetables, and several species have attained a status of notorious invaders in multiple countries or even continents. The four major genera of Tephritidae are *Bactrocera*, *Ceratitis*, *Anastrepha*, and *Rhagoletis*. With their common traits of a wide host range, high fecundity, and high dispersal capacity, *Bactrocera* species are particularly invasive. The genus *Bactrocera* comprises at least 75 species, in which the oriental fruit fly *Bactrocera dorsalis* (Hendel) is treated as a major biosecurity concern. *Bactrocera dorsalis* (*B. dorsalis*) belongs to a species complex that contains no less than 50 described species in Asia, and its taxonomic status has regularly been revised.

The oriental fruit fly is a debilitating pest of fruits and vegetables worldwide. Overall, *B. dorsalis* is thought to be a native to tropical Asia, with south Asia likely being its region of origin. Due to a wide host range at the larval stage and high fecundity of the adult, *B. dorsalis* can severely impact more than 250 species of vegetables and fruit worldwide. Because of its broad host range, high mobility, and climatic adaptability, *B. dorsalis* presents an obvious biosecurity risk. Over the last 90 years, it has expanded its distributional range to most of Southeast Asia and the Pacific. Oriental fruit fly is presently subject to quarantine restrictions in most countries, and incurrences into new regions or countries give rise to eradication programmes.

3.4 Taxonomy, biology and ecology

The oriental fruit fly *B. dorsalis* belongs to the insect family Tephritidae (tribe Dacini), and has been synonymized with *B. invadens*, *B. papayae* and *B. philippinensis*. Due to continuing taxonomic revision of the tribe Dacini, *B. dorsalis* was assigned to the *Bactrocera*, and its scientific name changed from *Chaetodacus ferrugineus dorsalis* (Hendel), *Dacus dorsalis* (Hendel), and *Strumeta dorsalis* (Hendel) to *Bactrocera dorsalis* (Hendel). The female fruit fly is easily recognized with black dot on the head and the scutellum is black with yellow stripes. The forewings are transparent with black colour patches and the thorax is brownish-black. The abdomen is tapered shape with yellow stripes as well as a distinct T-shaped black mark. The ovipositor is pointed and pin-like. The body length and width of the pupae are 8 mm to 9 mm and 12 mm to 13 mm, respectively. The male fly is dark brown with black stripes on its abdomen. The scutellum is black colour. Males are slightly smaller than females, with body length and width 7 mm to 8 mm and 9 mm to 11 mm, respectively (see **Figure 3.1** on p. 26). The eggs of *B. dorsalis* are white, shiny, shaped like a grain of rice, slightly curved and elongated, tapering at the anterior and posterior ends. The eggs are laid vertically or slightly angled in clusters of various sizes, into the pulp of fruit or soft tissue of vegetables (see **Figure 3.1** on p. 26). There are three larval instars (see **Figure 3.1** on p. 26). The pupa is segmented, cylindrical in shape and dark brown in colour (see **Figure 3.1** on p. 26).

The status of *B. dorsalis* as a highly invasive pest can be explained by numerous physiological, morphological, and behavioural adaptive traits involving all stages of its life cycle. Gravid females prefer to lay eggs beneath the peel of ripe fruits of fruit trees or vegetables, in batches of ten to 30 eggs in a cluster per fruit, with multiple oviposition events on the same plant or fruit by the same or different

females. On average, the female fecundity is between 1 200 and 1 500 eggs over its entire lifetime under field conditions. In the laboratory, females and males live up to 30–34 days. Under optimal environmental conditions, eggs take about one to two days after hatching out into larvae to find their way to the fleshy part of a fruit. Larvae concentrate on the inside of fruit and feed on the most nutritious parts of fruit pulp, which also helps to protect them from predator and parasitoid attack. The whole larval development period covers about eight to ten days. After completing the third instar, the mature larvae emerge from the infested fruit and fall to the ground to pupate in the soil. The pupal stage lasts for about eight to nine days. Mature larvae occasionally pupate in the fruit. Upon pupal eclosion, adults emerge from the soil and feed mostly on nectar but also sporadically consume pollen, rotten fruit or fruit juice. Adults exhibit phototaxis, so light stimulation has been indicated as a prerequisite for flight activities. About 15 to 20 days after emergence, adult flies become sexually mature. Only after mating do females initiate oviposition. Usually, mating takes place around sunset, commencing with males gathering around host plants in mass flights generally one hour before sunset. Males fan their wings and come close to females when detected in their territory. Wing fanning is used for courtship, with males remaining stationary with receptive females approaching the male. Where courtship is successful, mating couples remain paired during the whole night and separate at sunrise. Females can undergo multiple mating events during their reproductive lifetime.

Climatic conditions and host plant availability all affect *B. dorsalis* distribution and population density. The insect prefers to live in hot and humid environments, attaining optimum developmental at 25° C to 30° C. Fruit fly eggs can tolerate high temperatures, while its pupae exhibit strong cold tolerance. The threshold temperature for *B. dorsalis* development is 12.19 °C while its effective accumulated temperature is 334.40 degree-day. These demographic traits are typical of K-selected species, favouring growth and establishment under stable conditions. Rainfall is another essential factor affecting population fluctuation in *B. dorsalis*, while drought can pose an important mortality factor for pupae and emerging adults. Under proper soil and atmospheric humidity, adult mating and oviposition is generally facilitated.

3.5 Geographical distribution

To effectively prevent, control or even (locally) eradicate *B. dorsalis*, it is crucial to characterize its area of origin and invasion history. This pest is generally believed to have originated in tropical parts of Southeast Asia and the southern China, and subsequently colonized other Asia-Pacific countries via the trade of fresh fruit. Over the past century, *B. dorsalis* has thus established in India, Lao People's Democratic Republic, Myanmar, Nauru, Nepal, Pakistan, Ryukyu Islands of Japan, Saipan Island, Sri Lanka, Thailand, and Viet Nam. Outside Asia, *B. dorsalis* has spread to California, Florida, and Hawaii in the United States of America, and to French Polynesia, Guam, Kenya, Mozambique, Northern Mariana Islands, and southern Africa. Its wide host range, climatic adaptability, high reproductive output and dispersal capacity favor future expansion into areas that are currently cool and unsuitable for survival of viable populations.

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3.6 Host range

As a polyphagous pest, *B. dorsalis* can affect more than 250 species of fruits and vegetables, and attacks un-ripe and ripened fruit of multiple commercially valuable crops. In Hawaii, *B. dorsalis* attacks 150 to 173 fruit species. Major host plants of *B. dorsalis* in French Polynesia, Nauru, the Northern Mariana Islands, and other Pacific Island countries are mango, golden apple, sweetsop, Tahiti chestnut, papaya, tropical apricot, avocado, breadfruit, banana, guava, carambola, and citrus. In Asia, the host plants of *B. dorsalis* comprise 117 species of 76 genus of 37 families, with the preferred host fruits being mango, guava, lychee, citrus, rambutan, papaya, and sweetsop. Overall, mango, guava, and papaya constitute the main host crops of this species in its native and invaded range. The host range of *B. dorsalis* is likely to broaden with its continued geographic expansion.

3.7 Crop damage and economic impact

Fly-induced damage negatively affects fruit quality and yield. Fly-related damage largely consists of oviposition stings on the fruit surface and the subsequent larval feeding and decay of the fruit pulp (see [Figure 3.2](#) on p. 26). Generally, the females prefer to lay eggs in soft, tender fruit tissues by piercing them with their long and sharp pin-like ovipositor (see [Figure 3.2](#) on p. 26); but they may feed on rotten fruit (see [Figure 3.2](#) on p. 26). The females lay eggs in a depth of 2 mm to 4 mm in the fruit pulp before fruit maturity. Following egg eclosure, the maggots bore into and damage pulp tissue, leading to fruit rot, or yellowing and early fruit drop (see [Figure 3.2](#) on p. 26). In addition, the puncture marks made during oviposition will form wounds on the fruit surface, causing a large overflow or weeping of fruit juice, with scars forming on the fruit surface after wound healing, affecting the appearance and quality of fruit. The wound caused by an adult ovipositor can also lead to pathogen invasion, causing fruit rot and premature drop from the tree (see [Figure 3.2](#) on p. 26). For some fruit crops, damage increases as the fruit matures. Human consumption of fly-infested fruit can cause bowel wall inflammation, abdominal pain and diarrhea.

Horticultural production is key to the economic development of many Asian and African countries, and a valuable source of income for smallholder farmers. Fruit flies can greatly hamper development of the horticulture industry through direct production losses, control costs, and quarantine-imposed restrictions on exports to other regions or countries where the pest is absent. The global trade of fresh fruits and vegetables enhances the risk of *B. dorsalis* spread and invasion of uninfected regions. Depending on the infestation pressure and commercial value, infested fruits and vegetables can be completely or partially destroyed. The damage caused by the *B. dorsalis* can lead to direct impacts (losses of harvestable fruit, income losses due to market closure) and also has indirect impacts, by making damaged fruits more susceptible to invasion from pathogenic micro-organisms. For example, a *B. dorsalis* outbreak in Kenya affected 80 percent of locally grown mangoes and led to total loss of 76 000 tonnes of fruit. Furthermore, insecticide-centered control can have far broader impacts, including harming farmers' health, narrowing profit margins, and have non-target impacts on the wider ecosystem. Indirect losses, which can be considerable and prolonged, also extend to quarantine restrictions imposed by fruit-importing countries and their financial repercussions for *B. dorsalis* infected nations.

For instance, in Mozambique, the export revenue of banana fell by 10 percent because of a *B. dorsalis* infestation and imposition of quarantine management measures in recent years.

3.8 Integrated pest management (IPM)

Detection and inspection

Quarantine. Quantitative risk assessment is a central component of integrated *B. dorsalis* management. As *B. dorsalis* readily disperses through national or international trade of infested fruit, the harvested produce from infected areas should be strictly quarantined. Techniques for quick, accurate, and reliable species diagnosis are also important at the port of entry, where morphological identification, acoustic detection, near-infrared light detection, and molecular identification are practical for use in detecting *B. dorsalis*. Classification and identification of members of the *B. dorsalis* complex have traditionally been based on the morphological characteristics of the adult specimens. However, due to the high similarity in their external morphological characteristics, identifying individual species within the complex is very difficult. Meanwhile, the immature stages, including egg, larva, and pupa, cannot be accurately identified morphologically. Molecular identification techniques, not limited by the developmental stages, sexes, and integrity of the specimens, are powerful tools to accurately and reliably differentiate closely related sibling species within the *B. dorsalis* complex. In these initiatives, the mitochondrial DNA (mtDNA) cytochrome b (*Cytb*) gene is generally used as the molecular marker. In addition, DNA barcoding technology based on a 280–1 426 bp sequence of mtDNA cytochrome c oxidase subunit I (COI) gene can be used. Thermal treatment (for example, exposure to 60 °C for two hours or 45 °C for five hours) constitutes an effective post-harvest quarantine treatment for fruits infected by *B. dorsalis*.

Population monitoring. Controlling male adult flies based on adult behaviour is one of the major methods to reduce damage caused by this pest. The sex pheromone methyl eugenol (ME) attracts mature *B. dorsalis* males and has been effectively used for detecting, monitoring, luring purposes. The use of ME attractants at monitoring points could help to accurately track male or overall population dynamics, particularly when monitoring is performed over extensive areas that cover diverse orchard areas and neighboring (crop or non-crop) areas. ME-lure trap catches are also linked to climatic conditions and light intensity levels. One can extend the activity and attraction of ME baited lures with 40 days by mixing them with active carbon.

Prevention and control

Chemical control. Despite considerable effort to promote integrated pest management (IPM), synthetic insecticides remain the primary means of fruit fly management in many parts of the world (see **Figure 3.3** on p. 27). Irrational and excessive use of insecticides has led to a rapid development of insecticide resistance in *B. dorsalis*, and jeopardizes human and environmental health. Surprisingly, overhead spray applications have low efficacy against *B. dorsalis* adults, and low-risk insecticides, such as abamectin, spinosad or pyrethroids



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such as β -cypermethrin are only moderately effective against *B. dorsalis* larvae. Insecticidal baits pose a safe, effective and environmentally sound alternative to overhead applications. For example, baits composed of three percent brown sugar and 1:1 000 trichlorfon reduce *B. dorsalis* populations by approximately 90 percent when compared with untreated control. Protein baits can be developed with cheap materials such as beer yeast waste. The application of ME in combination with certain organophosphates in a ratio of 10:1 can increase fruit fly control by up to 81.3 percent. Bait sprays formulated with low-risk compounds such as spinosad result in high control efficacy against *B. dorsalis*. Ideally, insecticidal bait is applied in 'bait stations' that are arranged throughout an orchard or vegetable field. By integrating bait applications with other measures, such as the periodic removal of fly-infested fruits and inter-tree ploughing or raking, *B. dorsalis* infestation levels can be lowered by 70 to 100 percent. Insecticidal baits can also be paired with parasitoid releases, mass trapping, male annihilation tactics, sterile fly releases and biopesticides. Integrative approaches can lead to the virtual elimination of insecticide sprays, allay related health and environmental concerns, and keep *B. dorsalis* populations at bay over extensive areas as demonstrated in Thailand or Mexico, for example.

Biological control. Many biological control options exist for *B. dorsalis*, including larval or pupal parasitoids, sterile insect technique (SIT), and entomopathogenic nematodes and fungi (see **Figure 3.3** on p. 27). Classical biological control i.e. the scientifically guided introduction of non-native natural enemies from the *B. dorsalis* native range, remains a supremely effective method to mitigate this invasive pest. Under classical biological control, the following parasitic wasps have been introduced: the egg-pupal parasitoid, *Fopius arisanus* (Sonan), the larval-pupal parasitoid, *Diachasmimorpha longicaudata* (Ashmead), the larval parasitoid, *Fopius vandenboschi* (Fullaway), and pupal parasitoids such as *Pachycrepoideus vindemiae* (Rondani) and *Spalangia endius* (Walker). In Hawaii and French Polynesia, *F. arisanus* has been successfully deployed to control *B. dorsalis*. Endemic parasitoids can also be highly effective to control this pest, for example as shown with the pupal parasitoid, *S. endius* in southern China. Other locally occurring parasitoids such as *Aceratoneuromyia indica* (Silvestri) and *Opius incisi* (Silvestri) also inflict high levels of fruit fly mortality.

SIT is a popular, environment-friendly management option of tephritid pests. This technique involves producing large numbers of flies in the insectary, sterilizing the males, and then releasing them over infested areas. If the sterile males overwhelmingly outnumber fertile wild males, the wild population can be greatly suppressed. Sterilization is accomplished through irradiation or chemo-sterilization. The irradiated male fly that has successfully mated with a virgin female can ensure that the female remains sterile for her whole life, with sterilized males able to disperse up to 140 m in seven to ten days following their field release. Ultimately, the wild population could be locally eradicated by maintaining a barrier of sterile male flies.

Fruit flies also pose susceptible to multiple insect-killing fungi, such as *Metarhizium anisopliae* (Metschn.) Sorokin and *Beauveria bassiana* (Bals.-Criv.) Vuill. and their toxic metabolites. For example, contact exposure to *B. bassiana* spores under laboratory conditions results in high mortality of *B. dorsalis* adults. Field tests further show that spray applications of 2×10^8 spores mL⁻¹ of a *B. bassiana*

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spore suspension lower *B. dorsalis* population levels by half. Nematodes can also be used, for example, with *Steinernema carpocapsae* (Weiser) displaying strong pathogenicity against wild fly populations.

A diverse set of insect natural enemies can be encountered in fruit orchards and vegetable fields. Insect predators, such as fire ants, rove beetles, lacewings, and ground beetles, attack later instar larvae, pupae, and newly emerged adults of *B. dorsalis*. Some natural enemies, such as the weaver ant *Oecophylla longinoda*, prey upon fruit fly adults and larvae, but also prevent oviposition by gravid females and improve fruit quality. Farmers can protect these beneficial insects and enhance *B. dorsalis* biological control by reducing (or suspending) insecticide applications, establishing perennial ground cover or conserving flowering weeds and shrubs. As some parasitoid species are attracted to low ME concentrations, this compound can be used to boost biological control in infestation hotspots. Weaver ant colonies can also be protected through a range of techniques, many of which have been refined over hundreds of years. The placement of infested fruits in so-called augmentoria – tent-like structures covered with a mesh that allows the escape of small-sized parasitoids – can reduce *B. dorsalis* infestation levels.

Trapping techniques. Volatile attractants are commonly used to track and prevent population build-up of *B. dorsalis* (see **Figure 3.3** on p. 27). ME is the best attractant of *B. dorsalis* and has been used for decades as a sexual lure in detection, monitoring and control programmes worldwide. Food-based attractants also can be used in traps, as newly emerged male and female adults require proteinaceous food for survival and sexual maturation. Different food attractants, such as hydrolyzed protein, fermenting sugars, and yeast prove highly attractive to *B. dorsalis*. By mixing food bait and sexual attractants, 50 percent more adults can be trapped than when using sexual attractant alone. Protein- or fermentation-based attractants combined with toxins can be used in traps for monitoring and spot-applied on the orchard floor or in baiting stations to suppress fruit fly populations. In China, a range of protein bait-based products are commercially available for *B. dorsalis* management.

Volatiles from fresh fruits such as mango, guava, and durian prove attractive to *B. dorsalis* adults. Female fruit flies are also attracted to semiochemicals that emanate from non-host plants e.g. *Polyscias guilfoylei* (Bull). Plant oils, such as salvia or clove oil, all exert a strong attraction on this fruit fly species and may possibly be used in its management. Sweeteners can also be singly used as baits or mixed with pesticides: aspartame, erythritol, and saccharin are even toxic to *B. dorsalis* adults (but possibly also to its natural enemies). Trapping technology based on colour cues is one of important strategies for controlling Tephritidae fruit flies. Research into the diurnal foraging and oviposition behaviours of *B. dorsalis* has shown its strong attraction to a yellow-green colour. Yellow-green sticky spheres are effective in capturing adult females and can be used for management or monitoring purposes.

