

BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Advances in monitoring of native and invasive insect pests of crops

Edited by Dr Michelle Fountain, NIAB-EMR, UK

Dr Tom Pope, Harper Adams University, UK



Contents

Series list	x
Introduction	xx

Part 1 Detection

1	Advances in techniques for trapping crop insect pests	3
	<i>Archie K. Murchie, Agri-Food & Biosciences Institute, UK</i>	
1	Introduction	3
2	Basic trapping elements	4
3	Making the trap attractive	5
4	Common trap types for collecting pest insects	8
5	Automated traps	25
6	Conclusion	29
7	Future trends in research	30
8	Where to look for further information	32
9	Acknowledgements	33
10	References	33
2	Advances and challenges in monitoring insect pests of major field crops in the United States	47
	<i>Erin W. Hodgson and Ashley N. Dean, Iowa State University, USA; Anders Huseeth, North Carolina State University, USA; and William D. Hutchison, University of Minnesota, USA</i>	
1	Introduction	47
2	Primary crops in the United States	48
3	Corn (<i>Zea mays</i> L.)	49
4	Soybean (<i>Glycine max</i> [L.] Merr)	61
5	Cotton (<i>Gossypium</i> spp. L.)	69
6	Conclusion and future trends	74
7	Where to look for further information	75
8	References	76

3	Quantifying captures from insect pest trap networks	91
	<i>Nicholas C. Manoukis, USDA-ARS, USA</i>	
1	Introduction	91
2	TrapGrid and other models to analyze trap networks	94
3	Applications	100
4	Practicum	106
5	Conclusion	111
6	Where to look for further information	112
7	Acknowledgements	112
8	References	112
4	Developments in crop insect pest detection techniques	117
	<i>Richard W. Mankin, USDA-ARS, USA</i>	
1	Introduction	117
2	Camera systems for pest detection at micro-scale ranges	123
3	Drone/camera systems for pest detection at meso-scale detection ranges	124
4	Landsat systems for detection of pests at macro-scale detection ranges	125
5	Sound- and vibration-sensors for pest detection	125
6	Case studies: augmenting traditional pest detection and biological control with nano-scale- and micro-scale-sensor technologies	128
7	Conclusion	130
8	Future trends in research	131
9	Where to look for further information	133
10	References	133
5	Monitoring airborne movement of crop insect pests and beneficials	147
	<i>V. Alistair Drake, University of Canberra and University of New South Wales, Australia</i>	
1	Introduction	147
2	Trapping	150
3	Visual observation	154
4	Radar	155
5	Optoelectronics	162
6	Radiotelemetry and harmonic radar	167
7	Case study: moths over a cotton crop	170
8	Conclusion	174
9	Where to look for further information	177
10	Appendix: safety and regulatory issues	178
11	Acknowledgements	178
12	References	179

Part 2 Identification, modelling and risk assessment

6	Advances in image-based identification and analysis of crop insect pests	197
	<i>Daniel Guyer, Michigan State University, USA; and Charles Whitfield, NIAB, UK</i>	
1	Introduction	197
2	Challenges and solutions in automated image-based insect identification	199
3	Understanding machine vision image-based insect identification	202
4	Automated and semi-automated image-based insect identification technologies	205
5	Commercially available systems	206
6	Conclusion	211
7	References	212
7	Advances in insect pest monitoring using pest population growth and geospatial data for pest risk assessment	215
	<i>Michael J. Brewer, Texas A&M AgriLife Research, USA; Isaac L. Esquivel, North Florida Research and Education Center, University of Florida, USA; and John W. Gordy, Syngenta Crop Protection, USA</i>	
1	Introduction	215
2	Pest monitoring basics and economic threshold adjustments	217
3	Geospatial data for pest risk assessment	223
4	Conclusion and future trends in research	235
5	Where to look for further information	237
6	Acknowledgements	238
7	References	238
8	Advances in pest risk assessment techniques focusing on invertebrate pests of European outdoor crops	243
	<i>Mark W. Ramsden, Samuel Telling, Daniel J. Leybourne, Natasha Alonso and Sacha White, RSK ADAS Ltd, UK; and Nikos Georgantzis, Burgundy School of Business, France</i>	
1	Introduction	243
2	Assessing the likelihood of pest infestations	245
3	Assessing the hazard of pest infestations	250
4	Reducing risk	252
5	Risk versus the perception of risk	253
6	Summary steps to pest risk assessment	254
7	Worked example: risk assessment of barley yellow dwarf virus in winter wheat	255

8	Conclusion	257
9	Future trends in research	258
10	Where to look for further information	258
11	Acknowledgements	259
12	References	259
Part 3 Invasive species		
9	Assessing the potential economic impact of invasive plant pests <i>Monique Mourits and Alfons Oude Lansink, Wageningen University, The Netherlands</i>	267
1	Introduction	267
2	Methods to assess the potential economic impact of invasive plant pests	268
3	Selection of appropriate level of complexity	275
4	Economic analyses to support pest risk management	279
5	Case studies: pine wood nematode (<i>B. xylophilus</i>) and <i>X. fastidiosa</i>	280
6	Conclusion and future trends	288
7	Where to look for further information	289
8	References	290
10	Developing effective phytosanitary measures to prevent the introduction of invasive insect pests <i>Alan MacLeod and Dominic Eyre, DEFRA, UK</i>	293
1	Introduction	293
2	International agreements and trade intervention	294
3	What are phytosanitary measures?	297
4	Phytosanitary measures within the framework of pest risk analysis	298
5	Examples of phytosanitary measures	299
6	Case study: strengthening phytosanitary measures against <i>Bemisia tabaci</i> and <i>Liriomyza huidobrensis</i> in the UK	307
7	Case study: EU measures against <i>Anoplophora chinensis</i>	309
8	Combining measures: the systems approach	311
9	Challenges	313
10	Conclusion	316
11	Where to look for further information	317
12