Preventative measures. Agronomic practices are usually adopted as auxiliary measures in *B. dorsalis* management. Basically, four measures are involved (see **Figure 3.3** on p. 27). The first is to select resistant plant varieties. Resistant strains breeding is a feasible method with varieties of guava, mango, sapota, and muskmelon bred with resistance to *B. dorsalis*. However, the biggest challenge in

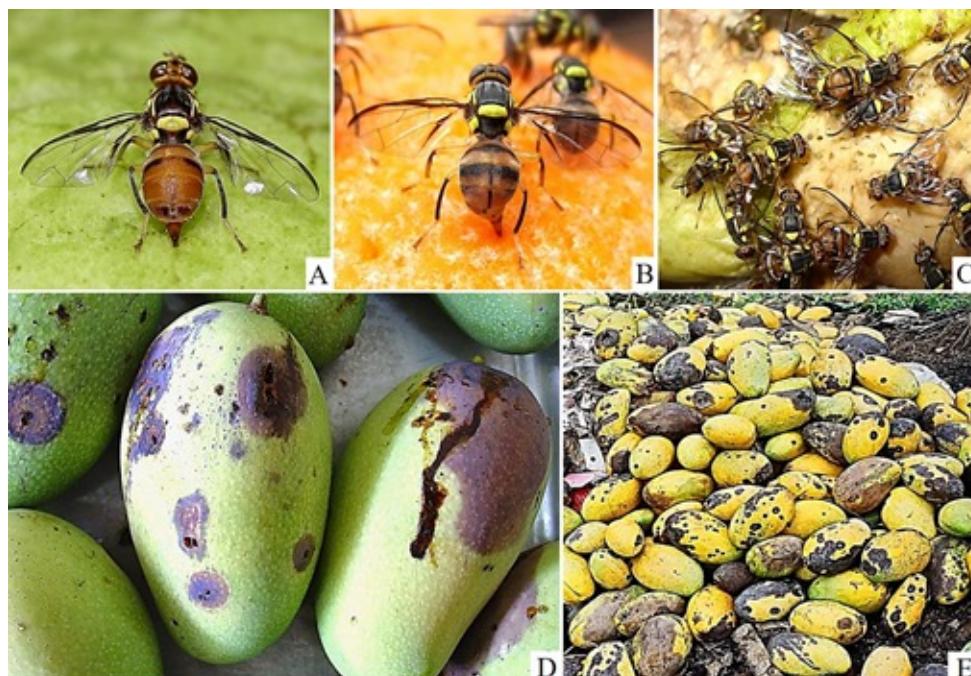
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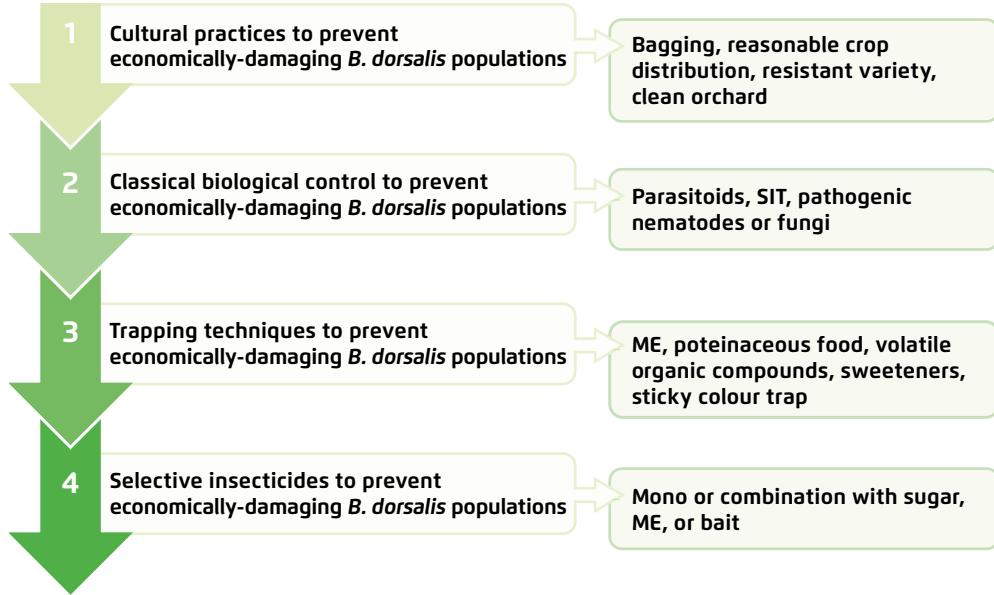
resistance breeding is to concurrently improve fruit quality. Also, late maturing varieties can reduce the overlap between susceptible period of fruit and *B. dorsalis* peak occurrence. The second is to adjust the crop distribution reasonably. By removing alternative host plants of *B. dorsalis*, one can interfere with its annual reproduction. The third is to keep the orchard clean. As a sanitary measure, the timely collection and disposal of infested ripe fruit is highly effective for *B. dorsalis* management. Moreover, optimized fertilizer and water management can promote the vigorous growth of fruit trees and shorten the period suitable for fly oviposition. The fourth is to physically bag the fruit. Fruit bagging prevents fly oviposition without negatively affecting fruit quality. While labour intensive, bagging fruits with white paper bags or plastic film at two- to three-day intervals reduces fruit fly infestation and represents an environmentally safe and effective management solution. A proper timing of fruit bagging is important; fruits should be bagged when the fruits are unripe or before fruit-colouring. Technology integration is key to effective fruit fly management; for example, fruit bagging can be preceded by insecticidal bait sprays in so-called 'bait stations' and paired with natural enemy conservation or augmentation.

Figure 3.1
Life stages of
Bactrocera dorsalis
A: Adult
B: Eggs
C: Larva
D: Pupa
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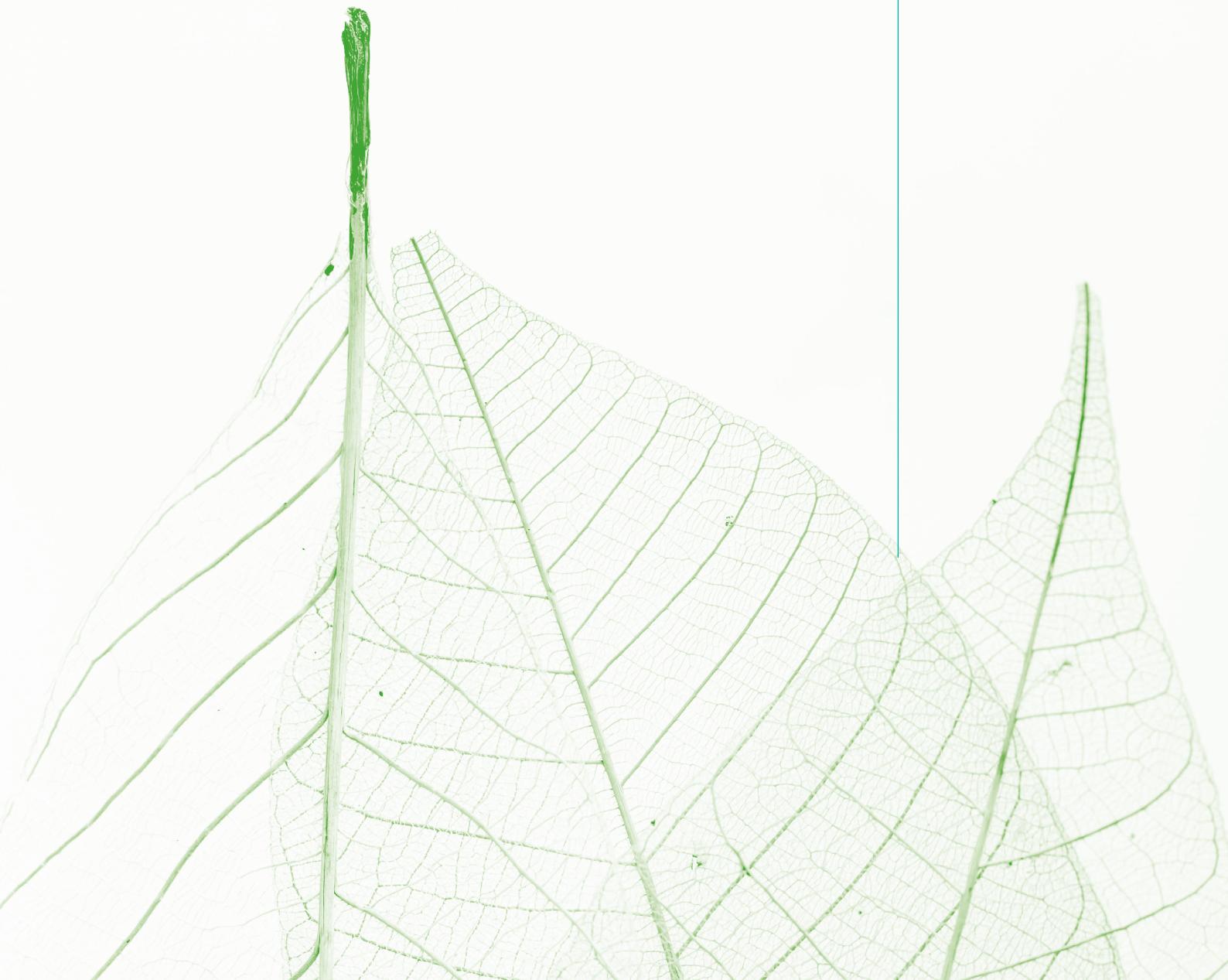
Figure 3.2
Damage caused by
Bactrocera dorsalis
A: *Bactrocera dorsalis*
female adult laying eggs
on guava fruit
B: *B. dorsalis* female adults
laying eggs on an orange
C: *B. dorsalis* adults
gathered, feeding on
rotten guava fruit
D: Symptoms of *B. dorsalis*
feeding damage on mango
E: Dropped mango fruits
caused by *B. dorsalis* damage
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**Figure 3.3**

Conceptual framework for IPM of *B. dorsalis*

Source: Zhang, Y. P., Huang, S. H., Li, D. S., Zhang, B. X. & Chen, M. Y. 2010. Control effect of *Beauveria bassiana* B6 Strain on *Bactrocera dorsalis* (Hendel). *Chinese Journal of Biological Control*, 26.





4. Banana Fusarium Tropical race 4

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4.1 Summary for policymakers

- ▶ Banana Fusarium wilt Tropical race 4 (TR4) poses a major threat to banana cropping systems globally and has recently made its arrival in South America.
- ▶ Large, genetically uniform banana plantations prove exceptionally vulnerable to disease establishment and proliferation.
- ▶ In uninvaded areas, quarantine measures should be strictly enforced, including a ban on the inter- or intra-country movement of diseased banana plantlets.
- ▶ Banana growers should be trained in symptom recognition, active prevention and the use of diagnostic toolkits.
- ▶ Aside from bred or engineered varietal resistance, biological control, reconstituted soil health and epigenetic priming all provide high levels of control.
- ▶ Systems approaches, including the use of low-cost agroecological measures, are essential for the active prevention, spread containment and long-term management of TR4.

4.2 Take-home messages for practitioners

- ▶ Fusarium wilt causes devastating losses in the world's banana crops and can exacerbate food security issues.
- ▶ Stringent on-farm hygiene, pathogen-free irrigation systems, vehicle and footwear disinfection and clean planting material are key preventative tactics.
- ▶ Diagnostic toolkits, molecular analyses and mobile applications are crucial to track disease spread, provide a speedy detection and facilitate rapid responses.
- ▶ Disease spread can be slowed through a judicious management of farmland soil, plant nutrition and insect pests, for example, *Cosmopolites* weevils.
- ▶ Integrative approaches involving organic amendments, diversification tactics and microbial biological control can help to manage TR4 sustainably.
- ▶ "Silver bullets" do not exist for TR4 disease mitigation; different preventative techniques and system-level interventions should instead be consciously prioritized.

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4.3 Introduction

Banana (*Musa* spp.) is one of the world's most important fruit and staple food crops, and ranks prominently among global agricultural commodities. In 2016, global banana and plantain production was 148 million tonnes, with India and China jointly accounting for 28 percent of total production. Other leading producers are Brazil, Colombia, Costa Rica, Ecuador, Indonesia, Mexico, the Philippines, and Thailand. The banana industry is threatened by a severe disease, Fusarium wilt or Panama disease. This disease is caused by the soil-borne fungus *Fusarium oxysporum* f. sp. *cubense* (Foc), and its highly virulent strain Tropical race 4 (TR4) can affect almost all main banana cultivars. The pathogen is believed to have originated in Southeast Asia and was first reported in Australia in 1876. Earlier strains of the pathogen already spread to banana-producing regions around the world, and Foc epidemics in tropical America decimated the then-dominant Gros Michel variety. During the 1950s, this variety was gradually replaced with resistant Cavendish bananas. However, since the 1980s, the Foc TR4 strain began to cause Fusarium wilt in Indonesia, Malaysia and Taiwan Province of China. TR4 outbreaks were initially restricted to the Asia-Pacific region, but a lack of effective quarantine measures has recently led to a rapid, global spread of this debilitating disease.

The Fusarium fungus blocks vascular tissues, thus preventing banana plants from absorbing water and nutrients. Initial TR4 symptoms include a yellowing of the older leaves (see [Figure 4.1](#) on p. 37) and the disease ultimately leads to severe wilting of banana plants. Foc TR4 causes a typical vascular wilt syndrome in the infected banana plant, with characteristic discoloration in roots, rhizome and pseudostem vessels, leaf yellowing and wilting. The first internal symptom of the disease occurs in the fine roots, which are the initial sites of infection, and then the fungus spreads to the rhizome and the pseudostem. Once Foc TR4 attaches to the host and overcomes the first host barrier, the pathogen begins to produce hyphae and microconidia inside the root cells. Next, chlamydospores produced from hyphae may develop in intra- and intercellular spaces. Foc TR4 passes through the infected vessels of the parent rhizome to new growing suckers. Characteristic symptoms of Fusarium wilt of banana are discoloration of interior parts of the rhizome, pseudostem and petiole, which may also progress to the peduncle. In the internal vessels of the pseudostem, the discoloration varies from pale yellow in the early stages, to dark red or even black in later stages (see [Figure 4.2](#) on p. 37). In more severe symptoms, the rhizome exhibits total discoloration accompanied by a sticky texture and even a rotten smell due to secondary decay. The most typical external symptoms include yellowing of the older leaves around the margins followed by wilting and necrosis. Splitting may develop at the base of the pseudostem and brownish streaks may be visible if the oldest leaf sheaths are examined. No internal symptoms are observed in fruits and the pathogen has not been recovered from fruit tissue (pedicel, skin or pulp). In contrast, healthy banana plants have mostly green leaves, and clean white vascular tissue in the rhizome, pseudostem and petioles, with no signs of discoloration.

4.4 Classification, pathobiology and ecology

Foc TR4 is a group of strains that cause disease in Cavendish cultivars under optimum growing conditions without predisposing environmental factors. A recent taxonomic study on the genetic and morphological diversity of Foc proposed the name *Fusarium odoratissimum* sp. nov. for the lineage that encompasses TR4. Foc is a soil-borne fungus that can produce three types of asexual spores i.e. macroconidia, microconidia and chlamydospores. The macroconidia are sickle-shaped, thin-walled and thin. Macroconidia usually bear three or four septa, a foot-shaped basal cell and a curved apical cell. These spores are generally produced from phialides on conidiophores and are involved in secondary infection. On the other hand, microconidia are ellipsoidal and have either a single septum or none at all. They are formed from short monopodialides in false heads. Lastly, chlamydospores are globose with thick walls and are either directly formed from hyphae or by the modification of hyphal cells. Chlamydospores can remain in soils for extended periods of time and usually act as inocula in primary infection. Macroconidia and chlamydospores are normally only formed on dead or dying host plants, while the latter constitute the primary survival structures of this pathogen.

Foc is genetically and pathogenically diverse. By classifying it according to race, depending on the group of affected banana cultivars, four races of Foc have been identified. Race 1, which was responsible for the Gros Michel (AAA) epidemic, also attacks Maqueño (AAB), Silk (AAB), Pome (AAB) and Pisang awak (ABB) cultivars. Race 2 affects cooking bananas such as Bluggoe (ABB). Race 3, which was originally reported in wilted *Heliconia* species, is no longer considered a valid Foc race. Foc race 4 is pathogenic to race 1- and race 2-susceptible cultivars and also to the Cavendish subgroup (AAA). Foc race 4 can be further divided into two groups: Tropical race 4 (TR4) and subtropical race 4 (STR4). Foc TR4 affects the same cultivars as STR4 but does not require the predisposing suboptimal growing conditions that occur in the subtropics for infection to occur in Cavendish. Genetically related Foc isolates can also be characterized into vegetative compatibility groups (VCGs) based on their ability to exchange genetic material via heterokaryon formation. Isolates that are vegetatively compatible with one another are thought to belong to the same VCG and typically share common biological, physiological, and pathological characteristics.

Over the years, research has focused on unraveling the *Fusarium* TR4 infection process and disease cycle. The pathogen infects the roots of both susceptible and resistant cultivars alike, but cannot progress further into the upper part of resistant cultivars, and the infection of vascularized fragments of the rhizome is more prominent in susceptible cultivars. In response to pathogens, bananas produce calluses, gums and gels in their xylem lumen to restrict infection. Foc manages to pass through the rhizome to the pseudostem, in advance of these mechanisms, in susceptible cultivars. When the plant dies, the pathogen moves from the vascular system into other tissues, forming abundant conidia and chlamydospores, which are released to the soil. Chlamydospores can remain dormant in the soil for years with persistent survivability, which is one reason for the difficulty of elimination. The pathogen often colonizes the outer root cells of grasses and weeds as an asymptomatic endophyte, and these alternative hosts can complicate containment and management. As a necrotrophic or hemibiotrophic pathogen, Foc TR4 can utilize an array of strategies to infect host plants. Chlamydospores of Foc TR4 can





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remain dormant for several years and then start a new disease cycle immediately when they perceive the root exudates of the host or directly contact susceptible root tissues. Experimentally, conidia of Foc TR4 adhere to the root surface at two days post-inoculation (dpi), and after which they can germinate along the grooves between epidermal root cells. Hyphae are then able to penetrate into the root xylem ten dpi and spread into the rhizome and pseudostem xylem a few days later. Many hyphae are observed in the pseudostem at 17 dpi, and the plant may die as early as 24 dpi. In addition, studies with strains of Foc transformed with a green fluorescent protein gene have shown that the pathogen may be present in the roots, rhizome and outer leaf sheaths of the pseudostem before the appearance of visible symptoms.

Other biotic and abiotic factors also mediate the development of disease symptoms. The presence of plant-parasitic nematodes can increase TR4 severity, with nematode wounds possibly facilitating infection and pathogen colonization. However, the intensity of Fusarium wilt in Gros Michel bananas is not influenced by the joint infection of nematodes (*Radopholus similis*) and Foc race 1, though root weight is greatly reduced in co-inoculated plants compared with inoculation with only Foc race 1 or *R. similis*. The soil microbiome and plant endophytes may temper the disease – either by creating a Foc-suppressive environment in the soil or by preventing further penetration and colonization by the pathogen within plants. Soils with an active and functionally diverse microbiota may have a higher capacity to suppress Fusarium wilt. In contrast, soils with poor biological diversity and sterile food webs would be more conducive to disease proliferation. With the advent of a more powerful methodology to evaluate the functional diversity of the soil microbiome, significant progress has been made on microbes associated with banana-Foc TR4 interactions. In China's Hainan province, soils that suppress banana Fusarium wilt have higher microbial richness and diversity indices as compared to conducive soils. Suppressive soils also have higher abundance levels of *Chthonomonas*, *Pseudomonas* and *Tumebacillus* spp. In Central America, healthy banana plants harbor a higher richness and diversity of Gammaproteobacteria than Foc-infected plants. In addition, healthy banana plants often harbor potentially beneficial endophytic microorganisms such as *Pseudomonas* and *Stenotrophomonas* spp.

The physical and chemical characteristics of orchard soils may also mediate disease intensity, making the soil either suppressive or conducive. Increased soil pH is probably the most consistently reported abiotic attribute associated with suppression of the disease, although more research is needed to fully understand the underlying mechanisms. The physical structure of soils can influence the disease an indirect fashion by modulating plant-water relations and beneficial soil organisms. Root development and microbial activity can be improved in well-drained and aerated soils, where Fusarium wilt is assumed to decrease. In contrast, compacted soils with low aeration may facilitate Fusarium wilt. On volcanic soils in the Canary Islands, higher content of water-stable aggregates and iron, and lower pH, electrical conductivity (EC) and soluble sodium were associated with conducive soils. In India, sandy clay loam soils with a low bulk density are more suppressive of Fusarium wilt of banana, while clay soils with a high bulk density are more conducive. However, comparative studies at different sites are still scarce. Temperature equally influences the growth of both the pathogen and the banana host, and thus, affects disease development. Bananas may be more vulnerable to infection under cold conditions, with varieties less tolerant of low

temperatures having a reduced defence ability. Under climate change scenarios, extreme weather events are likely to favour disease expression and spread.

Lastly, the banana weevil (*Cosmopolites sordidus*) may contribute to Foc TR4 spread and proliferation. These large-bodied, mobile insects can disperse over large distances within and between banana orchards, transmitting viable Foc TR4 spores on their exoskeleton and within their excreta for two to three days. Thus, banana wilt disease management cannot be viewed in isolation from other crop protection measures, but integrated pest-pathogen management is to be pursued. This is particularly relevant in newly invaded areas where quarantine measures routinely do not impede the movement of *C. sordidus* weevils.

4.5 Geographical distribution

Symptoms of Fusarium wilt were first observed on Cavendish cultivars in Taiwan Province of China in 1967, although TR4 wasn't confirmed until the use of VCG testing in 1989. TR4 rose to prominence after devastating outbreaks in Malaysian and Indonesian export plantations in the early 1990s, which were followed by reports of the disease in China, Australia's Northern Territory, and the Philippines. For more than 20 years, Foc TR4 was found only in east Asia, Southeast Asia and northern Australia. In 2013, the first incursions outside Southeast Asia occurred with reports from Jordan and Mozambique. In 2015, Foc TR4 was reported in Queensland, Australia, and in Lebanon and Pakistan. In 2017, Foc TR4 was reported in the Lao People's Democratic Republic and Viet Nam, followed by Myanmar in 2018. Whole-genome sequencing analysis of isolates revealed that the specific TR4 strain in the Lao People's Democratic Republic, Myanmar, and Viet Nam likely originated in China. In 2018, Foc TR4 was reported in Israel and the disease was declared to be actionable and under eradication. Foc TR4 was officially reported in India in 2018, though wilt symptoms had previously been observed in the state of Bihar in 2015. In 2019, Foc TR4 was detected in Latin America, when approximately 175 ha of Colombian banana plantations were found to be infested. In 2019, a suspected case of Foc TR4 disease was found in Thailand and Türkiye. Lastly, Foc TR4 was officially reported in Mayotte in 2020 and was only recently recorded in Peru.

4.6 Host range

Different races of Foc are determined based on pathogenicity to relevant host cultivars. Foc TR4 affects all cultivars in the Cavendish (AAA) subgroup in addition to those susceptible to Foc race 1 and race 2. VCG distribution depends on locally abundant banana varieties and prevailing climatic conditions in each area. For example, VCG 0120 of race 1 most commonly affects Cavendish bananas in the subtropics, while TR4 VCGs (0121 and 01213/16) most commonly affect Cavendish and other *M. acuminata* diploids and triploids in the tropics. TR4 has been isolated from a diverse range of *Musa* cultivars of the diploid genotype AA, the triploid genotypes AAA, AAB and ABB as well as AAAA and AAAB tetraploid hybrids. VCG 0121 is much more restricted in its range than VCG 01213/16, occurring only in parts of Indonesia and Malaysia as well as Taiwan Province of China. Varying levels of tolerance to TR4 have been reported in a wide range of banana genotypes including East African Highland bananas (AAA), somaclonal variants of Giant Cavendish, for





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example GCTCV varieties (AAA) from Taiwan Province of China, some B-genome cooking types such as Pisang Kepok (BBB), some diploids (e.g. Rose, AA), and some tetraploid hybrids, for example, FHIA 1, AAAB.

4.7 Impact

As the most destructive soil pathogen of banana, Foc TR4 has spread rapidly throughout the Cavendish-dominated banana growing world, where thousands of hectares have been affected. Fusarium wilt disease has been detected in all banana-growing regions of China, and the total area affected by this disease in mainland China has grown to 40 000 ha. In Australia alone, annual TR4-related losses are estimated at more than AUD 138 million – almost USD 90 million. According to FAO estimates, Fusarium wilt of banana has caused losses of USD 121 million, USD 253.3 million, and USD 14.1 million in Indonesia, Taiwan Province of China, and Malaysia, respectively. It has also been estimated that 17 percent of the world's banana-growing area will be lost due to TR4 infestation by 2040. Given the importance of banana as a lead food crop, TR4 not only leads to the loss of banana growers' livelihoods but also raises the likelihood of hunger, malnutrition and food insecurity globally.

4.8 Integrated disease management (IDM)

Inspection and diagnostics. The control of Fusarium wilt of banana is hampered by its long-term survival and slow onset of symptoms. Therefore, rapid and accurate detection of Foc TR4 during the early stages of infection is critical for the management of this disease. Visual checking for external symptoms is currently the only reliable means of identifying a suspect plant in the field, so regular inspection of crops for symptoms is essential for early detection. These inspections may take the form of coordinated government or company-run surveillance programmes, or less formal observation by trained farm workers who routinely inspect the crop while carrying out other crop management tasks.

Prior to the development of molecular techniques, the diagnosis of Foc was based on methods such as visual inspections of internal and external disease symptoms, morphological characteristics of the fungus, and by time-consuming pathogenicity or VCG testing. Polymerase chain reaction (PCR) is often considered the gold standard diagnostic tool for plant pathogens because it is rapid, with good specificity and sensitivity, and can be used directly on plant extracts, which makes the early detection of plant diseases possible. Therefore, methods based on PCR were developed to rapidly identify Foc in banana plants with and without symptoms by developing proper amplification primers. With these molecular methods based on PCR, not only could small quantities of Foc DNA be detected, but Foc race 4 could easily be distinguished from other Foc races 1 and 2. For example, a PCR-based diagnostic tool with two single nucleotide polymorphisms present in the intergenic spacer region was developed to specifically detect Foc TR4 VCG 01213.

Subsequent to the development of these PCR diagnostics, some limitations became apparent, especially when applied to extracts from plant tissue, rather

than purified isolations of the pathogen. *F. oxysporum* is a ubiquitous fungus and commonly occurs as an endophyte/saprophyte within bananas. Some non-pathogenic strains have proven to be cross-specific with PCR diagnostics, so best practice is to perform diagnostics on pure cultures of the fungus, derived from symptomatic tissue. Recently, more robust PCR assays targeting genes strongly correlated with pathogenicity, such as secreted in xylem (SIX) genes, have been developed for Foc. PCR-based methods are restricted by technical factors; for example, requirements of expensive equipment and reagents. To overcome this limitation, isothermal DNA amplification methods are widely used for plant pathogen detection. Loop-mediated isothermal amplification (LAMP) is valued for its high efficiency, specificity, simplicity and rapidity. Accordingly, a novel and highly specific LAMP assay was developed for Foc TR4 based on a sequence-characterized amplified region marker sequence. Real-time fluorescence LAMP assays were also developed for the rapid and quantitative detection of Foc TR4 in soil or infected plants with high sensitivity, and no cross-reaction with other related pathogens was observed. These methods open the door to extending molecular diagnosis into fieldwork as a simple and rapid alternative molecular diagnostic tool to lab-based PCR. Yet, one needs to evaluate whether portable detection kits are fit-for-purpose, or whether back-up is needed with laboratory-based verification. Lastly, computer vision and artificial intelligence can provide a timely and accurate in-field detection of banana wilt disease, and automated mobile applications have been adopted by countless banana growers in the developing world. Aerial imagery can equally be used secure a speedy detection of disease hotspots, especially in smallholder-managed banana crops.

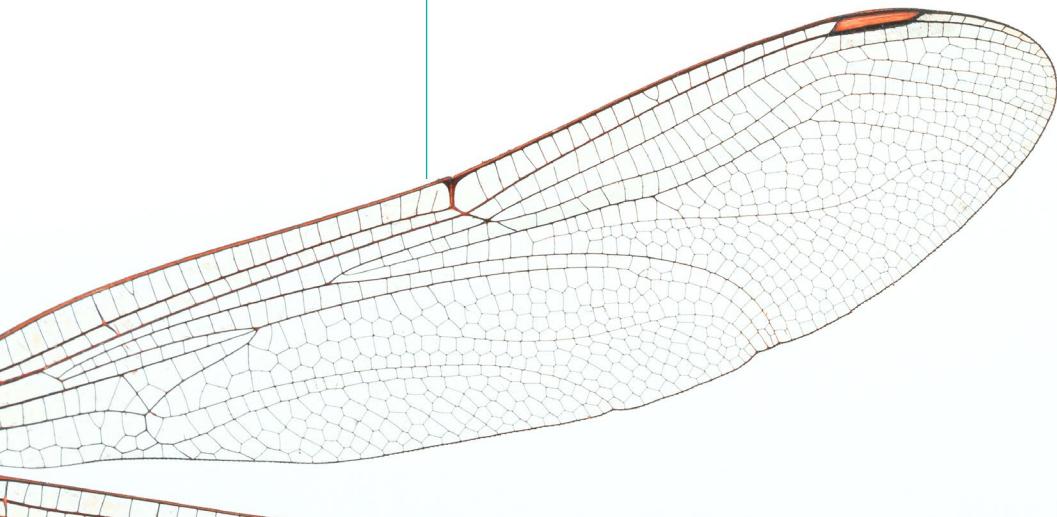
Prevention and control. Since its first appearance in commercial banana plantations, chemical and biological methods and cultural practices have been used to manage Fusarium wilt disease. However, once plants are infected, there is no completely effective control for the disease. International or intranational quarantines have had limited success in limiting the inter-continental, inter-country and inter-regional spread of the pathogen. The use of natural, bred or engineered-resistant cultivars is considered the most effective method to control Panama disease. At present, no commercial cultivars possess the levels of resistance to Foc TR4 as Cavendish has to Foc race1. Somaclonal variants of Giant Cavendish (GCTCVs) with varying levels of tolerance to TR4 have been identified from tissue culture plantlets exposed to high disease pressure in Taiwan Province of China. Yet, due to incomplete immunity, these resistant cultivars are only effective for a limited number of crop cycles under high disease pressure. They may also have less desirable agronomic traits compared with the favoured Cavendish trade cultivars. Genome editing potentially can accelerate the development of disease-resistant banana varieties, but societal acceptance of this approach is unsure. In Australia, regulatory approval was only recently granted to release of a genetically-modified TR4-resistance banana variety (QCAV-4) for human consumption.

Thus, IDM measures need to be judiciously implemented even when resistant cultivars are planted. When used in isolation, individual control measures have limited ability to reduce the impact and a combined approach is recommended. Practices such as cover crops (ground cover, intercropping) or crop rotation are key IDM components (**Figure 4.3** on p. 38). Cover crops can help to increase banana yields by sheltering beneficial organisms, which help to manage pests, improving soil nutrition and structure (through addition of organic matter and nitrogen

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fixation), suppression of weeds, and reducing pathogen inoculum by supporting a more diverse soil microbiome. The intensity of Fusarium wilt in Ducasse bananas (Pisang Awak, ABB) was reduced by 20 percent by using Pinto peanut (*Arachis pintoi*) as a ground cover. In shade-grown organic banana farms in the United Republic of Tanzania with the Mchare variety (AA genome group), intercropping with coffee raised above- and below-ground biodiversity and lowered Fusarium wilt intensity. *Allium* spp. are also suitable intercrops, although the underlying Foc TR4 disease suppression mechanisms wait to be characterized. Similarly, intraspecific diversification (e.g. through banana cultivar mixtures) potentially can reduce disease incidence. Crop rotation is also a good option to manage soil-borne diseases such as *Fusarium* sp. Incorporating pineapple (*Ananas squamosa*) and Chinese leek (*Allium tuberosum*) rotation crops regularly reduce the incidence of Fusarium wilt in subsequent banana crops.

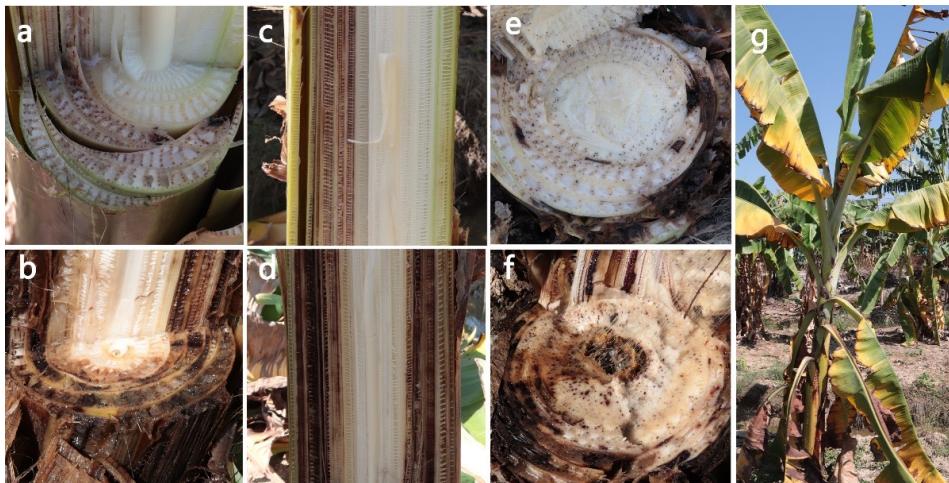
Soil microbes can help to protect plants against pathogen infection. Since 1945, different microbes, such as *Pseudomonas fluorescens*, *Trichoderma viride* and *Bacillus* spp. have been tested against Fusarium wilt disease. However, most of the published works involve *in vitro* assays or short-term greenhouse studies with limited field-level validation, showing only modest reductions of disease incidence. Host plant resistance can also be effectively induced by antagonistic fungi. For instance, when tissue-cultured banana plantlets are inoculated with fungi such as *Serendipita indica*, they exhibit markedly lower susceptibility to Foc TR4. Other microbial biological control agents, as applied through spore suspensions, organic amendments or commercial formulations at different stages of crop development, are showing ample promise. For instance, the application of *Pseudomonas* spp. strains achieves up to 79 percent disease control under field conditions, while endophytes and *Trichoderma* spp. strains ensure 70 percent control; Arbuscular mycorrhizal fungi, *Bacillus* spp. and non-pathogenic Fusarium strains up to 55 percent. Other fungal endophytes, associated with common weeds, exert up to 99 percent inhibitory activity under laboratory conditions and their usage awaits field-level validation. Ideally, endophytic biological control is integrated with tailored plant nutrition management or paired with epigenetic resistance priming, for example, with elicitors such as tea tree oil.



**Figure 4.1**

A serious Foc TR4 infestation in a banana orchard

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**Figure 4.2**

Disease symptoms of Fusarium wilt of banana

A: Cross-section of pseudostem showing moderate discoloration
B: Severe internal discoloration of infected pseudostem

C, D: Longitudinal section of pseudostem showing infected vascular bundles
E: Infected leaf bases and rhizome showing moderate discoloration

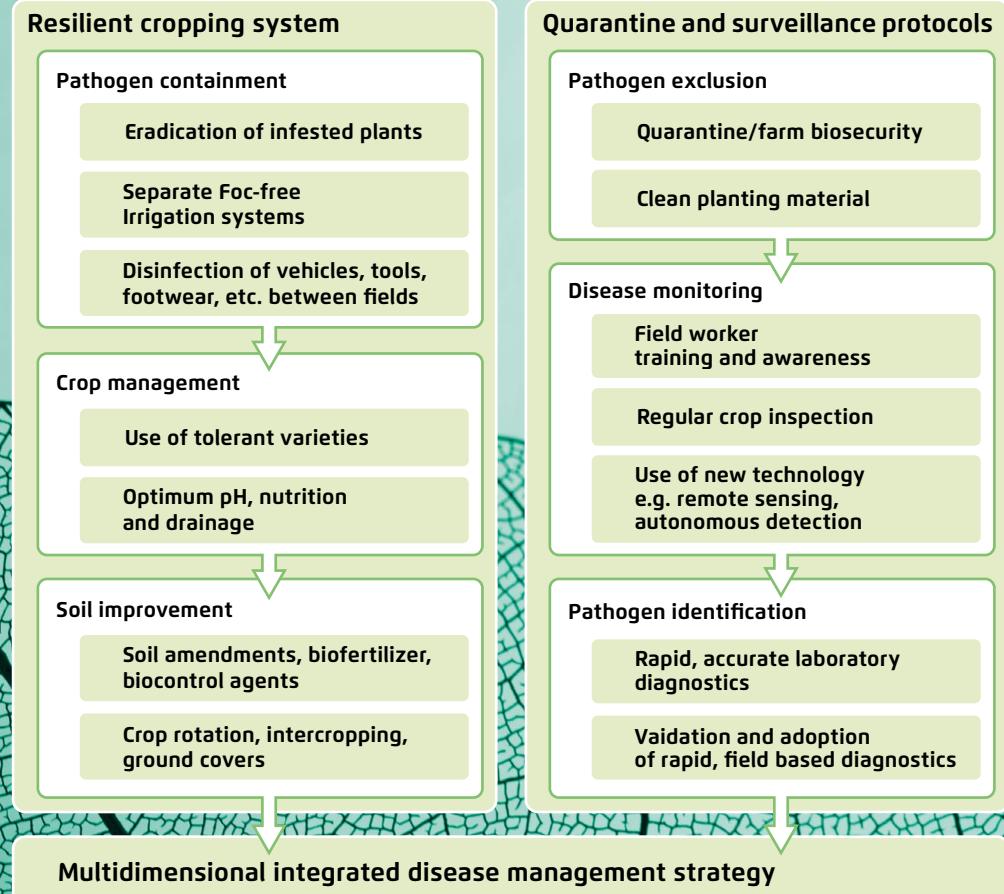
F: Severe internal discoloration of infected rhizome
G: External symptoms of Fusarium wilt

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Figure 4.3

Proposed integrated disease management (IDM) strategy for Fusarium wilt of banana

Source: Cook, D. C., Liu, S., Edwards, J., Villalta, O. N., Aurambout, J. P., Kriticos, D. J., Drenth, A. & De Barro, P. J. 2012. Predicting the benefits of banana bunchy top virus exclusion from commercial plantations in Australia. *PLoS One* 7(8).



5. Maize lethal necrosis

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5.1 Summary for policymakers

- ▶ Maize lethal necrosis disease (MLND) imperils food and livelihood security in many maize cropping regions of the world.
- ▶ Rigorous inspection and quarantine of traded maize seeds is crucial to prevent inter- or intra-country disease spread.
- ▶ As MLND outbreaks are tied to maize monocropping and absence of crop rotation, diversification tactics can bring relief.
- ▶ Much remains to be learned about the relative role of insects, soil, seeds, and alternative non-crop host plants in disease proliferation.
- ▶ To advance sustainable disease management, increased research attention needs to be given to maize varietal resistance, vector ecology and biological control.

5.2 Take-home messages for practitioners

- ▶ A diversity of diagnostic toolkits allows for early pathogen detection and rapid response.
- ▶ The use of certified, disease-free maize seeds is especially important in unaffected maize-growing regions.
- ▶ In-field sanitation, particularly the removal of maize volunteer plants and weeds, can lower the odds of disease carry-over between cropping cycles.
- ▶ Non-chemical preventative tactics such as crop rotation, crop diversification, and maize-free periods should be consciously prioritized over pesticide spray applications.
- ▶ Several MLND-tolerant maize lines are available for use in key growing regions.

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5.3 Introduction

Maize (*Zea mays*) is one of the world's main cereal grain crops, and is extensively used for food, animal feed and industrial purposes, such as starch. Its capability to grow under diverse climatic conditions makes it a key determinant of food, nutrition and livelihood security in many parts of the globe. Maize lethal necrosis disease (MLND) is a serious disease of maize that causes leaf necrosis, premature aging, small cobs or plant death and substantially lowers yield. During the 1970s to 1980s, MLND was reported in the Americas. Additionally, in recent years, MLND outbreaks have also affected smallholder maize growers in Asia and Africa. MLND is now reported from more than fifteen countries and has become a major biotic threat to the world's maize production.

MLND is caused by the synergistic infection of maize chlorotic mottle virus (MCMV) and one or more potyviruses. MCMV-infected maize plants routinely exhibit chlorotic mottling on leaves and mild stunting, while necrosis, severe stunting, shortened inflorescences, and premature plant death are occasionally associated with MCMV infection. More severe MLND-like symptoms may be caused by a mixed infection or environmental conditions. A single infection by one of the potyviruses typically causes mosaic, stunting, and mild chlorosis. Upon co-infection with MCMV, the effects are synergistic in disease progression and symptom development. MCMV titer and particle accumulation in co-infected plants is markedly higher than when plants are solely infected by MCMV. The concentration of MCMV is also higher in co-infected plants, but concentrations of other viruses such as sugarcane mosaic virus (SCMV) or maize dwarf mosaic virus (MDMV) are not changed. Maize plants prove susceptible to MLND throughout their development. The exact type and severity of symptoms depends upon the maize variety, infection stage, environmental conditions, amongst others. In most cases, chlorotic mottle starts from the base of the young leaves in the whorl and extends toward the leaf tips, followed by leaf necrosis at the leaf margins that progress to the mid-vein resulting in whole leaf drying and premature aging. If necrosis occurs in the young whorl leaves, the plants may show 'dead heart' symptoms. Severely infected plants form small cobs with little or no grain set. The disease can also lead to plant death before tasseling.

5.4 Classification, pathobiology and ecology

MLND is caused by co-infection of maize plants by maize chlorotic mottle virus (MCMV) in the genus *Machlomovirus* of the family *Tombusviridae*, with one of several cereal-infecting viruses in the *Potyviridae* family (collectively referred to as potyviruses or potyvirids). The latter include: SCMV, MDMV, and Johnsongrass mosaic virus (JGMV) (all three genus *Potyvirus*); and wheat streak mosaic virus (WSMV) (genus *Tritimovirus*). As compared to MCMV, maize-infecting potyviruses show great diversity within and between species. According to the standard of classification in the family *Potyviridae*, the species are determined by 76 percent nucleotide sequence identity and 82 percent amino acid similarity. While genome organization is relatively similar, biology, host range and ecology of these viruses vary widely. Virions of potyviruses (except the genus of *Bymovirus*) are flexuous filaments, 680 nm to 900 nm in length and 11 nm to 13 nm in diameter, with helical symmetry and a pitch of about 3.4 nm.

MCMV can be transmitted by insect vectors, seeds, and soil. After MCMV emerged in the United States of America, some putative vectors were tested for transmission. Six different species of chrysomelid beetles transmit MCMV, both at larval and adult stages with no latent time, while aphids and leafhoppers could not. These putative vectors include the cereal leaf beetle (*Oulema melanopa*), corn flea beetle (*Chaetocnema pulicaria*), flea beetle (*Systema frontalis*), southern corn rootworm (*Diabrotica undecimpunctata*), northern corn rootworm (*Diabrotica longicornis*), and western corn rootworm (*Diabrotica virgifera*). In areas where corn is planted continuously, viruses were spread from older plants to younger plants by larva and adult beetles. The adults prove to be more efficient vectors than larvae. Since MCMV was detected in *Diabrotica* sp. beetles in the field, beetles were considered as the major vectors for Kansas-Nebraska MLND outbreaks. Yet, when MLND emerged in Hawaii in the 1990s, the known beetle vectors were not present and maize thrips (*Frankliniella williamsi*) were shown to transmit MCMV in a semi-persistent manner, retaining transmissibility for up to six days after virus acquisition. Both larvae and adult thrips can transmit MCMV, but adults are more important in virus spread because they are more mobile. Recently, there has been speculation that high densities of thrips in affected fields in Asia and Africa are associated with the emergence of MLND. In the practice of detection and plant quarantine, it was found that MCMV can be seed-borne. When seeds were harvested from MCMV-infected maize plants in local markets in Kenya, 45 percent to 72 percent were positive by reverse transcription PCR (RT-PCR) detection. Maize seeds can thus be contaminated with MCMV from virus-infected plants, although infected seeds do not necessarily lead to diseased plants. In fact, rates of MCMV transmission to progeny plants were 0 percent to 0.3 percent. More recently, MCMV was detected in 0.3 percent of seedlings from imported maize seeds by Chinese researchers. Though the transmission rate is fairly low, it is of epidemiological importance as it increases the risk of seed-mediated disease spread.

In addition, the pathogen also appears to proliferate through contaminated soil. For MCMV, preliminary experiments showed that a high incidence (70 percent) of seedlings were infected with MCMV after they were planted in contaminated soil taken from MLND-infected fields, as compared with 4 percent of seedlings planted in sterile soil. Further research is needed to determine how long the length of a maize-free period is required to prevent MCMV transmission through soil.

The cereal-infecting potyviruses are transmitted by aphids in a non-persistent manner and are transmissible experimentally by mechanical inoculation. SCMV and MDMV are transmitted by *Rhopalosiphum maidis*, *Rhopalosiphum padi*, *Myzus persicae*, *Schizaphis graminum* and other species. Aphids are distributed worldwide and are ubiquitous in maize-growing areas. Aphid population dynamics are shaped by climatic parameters such as temperature and rainfall, and also affected by climate change. In addition, SCMV can be seed transmitted at the rate of 0.4 percent to 3.9 percent, depending on the maize variety. WSMV is transmitted by the eriophyid wheat curl mite (*Aceria tulipae*) in a persistent manner at low, though epidemiologically significant, rates. Potyviruses are further thought to be naturally present in maize and other monocot species. Seed contamination is likely the initial source of inoculum for MCMV, which finally sets off MLND in the newly emerged areas. Virus-infected maize plants may be the most important reservoirs in areas where MLND is already emerging, while other host plants such as sugarcane, sorghum, barley, wheat, millet or weeds may also be involved. Where maize is

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continually cultivated, maize plants constitute an important virus reservoir. As such, MLND outbreaks are exacerbated in areas with extensive monocropping.

Wounds are essential for viruses to penetrate the cell walls and can be created by mechanical injury from human activities or the feeding of insect vectors. The latter can acquire virus particles or genome as they feed on virus-infected plants. When they feed on virus-free plants, the virus particles or genome can be deposited or injected into cells through the wounds. Once inside the host cells, viruses will replicate using host machinery, move cell-to-cell through plasmodesmata and ultimately, induce systemic infection. Infected plants will be involved in secondary cycles and repeated cycles continuously with the aid of vectors, ultimately resulting in disease outbreaks. MCMV also induces changes in host plant volatiles to elicit attraction from maize thrips, which could enhance virus transmission.

5.5 Geographical distribution

MLND-associated viruses in the *Potyviridae* family are ubiquitous worldwide, and different species predominate in different geographical regions. SCMV is found worldwide, and MDMV is distributed widely in Europe and the United States. Meanwhile, WSMV, JGMV, and sorghum mosaic virus cause diseases on maize with limited distribution. In the United States, MDMV is common and SCMV is also present. In Africa, JGMV and MDMV are present, and SCMV is predominant. In the 1920s and 1930s, SCMV was described in southern and eastern Africa. In a survey during the 1980s, SCMV was observed in some areas of the United Republic of Tanzania and Kenya. However, the recent detection of SCMV in Kenya's coastal regions and Nairobi hint at a continued spread of the disease in eastern Africa.

As SCMV and MDMV are widely distributed, the geographical distribution of MCMV is crucial for the occurrence of MLND. MCMV was first identified in Peru in 1971, and MLND outbreaks were subsequently recorded in the states of Hawaii, Kansas and Nebraska in the United States. In recent years, the disease has been identified in Asia and Africa. In 2009, MCMV was detected in Yunnan province of China, inducing MLND through co-infection with SCMV. In 2011, the first outbreak of MLND in Africa was reported in east Africa along the Rift Valley regions of Kenya and the disease subsequently spread quickly. Now, MLND has been identified in several African countries, from Ethiopia in the north, to the United Republic of Tanzania in the south; and Kenya in the east to the Democratic Republic of the Congo. At present, MLND has been reported in more than 15 countries.

5.6 Host range

MCMV can systemically infect different varieties of maize. Sugar cane (*Saccharum officinarum*), sorghum (*Sorghum bicolor*), coix seed (*Coix chinensis*), and finger millet (*Eleusine coracana*) all appear to be natural hosts of MCMV. In the laboratory, many species, including many monocot crops and other weedy grasses, have been tested and found susceptible to MCMV by mechanical inoculation. However, the primary hosts all belong to the Gramineae, such as barley (*Hordeum vulgare*), proso millet (*Panicum miliaceum*), foxtail millet (*Setaria italica*), wheat (*Triticum aestivum*), napier grass (*Pennisetum purpureum*), African couch grass (*Digitaria abyssinica*),

purple nutsedge (*Cyperus rotundus*) and sand lovegrass (*Eragrostis trichodes*). There is still no conclusive experimental evidence that MCMV can be transmitted from these hosts to maize plants by vectors, and what roles these alternate hosts play in disease infection cycles remain unknown. Similarly, maize-infecting potyviruses infect a range of gramineous crops, forages, and weeds.

5.7 Impact

MLND outbreaks can severely impact maize yields. In early reports from Peru, MLND-induced yield losses ranged between 10 percent and 15 percent. In Kansas, losses ranged between 50 percent and 90 percent, depending on the maize variety and the environment. In 2011, MLND was reportedly inducing serious damage to maize production in Kenya, affecting almost all commercial maize varieties and causing estimated yield losses of 30 percent to 100 percent, depending on the stages of disease and varieties of maize. Subsequently, MLND spread rapidly in sub-Saharan East Africa and most recently in Ecuador, across an area of nearly 1.2 million km². Given that harvested maize is primarily used for human consumption in many maize-growing regions of Africa, MLND directly imperils local and regional food security.

MLND also causes a wider range of societal impacts. The economic impact on smallholder farmers across Ethiopia, Kenya, Rwanda, the United Republic of Tanzania, and Uganda was estimated to be USD 291 million to USD 339 million, with somewhat greater annual losses estimated over the next five years. In MLND-affected areas, maize production costs also increase as farmers resort to herbicides and insecticides to control weeds and insect vectors. Input costs also increase as pesticide-coated seeds are increasingly sold by seed companies. Aside from its impacts on farmers' vulnerability to poverty, this increased reliance upon prophylactic, curative pesticide use carries major risks for human and environmental health.

5.8 Integrated disease management (IDM)

MLND poses a serious threat to global maize production. To manage this disease sustainably, many factors must be considered, including agronomic variables, profitability, inputs and environmental contamination. Integrated disease management (IDM) constitutes a suitable approach and includes three parts applicable according to the occurrence of MLND: strengthening detection, active prevention, and effective control.

Diagnostics and early detection. The first step in controlling plant diseases is the timely, reliable identification of the causal pathogens. Rapid and sensitive detection of MCMV is critical for the early warning and rapid application of prevention measures to control the wide spread of MLND. Many methods can be used to diagnose the virus or the disease, including symptomatology, serological methods, nucleic acid-based methods, and electron microscopy. Symptom detection, serological and nucleic acids-based methods have been widely used in the practical diagnosis of MLND. However, it is very difficult to make a definitive diagnosis based solely on symptoms, as the symptoms vary significantly based on maize varieties, time of infection, environment and the possibility of multipathogen infection. Suspected MLND plants thus need further confirmatory tests, for example by serological or nucleic acid-based methods.



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Since the early 1960s, serological methods have been used for the detection and diagnosis of plant viruses. Various immunological methods are used for the rapid, specific identification of large numbers of field samples. Serological tests are based on an antigen-antibody reaction, which is associated with colorimetric properties. Many different methods are used including enzyme-linked immunosorbent assay (ELISA), triple antibody sandwich ELISA, double antibody sandwich ELISA, direct antigen coating ELISA, dot-immunobinding assay, western blots, immuno-capture reverse transcription-polymerase chain reaction (IC-RT-PCR), immunoelectron microscopy and tissue blot immuno-assays. The characteristics that are most desirable for virus detection are high sensitivity, speed, simplicity, low costs and easy automation which comprise the serological methods extensively used in the identification of viral diseases. They have been successfully used in the identification of MCMV, SCMV, WSMV and MDMV.

Nucleic acid-based methods detect the presence of the virus genome and are widely used in the detection of many viral diseases because of their specificity, sensitivity, and speed, especially in cases where antibodies of viruses are not available. Polymerase chain reaction (PCR) and its different variants are among the most-used nucleic acid-based methods. These include reverse transcription PCR (RT-PCR), real-time PCR, multiplex PCR, nested PCR, IC-RT-PCR) and fluorescence RT-PCR. Many researchers are dedicated to optimizing the sensitivity and specificity of the detection. The real-time PCR detection has been successfully used in MCMV detection in maize seeds and leaves. RT-PCR has been routinely used to detect MCMV or other potyviruses in crops, weed plants and vectors. Apart from the detection of viruses, PCR products can be sequenced to provide detailed genome information for the identification of virus isolates, phylogenetic analyses, for example.

Recently, next-generation sequencing (NGS) has been applied to the diagnoses of new unidentified viral diseases. Such diagnoses are not restricted by the availability of antibodies, knowledge of genome sequences and other information. This method involves the generation of a nucleic acid library in a non-specific manner, high-throughput sequencing and bioinformatic analysis. The identification of a virus is based on similarity searching against a virus genome sequence database. NGS has been successfully used to identify and characterize new and existing viruses in many plant species. The MLND outbreak in Kenya is one of these cases, which was confirmed as a co-infection of MCMV and SCMV. With further technological development and cost reductions, NGS has been increasingly used in plant viral diagnostics. Finally, other sensitive detection methods are being developed, such as one-step reverse transcription loop-mediated isothermal amplification (RT-LAMP) assay and recombinase polymerase amplification (RPA) detection, which could also be used as a routine screen for MCMV infection in the future.

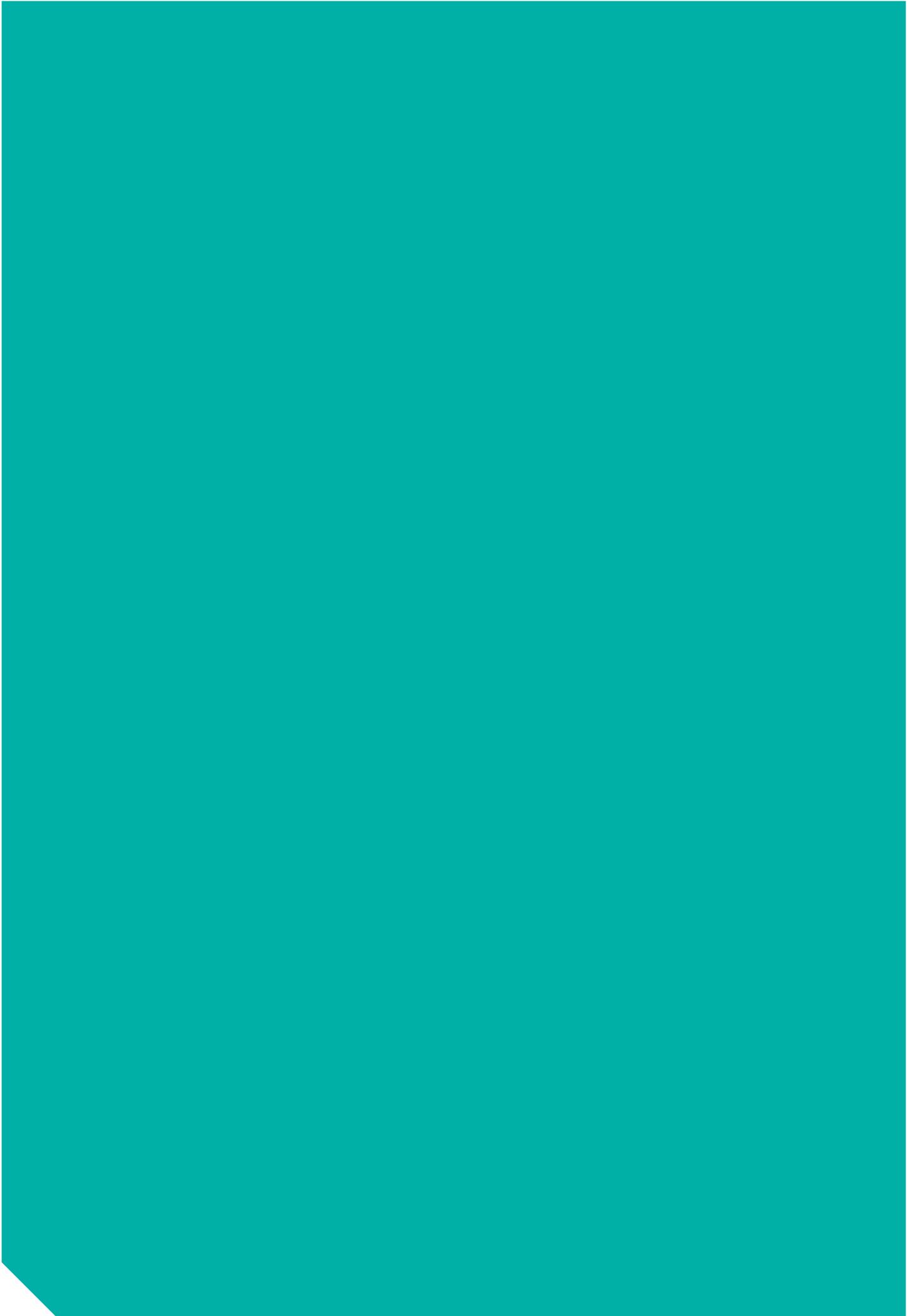
Active prevention. Seed transmission can enable long-distance spread of MCMV. When using seed from MCMV-infected plants, the pathogen is likely to be present and seed transmission rates up to 0.3 percent have been recorded in Hawaii and China. Though MCMV presence does not necessarily relate to infectivity, long-distance transmission still poses a real risk. Thus, governments worldwide should strengthen the inspection and quarantine of imported maize seeds, not limited to seeds used for planting or breeding. In those countries where MLND occurs, transportation of

seeds or other maize products should be prevented from the disease-affected areas to disease-free areas. In addition, the general public and farmers should be informed and educated about the disease, through different channels.

Effective control. At present, the options for MCMV management include sanitary measures, cultural means, chemical control and use of disease-resistant varieties. Comprehensive field sanitation is to be a frontline treatment, as it can greatly reduce initial inoculum. As maize plants are the primary pathogen source in MLND-affected areas, infected plants (and host weeds) should be removed from the field to reduce pathogen and vector populations. In the meantime, the use and replanting of recycled seeds must be avoided, and only certified MCMV-free seeds should be used. The continuous year-by-year cultivation of maize helps to sustain a local virus reservoir with infected plants and vectors. To break maize planting cycles, farmers are advised to rotate or diversify crops with alternative non-cereal crops, such as potatoes, sweet potatoes, cassava, and beans. Overhead spray applications of herbicide and chemical or microbial insecticides can contribute to weed and vector control, and thus reduce the rate of infection and disease severity. Similarly, biological control can lower thrips, aphid, and chrysomelid beetle vector populations and thereby slow virus spread within and between fields. Yet, to fully tap its potential, the in-field ecology of these potential vector species needs to be thoroughly characterized across geographies and cropping contexts. Good results have been obtained by annually implementing 60-day maize-free periods, eventually in combination with chemical or biological vector control. Overall, sustainable disease management can be attained by combining crop rotation with some of the above practices. As a rule, non-chemical management conserves naturally occurring natural enemy communities, naturally regulating vector populations and can thus prevent disease outbreaks over time.

Tolerant or resistant varieties provide suitable means to manage MLND, with the chr3, 6 and 10 resistance loci conferring maize resistance to all tested potyviruses. Some inbred lines with potyvirus resistance loci also provide tolerance to MLND under controlled conditions. Recently, many pre-commercial, commercial maize, and inbred lines have been screened by researchers and organizations in Hawaii, Kenya or the United Republic of Tanzania. Some tropical lines were screened with moderate tolerance to MLND by inoculation of MCMV and SCMV. Following a screening of 152 landraces and 33 inbred lines of Tanzanian maize, five MLND-tolerant candidates were selected for further testing to explore their use in resistance breeding. The 65 maize genotypes obtained from the Kenya Agricultural and Livestock Research Organization (KALRO), International Maize and Wheat Improvement Center (CIMMYT), and others were selected to test the reaction to MLND. This validated the presence of MLND tolerance in MLN013 (CKDHL120312) and MLN001 (CKDHL120918). The genetic marker associated with symptom development was identified and the quantitative trait loci were transferred into susceptible maize populations to validate the resistance and the maize F1 plants derived from crosses indicated the ability to improve MLND tolerance. Complete immunity, however, has not been observed. To date, good progress has been made in the development of MLND-tolerant maize hybrids. By increasing research on MLND-resistant maize hybrids, one possibly can attain long-term, sustainable control of MLND.





6. Potato late blight

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6.1 Summary for policymakers

- ▶ Potato late blight (PLB) is the world's most devastating disease of potatoes, causing up to USD 10 billion annually in yield loss and management expenditure.
- ▶ Current disease management relies upon repeated fungicide spray applications and generates major socioeconomic and environmental impacts.
- ▶ Decision support systems, active disease prevention and regular monitoring of pathogen strains can help to scale down and rationalize pesticide use.
- ▶ Novel breeding strategies such as marker-assisted selection and genome editing can generate durable varietal resistance.
- ▶ Increased R&D investment in emerging technologies such as phytochemicals or microbial control could revolutionize PLB management.

6.2 Take-home messages for practitioners

- ▶ Sound agronomy practices such as proper tillage, field sanitation, crop rotation, plant nutrition, weeding, and irrigation is pivotal to prevent potato late blight.
- ▶ Selection of disease-free potato seed tubers is a first, important step in preventing PLB epidemics.
- ▶ Decision support tools help growers to assess the exact timing and application frequency of chemical and/or biological fungicides based upon environmental conditions.
- ▶ Once locally validated and properly refined, beneficial microbes and phytochemicals can provide pesticide-free control of PLB.
- ▶ To manage PLB in a sustainable and environmentally sound manner, various non-chemical strategies should be consciously integrated.

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6.3 Introduction

Potato late blight (PLB) is a devastating disease worldwide, caused by the oomycete *Phytophthora infestans*, that caused the Irish potato famine in 1845–1852. Originating in either Mexico or South America, PLB now affects virtually all major potato-producing countries including Canada, China, India, and the United States of America. As the most important biotic constraint to the world's potato sector, PLB poses a major threat to global food security.

In the field, symptoms of PLB infection typically first emerge as dark grey to brown water-soaked spots on leaf tissues, surrounded by white mould-like growth around the perimeter. Under high humidity (over 90 percent) and low temperatures (10° C to 23° C), the infection rapidly spreads within and between plants through systematic filamentous growth and spread of infectious asexual sporangia through air and water splash. This could lead to infection and necrosis of all plants in an entire field within five to ten days. Underground tubers can become infected through systematic spread of the infection and through washing off of conidia-containing sporangia. Infection of tubers is usually initiated at physically weak spots such as the eyes, lenticels, and existing wounds. The filamentous growth of the pathogen within the tuber leads to colour change, and is often compounded with secondary infection by soft rot bacteria, rendering the tuber rotten and unfit for human and livestock consumption.

Over the past decades, growers and researchers have made impressive strides in implementing successful local epidemic forecasting systems and guided chemical pesticide management regimes for efficient PLB control in the field. Meanwhile, molecular and genomic research have improved our understanding of the pathogenic interaction between *P. infestans* and host plants, shedding light on the development of next-generation, environmental-friendly management strategies for PLB. Integrated pest management (IPM) or integrated disease management (IDM) draw on multiple preventative and curative practices to balance the immediate effectiveness and long-term environmental and ecological costs of pest control. This approach represents a more sustainable option compared to traditional regimes that emphasize responsive, pesticide-dependent control.

6.4 Classification, pathobiology and ecology

As a hemibiotrophic pathogen; that is, those that establish within the plant tissue while keeping the host alive, *P. infestans* initiates its infection as a biotroph, deriving essential nutrients from living host cells. Specialized invasion organs such as ex planta appressoria and penetration pegs are formed at the tips of germinating zoospore cysts to pierce through physical barriers at plant surface. Infection vesicles will form within the initially penetrated plant epidermal cell, and support subsequent filamentous hyphae growth within plant tissue intercellularly. As the hyphae expand, digit-like haustoria form to invade host cells along the way, residing between the cell walls and plasma membranes of plant cells for nutrient uptake. Established biotrophic infection of *P. infestans* supports the pathogen's shift towards a necrotrophic lifestyle, obtaining nutrients from dead plant tissues, and later development of reproductive sporangiophores and sporangia on the abaxial leaf surface.

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At each stage of the *P. infestans* infection, host plants are known to mount an array of defence responses and the molecular interplay between host defence and *P. infestans* pathogenesis mechanisms at various fronts play a determining role in the eventual outcome of either disease or no disease. On the plant epidermis, the physical pressure exerted by the penetration peg, as well as recognition of apoplastic pathogen elicitor molecules by receptors on the plant cell membrane, could induce active microfilament rearrangement, localized callose deposition, and activation of reactive oxygen species-, salicylic acid-, and ethylene-mediated signaling pathways, which regulate the production of antimicrobial small molecules and proteins. Within plant tissues, plant-produced peptidases and proteases are secreted into the apoplast to inhibit intercellular growth of *P. infestans* hyphae. Ultimately, specific recognition of *P. infestans* pathogenesis molecules within plant cells by intracellular nucleotide-binding domain and leucine-rich repeat domain-containing receptors (NLRs), encoded by plant resistance (*R*) genes, could lead to localized programmed cell death. This would restrict further expansion of the pathogen at its early biotrophic phase, a process well known as the plant hypersensitive response (HR).

Despite diverse host defence mechanisms, a large number of pathogenesis-related molecules are produced and secreted by *P. infestans* to overcome host defence and facilitate successful invasion. These so-called effector molecules could function either within or outside of host plant cells, participating in diverse physiological processes such as nutrient uptake, plant cell wall degradation, and host defence signaling interference. Interestingly, genes encoding such effector molecules tend to reside on the repeat-rich regions of *P. infestans* genome, which demonstrate higher rate of evolution, suggesting that the rich arsenal of effectors of this pathogen may be a result of its enhanced genome plasticity. Indeed, the rapid emergence of novel *P. infestans* pathogenic strains (or races) has been a major challenge in producing crop cultivars with durable genetic resistance against PLB.

6.5 Impact

Globally, PLB-related productivity loss and management costs amount to between USD 3 billion to USD 10 billion per annum. In developing countries where efficient chemical control is often too costly, PLB routinely leads to over 60 percent yield loss. In these areas, insufficient control for PLB and other crop diseases leads to potato productivity levels four-fold lower than in developed countries. In some potato-producing areas, eight to 20 different spray applications are used per season and the associated pesticide costs often account for 10 to 25 percent of the local market value of the potato crop. As such, conventional, pesticide-centered potato disease management carries huge socioeconomic and environmental costs.

6.6 Integrated disease management (IDM)

Agronomic practices. Successful PLB management starts with careful agronomic management that revolves around two main principles: avoiding excessive moisture in the environment, and reducing the initial inoculum load around the field. For the first principle, tilling and other practices that improve soil aeration and drainage are recommended to reduce soil moisture. In potato fields bordered

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by trees and dense vegetation, disease outbreaks can be exacerbated. Excessive irrigation is strongly discouraged, and should be carefully managed to minimize the duration of leaf wetness. This entails avoiding irrigation in the late evening and, where possible, prioritizing drip irrigation over sprinkler irrigation. Proper spacing between plants and hillling also reduce shading and potential contact of infectious *P. infestans* sporangia with the tubers. Reduction of infectious *P. infestans* spores and sporangia in the environment that may serve as the initial inoculum is also key to alleviate PLB prevalence. Selection of disease-free seed tubers is the first step in eliminating a source of PLB inoculum. Cutting and wounding of seed tubers is also discouraged, and should be supplemented by pesticide treatment if the physical damage is unavoidable. In some growing areas, cull piles and volunteer plants from previous growing seasons constitute the primary source of the initial inoculum, as the pathogen can only overwinter on living plant tissues. Crop rotation schemes, i.e. rotation with non-host crops, should be established over three to four year time frames, given that oospores can survive in soils for more than two years and serve as source of primary inoculum triggering early epidemics. Similarly, control of solanaceous weeds can help to reduce the inoculum load. Fertilization should be balanced, avoiding excess nitrogen as this increases canopy growth and cover, delays maturity and enhances foliage exposure to infection. As infections of *P. infestans* are typically initiated on aerial organs by airborne spores and sporangia, elimination of above-ground tissues through either chemical desiccation or physical defoliation is also recommended prior to tuber harvest. Crop diversification can also bring relief; experimental work in Ethiopia, the Kingdom of the Netherlands or Germany shows that PLB disease development is markedly reduced and tuber yield is often, though not consistently increased by intercropping potato with onions, garlic, cereals or grass-clover mixtures. Besides, an increase in crop genetic diversity through varietal mixtures can enhance potato yield, reduce PLB incidence and drastically lower the likelihood of fungicide resistance development.

Chemical control. In many parts of the globe, fungicidal spray applications constitute the mainstay of PLB management but its efficacy is remarkably suboptimal. For example, 36 different fungicides and fungicidal mixtures are registered in Europe for PLB control. While up to 16 spray applications are made per season in highly technified European potato systems, late blight still reduces yields by 15 percent. Based upon their mode of action, there are three types of pesticides for PLB control. Protectants are capable of preventing *P. infestans* infection by interfering with spore germination and/or initial penetration of plant surface processes; these products thus need to be present in or on plant tissues prior to the arrival and germination of *P. infestans* spores. Curative pesticides can stop the filamentous growth of *P. infestans* hyphae even after its initial penetration and localized colonization of plant tissues. Finally, anti-sporulants are applied to reduce formation of reproductive sporangiophores and sporangia. Alternatively, these pesticides can also be categorized based upon their site of action. Contact pesticides remain on the surface of plant tissues after application, and are therefore prone to run-off by wind and rain. Translaminar pesticides can be absorbed by plants and are retained within locally treated tissues, whereas systemic pesticides are transported throughout plants after the initial application and absorption.

Due to over-reliance on chemical fungicides and high pesticide usage intensity, several resistant *P. infestans* strains have emerged and chemical control is

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becoming increasingly complicated and untenable. Furthermore, the economic, health and environmental risks associated with fungicide-centered control have become increasingly apparent. In many regions, the rapid emergence of resistant strains has already resulted in a so-called "pesticide treadmill" that demands ever higher dosage and frequency of pesticide application. Given the above, alternative, non-chemical approaches are to be consciously prioritized. Equally, when and where deemed essential, fungicidal spray applications need to be carefully planned based upon local crop status and disease dynamics, and active ingredients must be rotated. Semi-quantitative scoring systems can be used to evaluate the efficacy of pesticide treatment regimens across diverse environmental spectra.

Decision support tools. Accurate prediction of the onset of potential epidemics holds the key to guide preventative pesticide treatment and hence, maximize the efficiency of chemical control of PLB. Since the 1940s, early observational studies of PLB outbreaks have unveiled the causal relationship between conducive environments and subsequent epidemic onsets. These associations have given birth to the most primitive forms of PLB forecasting models, such as the 90 percent humidity criteria. Through decades of development, there are more than dozens of PLB-forecasting decision support systems (DSS) that are often organized regionally to predict and monitor PLB epidemics on a near-continental scale. Current DSS integrates multidimensional environmental attributes collected through on-site sensors to quantitatively assess the probability of PLB onset, and calculates the residual efficiency of pesticides by considering the time and environmental conditions since the previous application. In addition to environmental data, quantitative detection methods of *P. infestans* from field-collected samples have evolved from simple polymerase chain reaction protocols, to more sophisticated techniques such as loop-mediated isothermal amplification, and recombinase polymerase amplification assays. Advancements in computer technology, artificial intelligence (AI) and smartphone penetration have paved the way for phone-assisted disease diagnosis. Handheld volatile organic compound (VOC) fingerprinting platforms now allow for a non-invasive diagnosis of PLB. Besides, volatile detection through electronic nose (E-nose) approaches is increasingly used in the early and non-destructive detection of diseases. Furthermore, since most current resistant potato cultivars were bred by stacking major effect resistance (*R*) genes, the probability of successful genetic resistance against PLB can be estimated by knowing the *R* genes present in the crop and the corresponding avirulence (Avr) genes present in the local *P. infestans* population. Incorporation of these data into sophisticated predictive models have drastically improved the efficiency of chemical control of PLB, as well as promoting the durability of crop genetic resistance, further underscoring the value of an integrated disease management strategy.

Host plant resistance. Since the 1840s Irish potato famine, growers and breeders have engaged in producing genetically-resistant potato cultivars. Genetic resistance against PLB can either be race-specific, such as vertical resistance; or race non-specific, such as horizontal resistance. These two classes of resistance are each associated with distinct modes of action. The specificity of race-specific resistance typically arises from the one-on-one recognition of particular pathogen effectors by host NLRs, which triggers hypersensitive response (HR) to restrict initial *P. infestans* infection. Hence, the genes that convey race-specific resistance are exclusively *R* genes. Although numerous potato *R* genes that have mediated

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disease resistance have been broken down by epidemic strains, long-term field observation suggest several genes, including *RB*, *Rpi-vnt1*, *Rpi-Smira2* (*R8*), and *Rpi-blb2*, confer relatively broad-spectrum resistance to most of the *P. infestans* strains, by recognizing *ipiO1*, *Avrvnt1*, *Avr8* and *Avrb1b2* effector genes or their gene-family members. In contrast, race non-specific resistance involves complex genetic architecture and diverse molecular mechanisms, ranging from signaling components of plant defence response to metabolic and regulatory genes of antimicrobial molecules. Yet, perhaps the best examples of non-*R* gene-mediated PLB resistance are mostly reported in non-host plant species of *P. infestans*, such as *Arabidopsis thaliana*, *Nicotiana benthamiana*, and *Capsicum annuum*, which are impossible to introduce into the cultivated potato germplasm through traditional breeding methods. Therefore, from a practical perspective, *R* genes-mediated PLB resistance remains the most useful genetic resource for potato germplasm enhancement; though it would be quickly rendered ineffective under field conditions as novel *P. infestans* races emerge. Nevertheless, genetic stacking of multiple *R* genes provides more effective and durable protection against PLB.

Traditionally, *R* genes have been identified through genetic mapping with populations derived from crosses between cultivated potatoes, their wild relatives. As such, more than a dozen of *R* genes have been cloned from various wild potato species. Advances in sequencing technologies and genomics have accelerated the process of *R* gene discovery across a wide phylogenetic range. Resistance-gene enrichment with custom-designed biotin probes, followed by short read sequencing (RenSeq), allowed for the specific detection of *R* genes. The combination of RenSeq with third generation single-molecule real-time (SMRT) sequencing further enabled direct recovery of full-length *R* genes from species without a reference genome. This technology has been recently applied for genome-wide curation of *R* genes across 18 *Solanum* species and diverse *A. thaliana* accessions. As the third-generation sequencing technologies become more accessible, *R* gene discovery and functional association with resistance phenotype against specific *P. infestans* race may quickly become a routine practice.

Unlike *R* genes-mediated resistance studies, genetic dissection of race non-specific resistance is challenging due to its complex genetic architecture and relatively small effect size. Therefore, it is perhaps not surprising that current examples of race non-specific resistance-related genes are typically characterized through a reverse genetic approach. In these studies, transient or stable genetic knockout mutants of the target genes were usually tested and demonstrated increased susceptibility. Yet, as most of the genes tested were parts of conserved signaling and metabolic pathways, genetic perturbation at these targets likely would have complex pleotropic effects that extend beyond the target resistance phenotype. Furthermore, there is little guarantee that overexpressing a gene that lowered resistance when knocked down (or out) would result in enhanced resistance. Thus, research on race non-specific resistance of *P. infestans* still finds itself in its infancy.

Another major bottleneck in the genetic enhancement of *P. infestans* resistance or any trait at all, is the slow process of tetraploid potato breeding. Unlike diploid crop species, where a desirable trait/allele can be directly introgressed into an elite cultivar, attempts to introduce exogenous genes into tetraploid potatoes are hampered by high levels of heterozygosity, insufficient target gene copy numbers, and self-incompatibility. Furthermore, though accumulating effective *R* genes are

being discovered in wild potato species, few of such species can be successfully crossed with the cultivated species to produce viable offspring, and thus, obstruct introgression of these genes into the cultivated germplasm through traditional breeding. Though transgenic approaches can possibly resolve the issue, this approach is constrained by public and political attitudes in many countries.

Emerging technologies. Various PLB management innovations have been developed and tested, posing potential game-changers for sustainable disease management. Multiple commercially available phytochemicals, such as eugenol, matrine, carvacrol and zeylenone have been tested as environmental-friendly biopesticides. For example, application of 0.3 percent eugenol provides comparable, if not superior, levels of protection of the potato crop as compared to mainstream fungicides such as mancozeb, and results in higher yield. Eugenol inhibits *in vitro* growth of *P. infestans* grown on oatmeal agar ($IC_{50} = 63.9 \text{ mg L}^{-1}$), and this effect can be further enhanced by delivery with nano-material carriers. Zeylenone, which is isolated from the vine *Uvaria grandiflora*, affects energy metabolism of *Phytophthora* spp. and could be developed as a botanical fungicide.

Microbial control of *P. infestans* carries lots of promise and can readily complement the current management toolkit, yet this potential is, surprisingly, largely unexploited. For example, a *Trichoderma* strain HNA14 over-competes with *P. infestans* growth *in vitro*, inhibits *P. infestans* growth through mycoparasitism and production of toxic metabolites, and greatly reduces PLB disease incidence in the field. The bacterium *Myxococcus fulvus* B25-I-3 exhibits antagonistic activity against *P. infestans* and inhibits its asexual and sexual reproduction. Equally, by combining different potato-associated *Pseudomonas* spp., biological control of *P. infestans* can be greatly improved. In addition to direct inhibitory effect on *P. infestans*, some microbial agents also trigger plants' defence response and systemically induce resistance. Further, the use of microbial derivatives and metabolites waits to be furthered as an eco-friendly management approach for PLB. Also, functional assemblies of synthetic microbial consortia likely demonstrate superior biological control performance than single microbe strains, and this potential needs to be fully explored.

RNA interference (RNAi) is another novel technology that has recently been added to the PLB management toolbox. Originally discovered as a part of plant antiviral defence mechanism, RNAi is now believed to play an important role across diverse environmental adaptation processes in plants, including defence against filamentous pathogens. Some *Phytophthora* effectors can inhibit the RNA-silencing pathway in plants. Host-induced gene silencing in *P. infestans* by potato was first demonstrated in 2015, suggesting that required molecular machinery for cross kingdom RNAi is present in the potato-*Phytophthora* pathosystem. The more recent discovery of a *P. capsici* (a related *Phytophthora* species) effector that suppresses the plant cross kingdom RNAi mechanism further suggests that bi-directional, small RNA trafficking and functionality probably presents yet another battleground between *Phytophthora* pathogens and their host plants. In particular, double-stranded RNA-based formulations are effective against late blight and their efficacy can be further enhanced through improved delivery systems. This technology poses a valuable alternative to transgenics and synthetic fungicides.



7. Rice brown planthopper

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7.1 Summary for policymakers

- ▶ In Asia's rice-cropping areas, brown planthopper (BPH) poses a significant threat to food and nutrition security, and farmer livelihoods.
- ▶ Fast-emerging BPH problems can be primarily ascribed to improper pesticide applications together with excessive fertilizer use.
- ▶ BPH populations rapidly acquire resistance to single-factor solutions such as new insecticidal compounds and varietal resistance.
- ▶ Good agronomic practice can improve the resilience of rice ecosystems and resolve BPH issues, but these messages often do not reach rice growers or are regularly diluted by agrochemical suppliers.
- ▶ Naturally-occurring biological control agents defuse BPH problems at zero cost to farmers; their conservation is key to sustainable pest management.
- ▶ Amended policies could discourage insecticide-based control, amend plant nutrition and generate forward momentum for nature-based solutions.

7.2 Take-home messages for practitioners

- ▶ BPH population outbreaks are symptomatic of poor crop management, as typified by an overuse of agrochemical inputs and lack of organic manuring.
- ▶ As BPH populations rapidly adapt to varietal resistance, continuous efforts are required to breed less-susceptible rice clones and integrate them with non-chemical measures.
- ▶ Good agronomy – for example, organic matter amendments, irrigation, planting time, sowing density and crop diversification – can lower BPH infestation pressure.
- ▶ Refraining from insecticide use in the first 40 days allows resident natural enemy populations to build up and slows pest population build-up.
- ▶ Participatory, on-farm trials can showcase the beneficial impacts of biological control on multiple rice pests and diseases.

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7.3 Introduction

Rice allegedly feeds more than half the world's population, though its sustainable production has been recurrently threatened by outbreaks of the brown planthopper (BPH), *Nilaparvata lugens* (Stål) (Hemiptera: Delphacidae). BPH damages rice plants directly by sucking phloem sap and indirectly by transmitting rice grassy stunt virus (RGSV) and rice ragged stunt virus (RRSV). Feeding by BPH often leads to plant wilting and subsequent death, known as hopperburn. Before the 1970s, BPH was a secondary rice insect pest; thereafter, the pest status of BPH increased steadily due to the adoption of high-yield rice varieties, condensed planting, excessive nitrogen application, insecticide spraying in early season and development of insecticide-resistant populations. During the 1980s to 1990s, drastic reductions in pesticide use under FAO-led Farmer Field School (FFS) programmes and country-level pesticide bans substantially lowered BPH infestation levels. However, over the past two decades, BPH has once again become one of the most limiting rice pests and attained outbreak levels in China, India, Indonesia, Malaysia, the Philippines, Thailand and Viet Nam.

7.4 Biology and ecology

The planthopper has three life stages: egg, nymph, and adult. Adults have two distinct wing morphs: macropterous (long-winged, see [Figure 7.1](#) on p. 63) and brachypterous (short-winged, see [Figure 7.1](#) on p. 63) forms. In the macropterous form, females measure 4.2 mm to 4.8 mm; and males measure 3.6 mm to 4.2 mm in length. The corresponding figures for the brachypterous form are 2.8 mm to 3.2 mm, and 2.4 mm to 2.8 mm, respectively. In macropterous BPH, wings extend over the posterior end of the abdomen, while for brachypterous BPH, the forewings and hind wings are shorter than the sixth or first abdominal segment, respectively. Irrespective of wing forms, the wings are transparent, with a black apex of the claval area; the body is yellowish-brown or brown to dark brown. BPH females deposit groups of banana-shaped eggs (1.00 mm by 0.20 mm), also called an 'egg-strip', into the sheaths or midribs of leaves (see [Figure 7.2](#) on p. 63). The newly laid egg is white and then becomes yellowish, with an obvious red point at one end before hatching (see [Figure 7.2](#) on p. 63). The planthopper has five nymphal stadia, which are distinguished by the shape of the mesonotum and metanotum, wing-pad development, arrangement of the spins on the hind leg, the numbers of antennal sensilla, and body size (see [Figure 7.3](#) on p. 63). At 20 °C to 30 °C, development from the first to fifth instar can take approximately 12 to 24 days.

The two wing morphs of BPH are characterized by varying bionomics. The long-winged morphs are potential migrants and adapted for colonizing new habitats, while the short-winged ones are sedentary and adapted for breeding in a suitable habitat. During early growth stages, the colonizers are always long-winged. Low nymphal density, plentiful food supply, and optimal temperatures favour the development of short-winged morphs. Wing-form formation is regulated by the juvenile hormone gene. Female adults usually mate at three days after emergence and start to oviposit on the day following mating. Brachypterous females lay up to 350 eggs, while macropterous females generally lay fewer eggs. Eggs hatch in seven to 11 days at between 20 °C and 30 °C. The nymphal period is about ten to 18 days in the tropics, depending on the food conditions, density, and temperature.

The nymphs, like the adults, usually stay on the lower parts of rice plants, feeding on plant sap. However, when the population numbers are extremely high, the nymphs and adults are observed to swarm even on flag leaves. The BPH nymphs and short-winged morphs disperse in the fields by walking and hopping, while long-winged ones disperse by flying. Through windborne migration, long-winged individuals colonize the summer rice-growing areas in subtropical and temperate regions. Their flight is greatly influenced by age, sex, and environmental conditions.

Diurnal flight activity BPH has a unimodal crepuscular pattern in the tropics, but a bimodal crepuscular curve in the subtropical and temperate zones. BPH individuals are thereby transported by prevailing monsoon winds from their permanent breeding grounds in the tropics.

The number of BPH generations depends largely on local temperatures and the presence of susceptible rice plants. In the tropical lowlands, BPH can have as many as eight generations, while in southern Japan and central China, there are five generations during one rice cropping season. In contrast, on modern, high-yielding intermediate maturity varieties in the tropics, there are only three generations during one cropping season. In subtropical and temperate regions, seasonal prevalence and BPH outbreaks depend on the timing and frequency of immigrations, rice-cropping patterns, and local temperatures. Early and frequent immigration can contribute to BPH population increases and even outbreaks in the late season. Rice availability, especially rice-cropping patterns, such as one or two seasons and timing of rice, can drastically shape the population dynamics in a region. Temperature is critical for egg hatching, development, survival, mate location, and population growth in BPH. Insecticide overuse is a major driver of BPH population resurgence; for example, by tuning down the rice plant's natural defences and by degrading natural pest regulation. Increased fertilizer use can also contribute to BPH population growth by favouring pest development. In addition, continuous irrigation favours BPH outbreaks. Generally, the pest occurs more heavily in wetland paddy rice fields than in upland rice fields, and in direct-sown fields than in transplanted fields.

7.5 Host plants

While BPH is generally viewed as a monophagous herbivore on cultivated rice (*Oryza sativa*), it equally affects several wild rice species and other grasses. A host plant of an herbivorous insect should be able to attract oviposition under natural conditions, and sustain subsequent development of its eggs into larvae, pupae, and fertile adults.

7.6 Geographical distribution

Though BPH develops year-round in the tropics, it is unable to overwinter in subtropical and temperate regions and its local occurrence thus depends on immigration from the tropics. With climate change, its overwintering boundary is gradually shifting northward. The planthopper occurs widely in south, Southeast and east Asia, the South Pacific islands, and Australia. This includes: parts of Australia, Bangladesh, Brunei Darussalam, Cambodia, parts of China, Democratic People's

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Republic of Korea, Federated States of Micronesia (including Yap Island), Fiji, Guam, India, Indonesia, Japan, the Lao People's Democratic Republic, Malaysia, Myanmar, Nepal, New Caledonia, the Northern Mariana Islands, Pakistan, Palau, Papua New Guinea, the Philippines, the Republic of Korea, Singapore, Solomon Islands, Sri Lanka, Thailand, Timor-Leste, and Viet Nam.

7.7 Crop damage and economic impact

The brown planthopper infests rice crops at all stages of plant growth. The symptoms of damage depend on the time of attack in relation to plant growth, intensity of injury (which is related to BPH population density), duration of infestation, and environmental factors affecting both insect bionomics and plant growth. As a serious insect pest of rice, BPH can cause 10 to 20 percent yield losses during moderate infestation, and 40 to 60 percent yield losses or even total crop loss, during severe infestations. Both nymphs and adults can cause damage in at least three ways: First, through direct removal of nutrients through extensive feeding. Insect feeding thus reduces the net photosynthate available to the plant for sustenance and storage, leading to leaf chlorosis and yellowing and plant drying – hopperburn (see [Figure 7.4](#) on p. 64). In addition to direct yield loss, grain quality is also compromised with a high percentage of dead, immature, and broken grains in infested plants. Secondly, through the transmission of rice viruses. RRSV and RGSV are transmitted by BPH. The viral diseases caused by RRSV and RGSV occur sporadically but catastrophically, especially in tropical Asia. The diseases can occasionally result in substantial rice-yield losses, such as the loss of 828 000 tonnes of rice valued at USD 120 million during 2005 to 2006 in southern Viet Nam. Third, through exposure to disease infection. BPH feeding and oviposition expose the plants to infections via fungal and bacterial diseases, such as rice sheath blight and sclerotial disease of rice. BPH-produced honeydew is often covered with sooty mould, with adverse impacts on plant physiology, crop yield, disease susceptibility and incidence of lodging.

7.8 Integrated pest management (IPM)

Although the optimum make-up of integrated pest management (IPM) programmes can be context-dependent, its core components are the same ([Figure 7.5](#) on p.65). IPM always involves detection and inspection, which allows farmers to compare BPH infestation pressure with locally appropriate spray thresholds or decision rules, and to thus define interventions that are economically justified. Prophylactic measures such as insecticidal seed treatment violate the core principles of IPM; also, as unguided 'blanket' treatments their use is often not warranted and economically sound. When opting to take curative interventions, the various options have to be carefully weighed in terms of practicality, effectiveness and human and environmental safety. As per the IPM definition, non-chemical crop protection solutions such as sound agronomy, agroecological measures and biological control constitute the 'first line of defence' while chemical insecticides are to be treated as a "measure of last resort". Utmost care must be taken to ensure the compatibility of different management options, for example by picking chemical insecticides that do not kill naturally occurring or released natural enemies.

Detection and inspection

Accurate diagnostics, timely detection and thorough inspection are key ingredients of any early-warning system. There are several ways to detect the presence of BPH in the field. At the plant base, cotton-white to brown nymphs and brown winged and wingless adults may be found, or honeydew and sooty mould found that often accompany large number of insects. At the leaf sheath or midrib parts that are showing brown steaks, dissection and ten-times magnification will show banana-shaped white eggs covered with a dome-shaped egg plug. Furthermore, by observing the fields, hopperburn or yellowing, browning, and drying of plants, or plants with ragged stunt or grassy stunt diseases may all be found. BPH populations can be monitored by visually inspecting the seedbed on a daily basis or visiting standing rice crops on a weekly basis, carefully observing plant stems and the water surface.

For older rice plants, it is recommended to slightly bend the rice stem and to gently tap it near the base, recording the number of planthoppers that fall onto the water surface. Apart from field scouting, light traps are often used to monitor infestations, population dynamics or immigration. Routine revision of these traps can help to assess BPH population size and seasonal dynamics. When daily trap-captures reach hundreds of BPH individuals, fields should be scouted daily for damaging BPH populations and corrective action can be taken. Abrupt increases in light trap catches are indicative of immigration (in subtropical and temperature settings), while the indicative value of these traps is low in areas where BPH occurs year-round.

Economic injury level

The economic injury level (EIL) is defined as the lowest BPH population density that inflicts economically important damage. It associates field-level pest populations, pest-induced crop damage, and crop damage with economic loss, and is a sound basis for curative action such as biopesticide spray applications. Although EIL has been established for many pests and is much used in surveillance and alert systems, its usefulness needs to be locally validated due to: spatial and temporal variations in rice price and management cost; strength and stability of natural biological control; and susceptibility of local crop cultivars. When revising published EILs for BPH, they vary substantially between geographies and crop phenological stages. Thus, EILs should be finetuned to local farming contexts.

Prevention and control

Agroecological preventative measures constitute effective, economically sound and nature-friendly approaches to manage BPH. Indeed, 'smart farming' through sound agronomy, crop sanitation, and biological control can consistently prevent BPH outbreaks and avert crop losses. As many of these measures are well-calibrated and properly validated for Asian rice production systems, they are to be the mainstay of any IPM programme. As an added plus, many of these pest prevention strategies are low-cost, safe and entirely practicable. Yet, quite surprisingly, their actual in-field implementation is lagging and they routinely make way for pesticide-intensive approaches.



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Cultural practices. Cultural practices can be classified as primary practices (directly targeting insect pests) and secondary practices (with secondary effects on insect pests), the former including plant resistance and the latter including fertilizer and water management. Host plant resistance remains the most economically viable and environmentally friendly option. More than 40 BPH resistance genes have been identified and various resistant rice varieties have been developed for instance at national programmes in China or Japan and at the International Rice Research Institute (IRRI). However, most of these genes do not provide broad resistance against BPH populations. Meanwhile, BPH populations have rapidly adapted to the resistant varieties (especially for BPH1 and BPH2) and their effectiveness is thus, highly variable spatially and temporally. To complicate matters further, there is a major lag in the deployment of varietal resistance. Given the above, routine screening and the deliberate avoidance of highly susceptible varieties is highly effective and may even outperform resistance breeding. Durable control can be attained by rotating or using field mixtures of resistance genes, gene pyramiding could rapidly deplete the availability of effective resistance genes. It is important to understand the gene function and resistance mechanisms and to explore the mechanisms of pest adaptation to resistant rice varieties. Patterns of BPH virulence against resistance genes also need to be understood. Cutting-edge genomics tools, such as marker-assisted gene pyramiding, are expected to accelerate the breeding of BPH resistance cultivars.

Fertilizer and water management can affect BPH by modifying the rice plant's suitability and attractiveness. Nitrogen fertilization affects plants' stress response by altering the titers of several amino acids such as asparagine. In moderately resistant rice lines, high nitrogen levels can lead to higher tolerance, lower crop damage and often (though not always) do not significantly affect BPH population densities. The application of nitrogen fertilizer is, therefore, preferably split into three stages: at tillering, booting, and heading. On the other hand, the application of animal manure consistently leads to low nitrogen and asparagine content in fertilized plants and indirectly augments biological control by favouring decomposer or detritivore populations – ultimately leading to lowered BPH densities. Silicon amendment can also enhance rice resistance to BPH. As BPH prefers irrigated lowland to upland rice, standing water favours BPH multiplication. Lastly, proper crop spacing and area-wide cropping patterns can decrease BPH population buildup. By avoiding staggered planting, synchronizing planting and harvesting, and rotating rice with other crops, the BPH life cycle can be broken and its region-wide population levels lowered. Yet, in order to be effective, all the above measures need to be tactically integrated and implemented at a community or regional scale.

Biological control. Rice ecosystems harbour an exceptionally rich community of natural enemies that naturally control BPH at zero cost to farmers. Nearly 100 different species of parasitoids, invertebrate predators and entomopathogens (or so-called natural enemies) have been recorded in Asian rice fields. Spiders, the mirid bug *Cyrtorhinus lividipennis* Reuter and rove beetle *Paederus fuscipes* Curtis are among the dominant predators in subtropical paddy fields, while mymarid egg parasitoids and dryinid nymphal parasitoids are also prominent BPH natural enemies. In Thailand, the wrinkle-lipped bat (*Tadarida plicata* Buchanan) annually prevents 2 900 tonnes of rice losses by feeding upon a related planthopper pest. All the above organisms, plus a diverse set of insectivorous frogs and birds, can be used in conservation and/or augmentation biological control schemes.

Conservation biocontrol capitalizes on the natural pest regulation provided by resident natural enemies. When these beneficial organisms occur at high abundance, the risk of hopperburn or crop loss is consistently low and insecticide use is unwarranted. In fields where natural enemies are less abundant or speciose, strategies can be implemented to enhance their population numbers. These involve measures to diversify rice ecosystems, organic manuring, a deliberate avoidance of early-season treatments and selective insecticidal compounds. As many insecticides affect a wide range of pest- and non-pest organisms, the use of more selective or narrow-spectrum insecticides can help to conserve BPH natural enemies. Also, early season applications of insecticides and insecticidal seed treatments disrupt the population growth of natural enemies and should thus be actively avoided. Most natural enemies do not solely attack BPH but also feed upon detritivores or decomposer organisms, and their abundance and (pest control) action can thus be raised through organic matter addition. Crop diversification poses another lever; for instance, by establishing flowering plants, such as sesame, or *Leersia sayanuka*, on rice bunds to provide pollen, extra-floral nectar or alternative hosts to resident natural enemies. In Thailand, Viet Nam and China, these diversification strategies can drastically curb insecticide use, raise grain yields and improve farm revenues. Some of these plants can generate a much-appreciated secondary source of food or income. Lastly, in rural Cambodia, rice growers erect leaf-thatched structures for resident bat populations and thereby enjoy bats' pest-control services (at no cost) and nutrient-rich excrements or guano.

Augmentative biological control relies upon the periodic release of laboratory-cultured invertebrate or microbial natural enemies. These releases can either be made at the onset of the cropping cycle or during times of rapid pest population growth. The predatory mirid bug, *C. lividipennis* can potentially be used for augmentative releases, as it preys upon BPH eggs and young nymphs and can easily be mass-reared in biofactories. However, given that *C. lividipennis* is often under bottom-up or 'donor control' and thus does not exhibit regulatory action on BPH populations, its potential is to be carefully scrutinized. Other parasitoid or predator species that act in early-season and/or at low BPH densities carry some value particularly when aiming to fortify the preventative action of resident natural enemies. Besides predatory insects, the entomopathogenic fungus *Metarhizium anisopliae* also affords substantial control alone or in combination with selective insecticides. Overall, as relatively few organisms are currently available for augmentative release and this mode of biological control is mainly geared towards resolving human-induced BPH outbreaks, it might be valuable to put added emphasis on pest prevention and natural enemy conservation instead. Some agents also act slowly, especially when compared with 'knock-down' insecticides, and their potential is underappreciated by many rice growers many of whom are also ill-informed of the identity and ecological role of insect natural enemies. At present, many rice farmers know less than a handful of large-bodied, diurnal predators, undervalue the contribution of biological control and, consequently, largely revert to insecticide-based approaches.

Chemical control. Under IPM, insecticides are treated as a 'measure of last resort'; that is, they should be used only after all other non-chemical or agroecological measures fail to keep BPH population levels below EILs. When BPH occurs at low densities or early in the rice growing season, insecticide use is not economically justified. The exact timing of insecticide application – for example, at the crop phenological stage, or under BPH infestation pressure – is thus guided by a dynamic economic threshold

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that is determined by rice price variability, natural-enemy populations, insecticide product and application cost, and rice variety. Local plant protection agencies can advise on the exact timing, necessity and economic rationale of insecticide application. When opting for insecticide-based control of BPH, application timing, compound selectivity and resistance development must be carefully considered. One key concern regarding unguided applications of broad-spectrum insecticides is that those often trigger BPH population resurgence by killing off resident natural enemies. Insecticides vary greatly in their selectivity against natural enemies, with compounds such as triazophos, carbaryl and deltamethrin being highly toxic to beneficial organisms. Early-season applications are not warranted, as these consistently weaken BPH biological control and cause pest resurgence. As a result, most BPH outbreaks can be directly ascribed to over-use and/or poor timing of insecticide sprays.

When devising sustainable BPH management schemes, the use of systemic insecticides is to be avoided. Sucking pests are often treated with compounds that target nicotinic acetylcholine receptors i.e. neonicotinoids and triflumezopyrim. While many of these systemic insecticides exhibit comparatively low toxicity to vertebrates, they pose a major threat to biodiversity and the broader farming environment. These products are readily taken up by plants, translocate to pollen, nectar or guttation fluid, and thereby negatively impact beneficial organisms such as pollinators and natural enemies. Especially when neonicotinoids are applied in a prophylactic fashion (for example, as seed coatings), they impact a range of non-target biota and lower the overall resilience of the farm ecosystem. This, in turn, can favour BPH population build-up and augment pest-induced losses. Another key concern with insecticide-based approaches is the rapid rise in BPH insecticide resistance which can lead to control failure and aggravate crop losses. At present, there are more than 450 cases of insecticide resistance in BPH covering multiple modes of action and including new compounds such as neonicotinoids. While some of these compounds still provide acceptable BPH control, they often negatively impact resident natural enemy communities. To slow resistance development or prevent pest issues, it is essential to rotate insecticides of different modes of action and, far more importantly, prioritize non-chemical measures such as biological control, biopesticides and cultural practices.

**Figure 7.1**

Adults of brown planthopper
Nilaparvata lugens

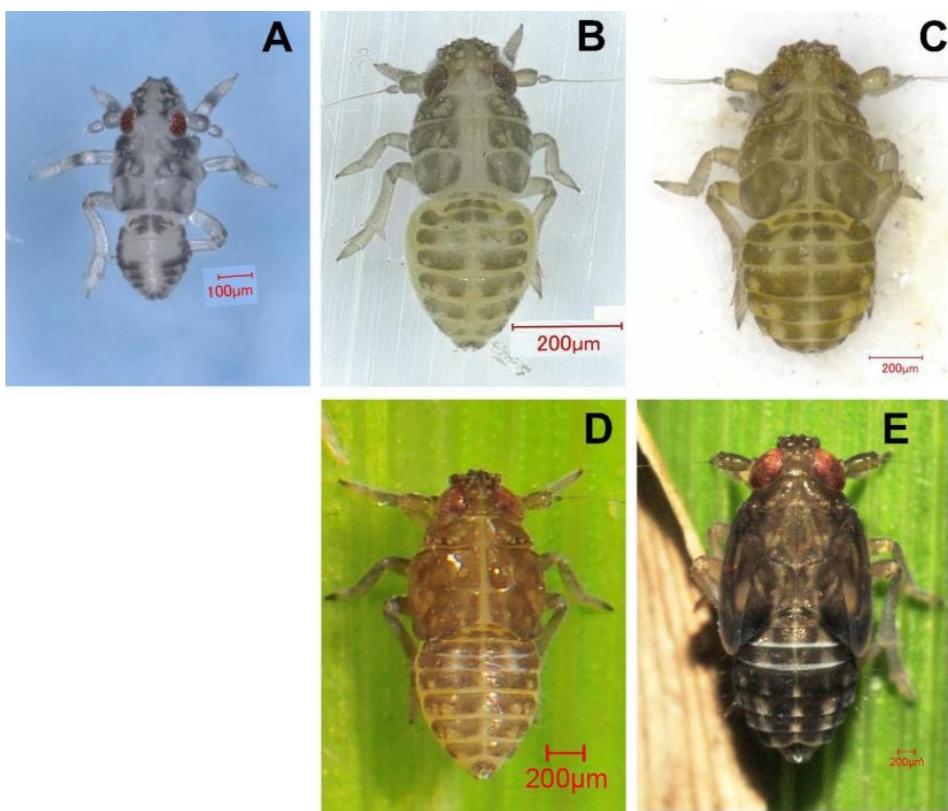
- A:** Macropterous (female)
- B:** Brachypterous (female)
- C:** Macropterous (male) –
- D:** Brachypterous (male)

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Lu, Z. X., Heong, K. L., Yu, X. P.
& Hu, C. 2004. Effects of plant
nitrogen on ecological fitness
of the brown planthopper,
Nilaparvata lugens in rice.
*Journal of Asia-Pacific
Entomology*, 7.



Banana-shaped eggs of brown
planthopper *Nilaparvata
lugens*

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**Figure 7.3**

The five nymphal stadia
of the brown planthopper
Nilaparvata lugens

- A:** First instar
- B:** Second instar
- C:** Third instar
- D:** Fourth instar
- E:** Fifth instar

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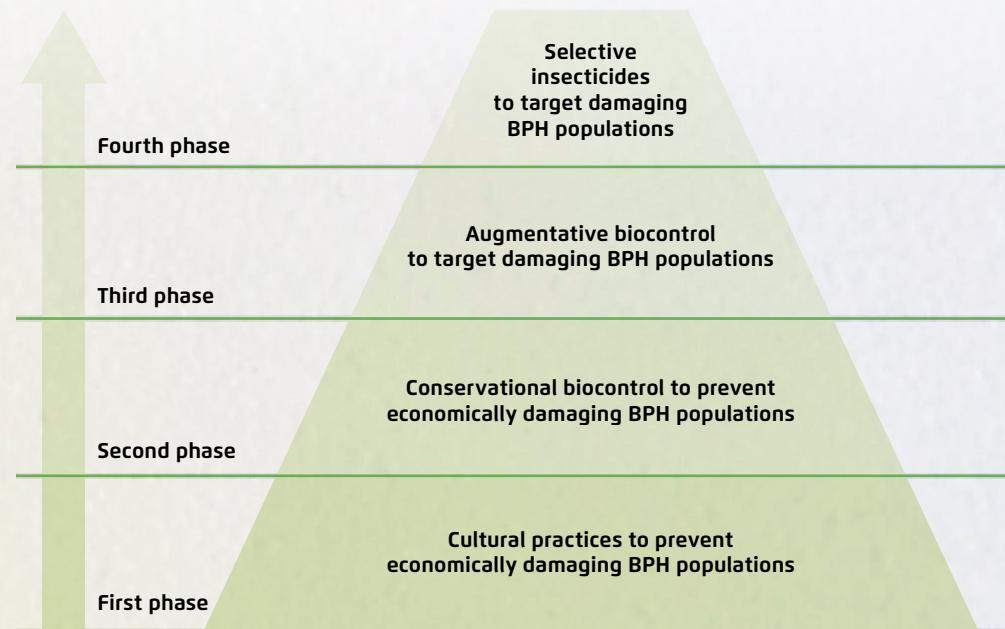
Figure 7.4

Hopperburn damage caused by brown planthopper *Nilaparvata lugens* (left) and BPH swarming on flag leaves (right)

**Figure 7.5**

Conceptual framework for IPM of BPH, colour intensity and width showing extent of priority and importance

Source: Adapted from Zehnder, G., Gurr, G. M., Kuehne, S., Wade, M. R., Wratten, S. D. & Wyss, E. 2006. Arthropod pest management in organic crops. *Annual Review of Entomology*, 52.







8. *Bemisia tabaci* whitefly

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8.1 Summary for policymakers

- ▶ Silverleaf whitefly (*Bemisia tabaci*) causes multi-billion-dollar losses in global agriculture through direct feeding damage, impacted photosynthesis and the vectoring of debilitating viral diseases.
- ▶ A sound understanding of whitefly-species identity is essential to tailor management interventions.
- ▶ Farmers need to be informed about the role of agroecological preventative strategies such as cultural control, sound agronomic practices, and physical control.
- ▶ Decision support tools such as monitoring aids and action thresholds enable growers to schedule and target biopesticide spray applications.
- ▶ Diversification tactics and pesticide avoidance improve pest control by resident natural enemies – often at zero cost to farmers.
- ▶ As *Bemisia tabaci* whitefly rapidly acquires insecticide resistance, efficacy of chemical control tends to be ephemeral.

8.2 Take-home messages for practitioners

- ▶ *Bemisia tabaci* whitefly is a species complex that affects more than 600 plant species, including multiple agricultural crops.
- ▶ Agronomic practices – for example, adequate planting times, sound water and fertilizer management, and sanitation – can prevent whitefly-related issues.
- ▶ In high-value crops, nylon screens, ultraviolet (UV)-absorbing nets, sticky traps, ‘dead end’ trap crops and reflective mulches can lower whitefly population levels.
- ▶ Arthropod and microbial natural enemies are commercially available and can be periodically released, for example, through banker plant systems.
- ▶ Diversified cropping systems lower whitefly pest pressure, slow virus spread and bolster natural biological control.
- ▶ To ensure the long-term efficacy of chemical control, selective, low-risk insecticides need to be used sparingly and consciously integrated with non-chemical measures.

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8.3 Introduction

Amongst more than 1000 whitefly species in the world, *Bemisia tabaci* (Gennadius) exhibits remarkable environmental adaptability, persistence and potential to inflict crop damage, particularly in tropical and subtropical regions. While *B. tabaci* is now recognized as a complex containing more than 35 cryptic species – i.e. morphologically indistinguishable species that are genetically diverse and reproductively isolated – many issues of the systematics and species nomenclature of the whitefly complex are yet to be resolved. Currently, the recognized cryptic species are tentatively named after their likely origins. The species complex contains some insect pests of worldwide importance, such as the Middle East-Asia Minor 1 (MEAM1), formerly known as the 'B biotype', and the Mediterranean (MED), formerly known as the 'Q biotype', and African cassava whiteflies such as the sub-Saharan Africa 1 (SSA1) and the sub-Saharan Africa 2 (SSA2). As shown below, the systematics and species recognition of the *B. tabaci* whitefly complex are not only an academic issue, but also a vital issue in the management of the whitefly pest. Substantial evidence is now available to show that cryptic species from the *B. tabaci* whitefly complex differ markedly in many aspects of biology, such as geographic distribution, range of host plants, capacity to develop insecticidal resistance, and ability to transmit different viruses.

8.4 Morphology and cycle

The life stages of *B. tabaci* include egg, four nymphal instars, and adult. Eggs are laid on the undersides of leaves, with the broad end touching the surface and the long axis perpendicular to the leaf (see **Figure 8.1** on p. 75). They are anchored by a pedicel that is inserted into a fine slit in the leaf surface. Eggs are whitish in colour when first laid (see **Figure 8.1** on p. 75), but gradually turn brown (see **Figure 8.1** on p. 75). Each female usually lays 60–100 eggs, depending mainly on the whitefly species, host plant, and temperature. Hatching occurs after five to nine days at 30° C.

Upon egg eclosion, the first flat, scale-like instar or 'crawler' is the only mobile nymphal stage (see **Figure 8.2** on p. 75). After moving to a suitable feeding location on the lower leaf surface, it becomes sessile for the remainder of its nymphal stage. The first three nymphal stages last two to four days each. The fourth nymphal stage lasts five to eight days and is commonly called pseudo-pupa as the insect stops feeding in the late half of that instar. The mature fourth instar nymph/pupa is commonly 0.6 mm to 0.8 mm in length with a pair of red eyes (see **Figure 8.2** on p. 75).

The adult emerges through a T-shaped rupture in the pseudo-pupa after which it expands and powders its wings with wax from abdominal glands. Copulation begins two to ten hours after emergence (see **Figure 8.2** on p. 75) and takes place two to four times daily during the early half of adult life with diminishing frequency thereafter. Females usually live for 15 to 30 days, and males have a shorter adult life between nine to 17 days. Ten to 15 generations occur within one year, depending on the whitefly species and geographic region.

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8.5 Taxonomic status and nomenclature

The species status of *B. tabaci* has been the subject of debate for decades and progress in its taxonomic classification has been complicated by numerous factors. As a result, there have been repeated descriptions of new species and synonymization. In the 1970s, the genus *Bemisia* (order Hemiptera, family Aleyrodidae, sub-family Aleyrodinae) was considered to contain 37 species of whiteflies, and *B. tabaci* was treated as one single species. Starting from the late 1980s, following the invasion of what is now called MEAM1 into the United States of America, the marked differences in the biology of various populations of *B. tabaci* called for recognizable separation with names for both academic and practical purposes. In 1993, the invasive *B. tabaci* and the indigenous *B. tabaci* were found to exhibit identical morphology, while their biology differed substantially and both species did not interbreed. Based on the evidence of reproductive isolation, the invasive *B. tabaci* was classified as a new species *B. argentifolii*. Despite the sufficient evidence for the status as a new species, the *B. argentifolii* was not accepted by the scientific community, largely due to the perception that the two genotypes consist of only a small portion of the genetic diversity of the whole *B. tabaci*. The confusion about the species status of *B. tabaci* then spread quickly and widely. In the 1990s and 2000s, there was a proliferation of *B. tabaci* biotype designations based primarily on genetic markers, whether protein or DNA. This led to a misuse of the term biotype with the resulting scientific confusion on the species status of *B. tabaci* giving rise to ineffective communication and suboptimal management.

By 2010, a comprehensive phylogenetic analysis was published using the 657 bp portion of the 3' end of the mitochondrial cytochrome oxidase subunit (mtCOI) gene sequence. By employing 3.5 percent divergence in mtCOI as the species boundary, scientists came to treat *B. tabaci* as a cryptic (or sibling) species complex containing 11 higher genetic groups and at least 24 putative cryptic species. Before *B. tabaci* systematics were properly clarified and formal scientific names were assigned, the region of origin for a putative species was used in its nomenclature (i.e. MEAM1, MED, Asia 1). By 2014, at least 34 putative species of the *B. tabaci* whitefly complex had thus been named. Importantly, for the approximately 20 putative species that have been subject to crossing experiments, most of them do not interbreed. This offers indisputable evidence that these are species with little or no gene flow among them.

Hence, a reliable assessment of whitefly species identity is essential to the development of effective, sustainable management approaches. The 2010–2011 naming system is, ideally, to be used as we await a final assignment of scientific names. For species identification using mtCOI, practical guides and standardized molecular diagnostics tools have been developed. These are particularly user-friendly and yield correct identifications in a matter of hours or days. Updated, comprehensive mtCOI reference datasets have also been made available, publicly and freely, of 1 071 unique sequences of the 696 base pairs for the *B. tabaci* species complex. This dataset provides a one-stop reference source when new species of the *B. tabaci* complex are discovered and need to be named.

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8.6 Geographical distribution

Species from the *B. tabaci* whitefly complex can be found worldwide, though most of them have a limited distribution in one continent. A few species, such as MEAM1 and MED, show a global distribution recorded in more than 70 countries and 40 countries, respectively, apparently via human-aided spread and invasion in recent decades. With the expansion of greenhouse production in many countries, these species are still expanding their distribution, particularly to the cool temperate regions where they did not occur before. New incursions of new whitefly species, especially the invasive MEAM1 and MED, is often caused by movement of infested plant materials. Plant movement thus facilitates the spread of insecticide resistance genes, leading to increases in the use of chemicals and, in turn, adverse impacts on the environment.

8.7 Host range

The *B. tabaci* species complex reportedly feeds on more than 600 plant species. Experimental host acceptance assays, field-level identification of whitefly species on various plants, and RNA-seq analyses indicate that most whitefly species have a comparatively narrow host range comprising few plant species from one to several families. Species such as MEAM1 and MED each have a relatively wide host range with dozens of host plants in more than ten plant families. The most common hosts of whiteflies belong to a less than a handful of plant families including Leguminosae (e.g. soybean, peanut, alfalfa, broad bean, pea), Compositae (e.g. chrysanthemum, sunflower, croton weed, snow lotus, crown daisy), Malvaceae (e.g. hibiscus, cotton, okra, large mulberry), Solanaceae (e.g. tomato, tobacco, bell pepper, eggplant, mandala), and Euphorbiaceae (e.g. cassava, poinsettia, Peking spurge, castor bean, Chinese tallow, croton).

8.8 Crop damage and impact

Whiteflies cause three types of plant damage. First, host plants are directly impacted by the phloem feeding of nymphs and adults (**Figure 8.3** on p. 76). These use piercing mouthparts to feed upon phloem sap in plant stems and leaves. Large populations can thus cause leaves to turn yellow, wilt, or fall off plants, occasionally causing plant death. Second, *B. tabaci* adults and immatures excrete honeydew. This drops onto leaf or fruit surfaces, acting as a substrate for the growth of sooty mould, impeding, photosynthesis and lowering fruit or fiber quality (see **Figure 8.4** on p. 76). Third *B. tabaci* whitefly transmit hundreds of plant viruses, including begomoviruses (*Geminiviridae*), criniviruses (*Criniviridae*), and torradoviruses (*Secoviridae*). The former contains over 400 species, all of which are believed to be whitefly-transmitted. Some of the most damaging (whitefly-vectored) viruses include cotton leaf curl virus, cassava mosaic virus, and tomato yellow leaf curl virus. Virus-infected plants exhibit a wide range of symptoms including yellowing, yellow blotching of leaves, yellow mosaic of leaves, leaf curling, leaf vein thickening, stem twisting, or plant stunting (see **Figure 8.5** on p. 77).

Whiteflies of the *B. tabaci* species complex cause enormous losses, estimated at USD 10 billion between 1980 and 2000. During 1991, whitefly outbreaks caused direct losses worth over USD 500 million in the United States alone. In the states of Arizona, California and Texas, cotton growers further spent USD 154 million between 1994 and 1998 to manage the whiteflies. Moreover, losses due to whitefly-transmitted virus diseases are substantial. For example, the whitefly-borne cotton leaf curl virus (CLCV) caused USD 1 billion annually in losses to Pakistani cotton production. Whitefly-vectored cassava mosaic disease (CMD) and cassava brown streak disease (CBSD) are believed to annually cause production losses of more than USD 1 billion in Africa.

8.9 Integrated pest management

Detection and inspection

Monitoring. Yellow sticky traps are a useful tool for monitoring *B. tabaci*. For example, 75 yellow sticky cards (24 cm x 20 cm) can be placed at canopy height in one hectare of crop field, at equal distances. Using this monitoring method, numerical thresholds can be defined for different management tactics: (i) at 0.25–0.5 adults/cm², biological control measures, such as the release of natural enemies, should be taken; (ii) at 3–4 adult/cm², chemical control measures or biopesticide spray applications are recommended to prevent whitefly outbreaks. Sampling via the leaf-turn method is also commonly used for whitefly monitoring and decision-making. Because the within-plant distribution pattern of whiteflies varies with plant phenology, and whitefly or plant species, sampling protocols must take these and, potentially, other factors into account. Accordingly, the exact whitefly infestation levels at which management intervention is warranted can vary widely.

Economic thresholds and action thresholds are prime decision criteria for farmers and pest management professionals, applicable to all pests, crops and farming contexts. In general, thresholds are experimentally defined as the pest infestation level at which curative control measures should be deployed (while accounting for a time lag to yield impact) to avoid significant crop damage. Economic thresholds are based upon an economic injury level (EIL) and thus, involve rigorous economic criteria, for example, tabulated input expenditure, labour costs, and value of the harvested produce. Under specific market and environmental conditions in China, an EIL was established for whitefly on cucumber plant at 18 adults per plant at the four-leaf stage and, on greenhouse tomato, at 13.6 adults per 100 leaves. On cabbage, thresholds have been set at 6.0 to 6.8 adults per plant in the seedling stage and at 2.1 to 3.8 adults per plant in the rosette stage.

More pragmatic thresholds with a far weaker economic foundation have been defined in some Chinese vegetable crops. These experimental action thresholds specify that natural enemy releases should be done once adult whiteflies reach densities of 0.5 to 2 adults/leaf, while higher densities (i.e. five to six adults/leaf) warrant the use of environmentally friendly insecticides or biopesticides. This has been taken a step further in European greenhouse systems, where simulation models are used to define the release size and timing of predators and parasitoids in order to keep whitefly numbers below EIL. Thresholds have also been defined that concurrently account for the actual population densities of whitefly and a



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key predator, *Nesidiocoris tenuis* (Heteroptera: Miridae). Yet, to ensure a broader diffusion of such economic thresholds, careful messaging and empirical validation under variable agroecological and socioeconomic conditions are a must.

In addition to the above, recent work has also examined the potential of other monitoring methods such as phototactic electrostatic traps or sticky cards equipped with light-emitting diodes (LEDs). Artificial intelligence (AI), computer vision and machine learning have been used to count the number of whitefly individuals on yellow sticky cards. These kinds of methods can eventually enable the development of real-time remote monitoring systems of *B. tabaci* in field or greenhouse systems.

Prevention and control

To manage *B. tabaci* infestations, farmers predominantly rely upon scheduled applications of synthetic insecticides because of their efficacy and convenience. However, chemical pest control causes environmental concerns and also leads to the widespread insecticide resistance development. As of 2024, there are 770 cases of *B. tabaci* insecticidal resistance worldwide covering no less than 69 different active ingredients. The integrated pest management (IPM) of whitefly calls for use of alternative or complementary methods such as cultural control, resistant host-variety planting, physical control, and biological control using predators and parasitoids (see **Figure 8.5** on p. 77).

Cultural control. Cultural control involves management practices that make the farming environment less favourable to whitefly reproduction, movement or survival, while favoring its resident natural enemies. Cultural control may rely upon various solutions, including physical barriers or other barriers to prevent the pest colonization, adjusted planting dates, rotation with non-susceptible crops, crop residue destruction and the establishment of resistant crops or cultivars. Though these can be deployed individually, they are ideally used in combination. Diversification measures such as intercropping or the use of trap and barrier crops can lower whitefly population levels to a considerable extent in both field crops and greenhouse settings. When established as a trap crop in cotton or vegetable fields, velvetleaf *Abutilon theophrasti* or *Nicotiana benthamiana* can simultaneously reduce population levels of whitefly and other insect pests. The latter plant even acts as a 'dead-end' trap crop, proving remarkably attractive and lethal to whiteflies.

A scientifically informed adjustment of planting dates can help to avoid peak times of whitefly colonization, and thus prevent pest issues. Early or delayed planting can be particularly effective in areas where whiteflies reproduce rapidly – for example, under hot, arid conditions. Highly susceptible crops, such as cucurbits, crucifers and certain solanaceous crops could be planted when whitefly colonization rates are low. Crop sanitation equally plays a central part in whitefly management. In cotton systems, infected plants should be destroyed because *B. tabaci* can continue to build up for six weeks after final irrigation and even defoliation. Crop residues, which harbour whitefly and virus inoculum, should then be destroyed shortly after the final harvest. Further, susceptible crops should not be planted near infestation sources. It is recommended to plant whitefly-susceptible crops (e.g. cotton) at least 0.75–1 km upwind from other key host crops or weed species that regularly harbour *B. tabaci*. Lastly, water and fertilizer management play important roles in whitefly management. Overuse of nitrogen fertilizer can increase whitefly abundance and the

ensuing honeydew production, thus exacerbating crop damage and yield or quality loss. Higher populations of *B. tabaci* are regularly observed on water-stressed, versus well-watered, cotton plants. In the meantime, *B. tabaci* that feed on well-watered plants produce more honeydew with higher sugar contents than on drought-stressed cotton, which can aggravate sooty mould issues.

Host-plant resistance. The establishment of crop varieties that are resistant to *B. tabaci* and associated viruses such as tomato yellow leaf curl virus, TYLCV, is a preferred solution to minimize whitefly-related damage. The *Mi-1* gene, present in many varieties of cultivated tomato and introduced into this plant from its wild relative, *S. peruvianum*, regulates resistance to *B. tabaci*, the aphid *Macrosiphum euphorbiae* and root-knot nematodes *Meloidogyne* spp.

Physical control. In greenhouse or tunnel systems, nylon screen netting (mesh diameter 0.125 mm) can effectively reduce whitefly infestation levels and yellow sticky cards are routinely used for monitoring purposes though these can also help to lower population levels. Yellow sticky card (24 cm x 20 cm) trap adult whiteflies efficiently when placed vertically among plants at or slightly above canopy level with one card per 3 m to 5 m. Under field conditions, reflective mulches repel whiteflies, oil-coated yellow mulches act as a trap for whiteflies, floating row covers can physically exclude whiteflies during specific stages of the host crop, while a variety of crop and non-crop plants can be established as barrier or (dead-end) trap crops.

In addition to the yellow wavelengths that are attractive to whitefly adults, filtration of ultraviolet (UV) light in the range of 280 nm to 380 nm can slow whitefly proliferation. Eliminating the UV portion of the light spectrum interferes with the 'UV vision' of insects and dramatically affects their orientation behavior in the crop. In protected vegetable crops, UV-absorbing polyethylene films, mesh nets or mulches filter most of the UV portion of the light spectrum and significantly reduces infestation pressure of whitefly, aphids, thrips and leafminers. These relatively simple, low-cost approaches can be key in avoiding whitefly-related issues.

Biological control. A diverse set of arthropod natural enemies have been recorded and studied in a wide range of cropping systems and geographies, and predation or parasitism consistently feature as the main mortality factors for *B. tabaci* in cultivated crops. More than 150 arthropod species belonging to nine orders and 31 families prey upon *B. tabaci* whitefly, most of which are beetles (Coccinellidae), true bugs (Miridae, Anthocoridae), lacewings (Chrysopidae), mites (Phytoseiidae) and spiders (Araneae). Predatory mirids are extensively used in the Mediterranean basin, where *Macrolophus caliginosus* and *Nesidiocoris tenuis* are highly abundant in crops where little or no broad-spectrum insecticides are used. In those settings, these predators provide efficient control of whitefly populations and a suite of secondary pests. The release of *N. tenuis*, at a rate of either 0.1 or four individuals/plant, can reduce *B. tabaci* populations by over 90 percent. Some predators however do exhibit zoophytophagous feeding habits and sporadically cause flower abortion and yield losses. The combined release of predators and parasitoids often improves whitefly control, as evidenced by the combined use of *M. caliginosus* and *Eretmocerus mundus* in greenhouse tomato greenhouses or simultaneous releases of predaceous mite *Amblyseius swirskii* and *Er. mundus* in sweet potato greenhouses and in open field eggplant.





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At least 115 hymenopteran parasitoid species have been described from *B. tabaci*, many of which belonging to *Encarsia* spp. and *Eretmocerus* spp. Out of these, *Er. mundus*, *Er. eremicus* and *Encarsia formosa* are commercially available in many parts of the world and their scheduled releases in greenhouse systems provide effective whitefly control. Under inundative release modes, parasitoids are released at 1:10 ratio (parasitoid/host) weekly for three to five consecutive weeks according to whitefly densities. Meanwhile, under inoculative release modes, one single targeted release in early season is aimed at establishing a stable parasitoid population over the entire crop cycle. Parasitoids can be released directly by vials and pupal cards; the latter can be stored for prolonged periods of time at low temperatures. Biological control can also be promoted through the use of banker plants, through which predator or parasitoid populations are sustained on whitefly-infested alternative host plants. By deploying these plants within a standing crop in early season, their timely colonization of the main crop is ensured. For example, papaya plantlets infested with *Trialeurodes variabilis* can serve as a source of *Encarsia sophia* to control *B. tabaci* on tomato and green bean. Several species of entomopathogenic fungi are commercially available, including *Beauveria bassiana*, *Aschersonia aleyrodis*, *Verticillium lecanii*, and *Isaria fumosorosea*. The cosmopolitan fungus *B. bassiana* significantly reduces the survival of *B. tabaci* nymphs while increasing its developmental time and pre-oviposition period. *Aschersonia aleyrodis* can parasitize early-instar whitefly nymphs and does not negatively affect its parasitoids. *Isaria fumosorosea* infects all adult and immature stages of *B. tabaci*. Biopesticide use is thus fully compatible with parasitoid-mediated biological control. In addition to their contact toxicity, entomopathogenic fungi such as *V. lecanii* also act as deterrents against *B. tabaci* adults. Several entomopathogenic fungi are affected by environmental factors such as temperature and humidity, and their overall contribution to sustainable *B. tabaci* management has been inconsistent. For example, *V. lecanii* requires high humidity to be effective – which can be circumvented by using *V. lecanii* toxins. Recent work further shows that by combining fungi such as *I. fumosorosea* or *B. bassiana* with selective insecticides or non-ionic surfactants, a synergic effect on *B. tabaci* can be attained. While good results have been obtained with certain systemic insecticides, it is important to bear in mind that these products are readily translocated to (floral, extra-floral) nectar and other plant exudates. As such, they can negatively impact resident natural enemy communities, weaken biological control and even trigger outbreaks of other arthropod pests such as spider mites. Extreme caution should thus be taken to integrate entomopathogenic fungi with systemic insecticides, as this practice likely enhances overall crop susceptibility to pest attack.

Chemical control and insecticide resistance management. Under IPM schemes, chemical control is a 'measure of last resort'; it should thus only be pursued once all other non-chemical management strategies fail. In the absence of locally effective biopesticides, synthetic insecticides can be employed to resolve *B. tabaci* outbreaks. However, the effectiveness of insecticide-based approaches is limited because *B. tabaci* has evolved resistance to insecticides of most chemical classes and modes of action. Among the *B. tabaci* species complex, species such as MED, MEAM1, Asia I and Asia II have developed resistance to a wide variety of active ingredients including relatively new compounds such as pyriproxyfen and neonicotinoids. To overcome insecticide resistance, one should (i) deliberately prioritize non-chemical management strategies such as biological control, crop diversification or biopesticides; (ii) use chemical insecticides according to label recommendations; (iii) select insecticides based on known local efficacy and selectivity e.g. to resident natural enemies; and

(iv) rotate insecticides of different mode of actions. Some low-risk insecticides, for example avermectin, spinetoram, sulfozaflor and cyantraniliprole, as well as new chemicals, such as spirotetramat and flupyradifurone, can be considered for use against *B. tabaci*. To avoid resistance development to these new chemistries, conscious integration of non-chemical measures such as biological control and biopesticides into insecticide rotation schemes is strongly recommended. As such, augmentative or conservation biological control can significantly extend the lifespan of new insecticidal compounds.

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Figure 8.1

Eggs of *Bemisia tabaci*

- A: Newly laid white eggs
- B: Developed eggs in brown

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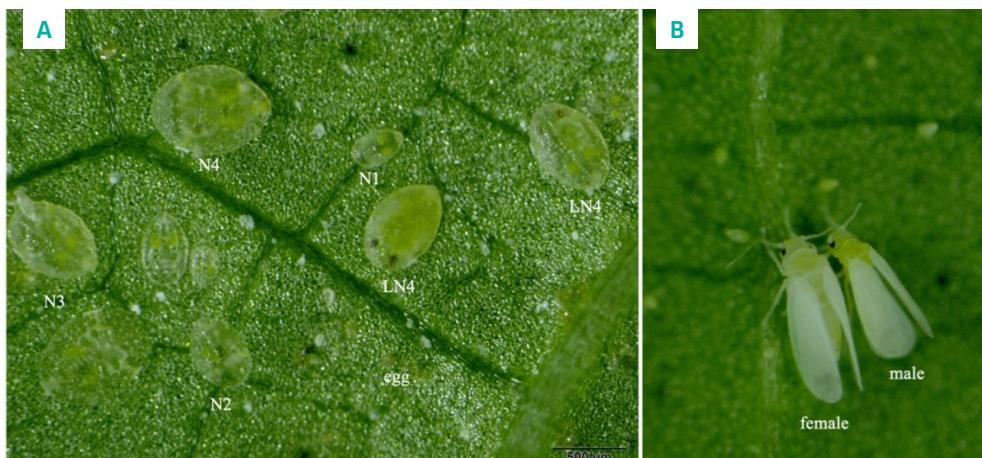


Figure 8.2

Egg

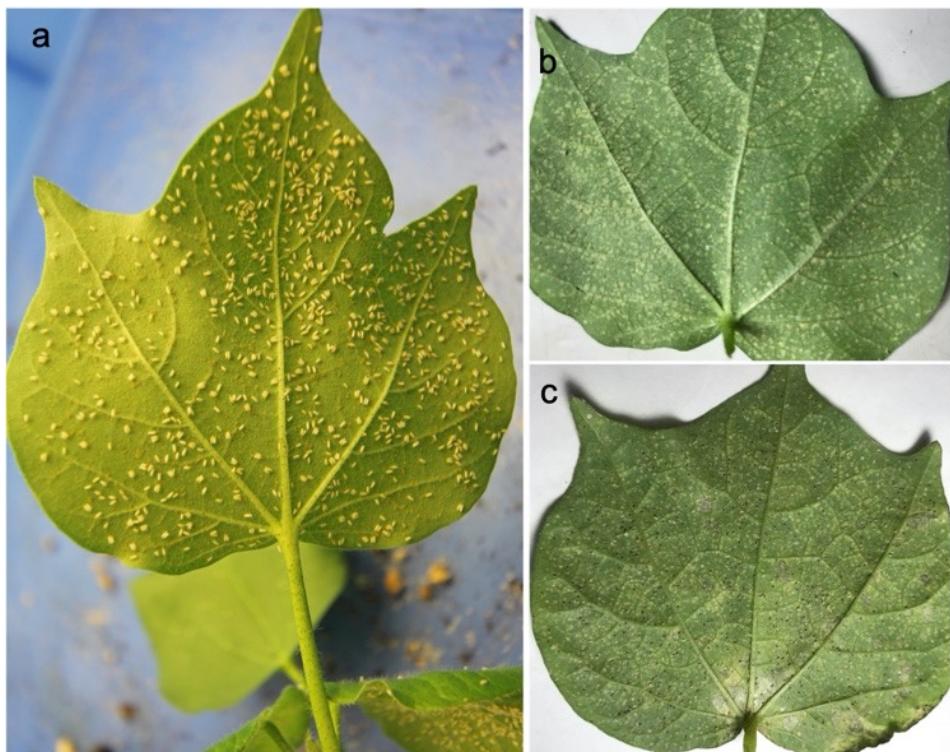
- A: Different nymphal stages
- B: Adults of *Bemisia tabaci*. N1-N4 represents nymphal stage one, two, three and four, respectively; LN4 represents late nymphal stage four, or pseudo-pupa

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Figure 8.3

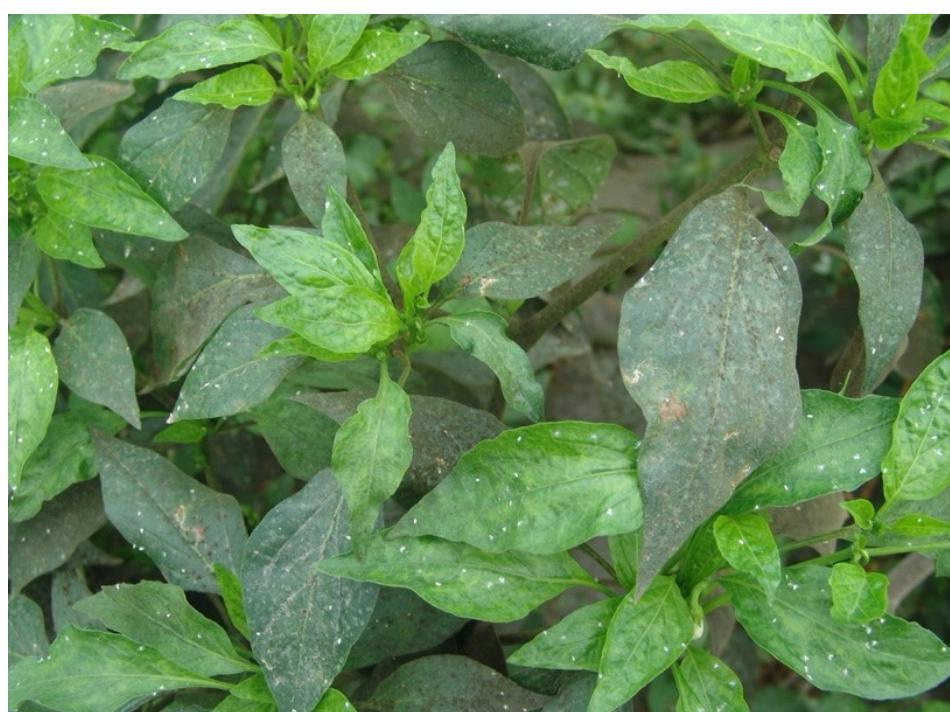
Cotton leaf with a: whitefly adults; b: healthy nymphs; and c: nymphs parasitized by *Encarsia sophia* and developing to black pupae

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**Figure 8.4**

Heavy sooty mould on leaves of whitefly-infested bell pepper

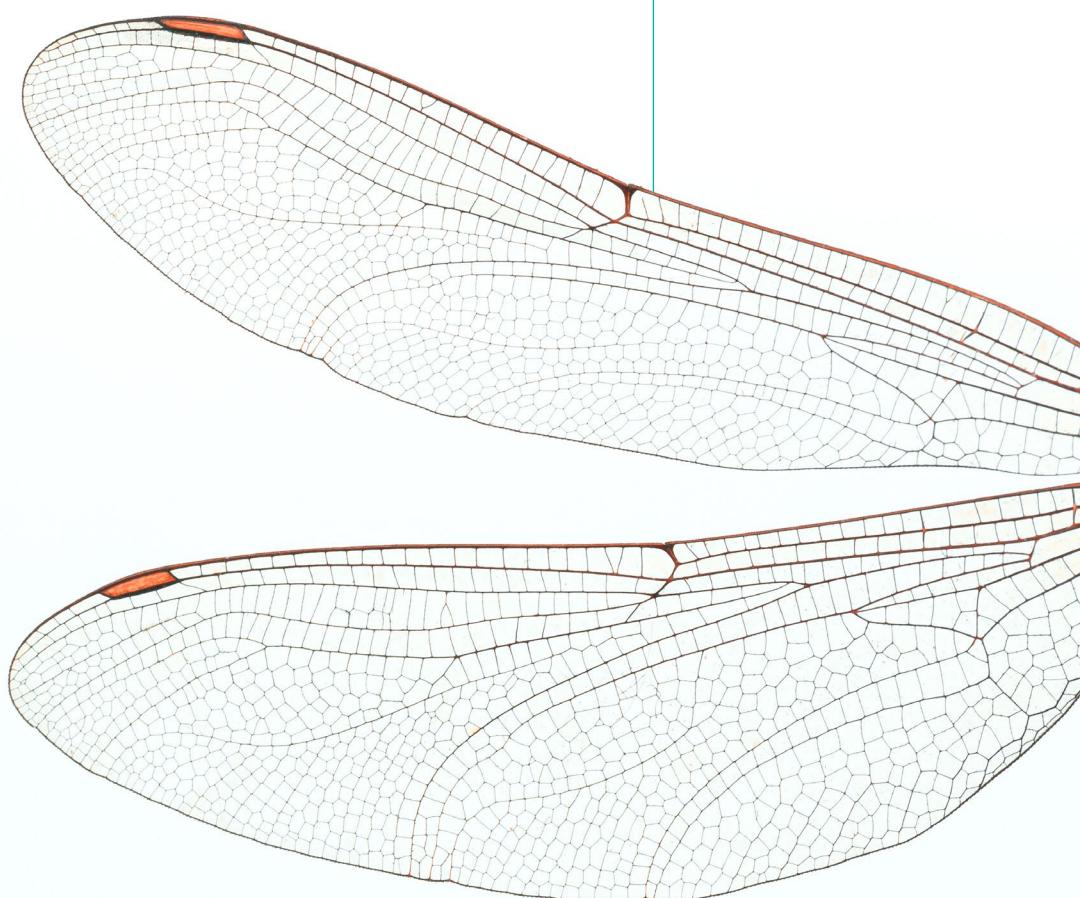
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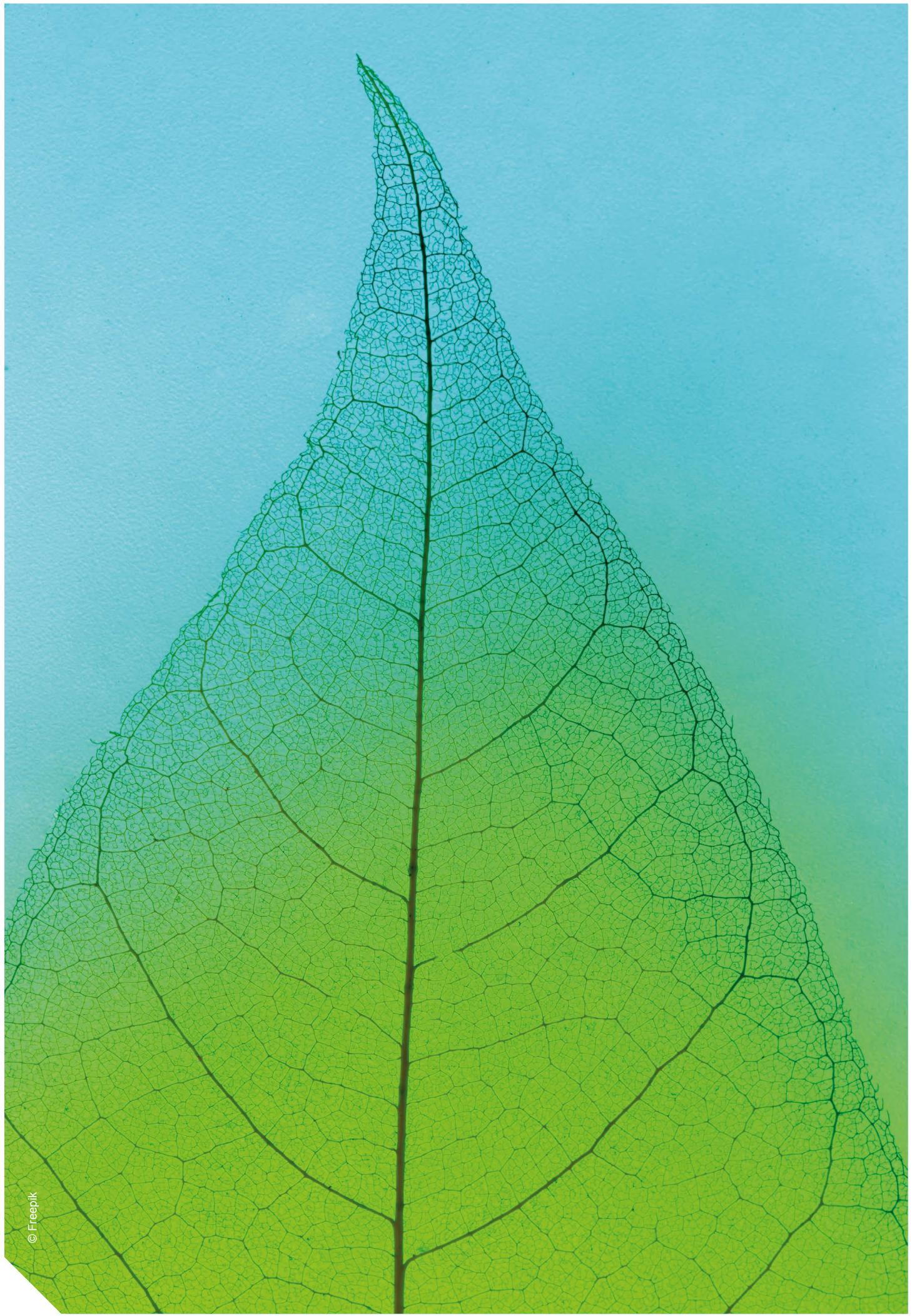


**Figure 8.5**

Tomato plants infected by (whitefly-vectored) tomato yellow leaf curl virus

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9

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Chapter 3 *Bactrocera dorsalis* fruit fly

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Chapter 4 Banana Fusarium Tropical Race 4

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Chapter 6 Potato late blight

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Chapter 7 Rice brown planthopper

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Chapter 8. *Bemisia tabaci* whitefly

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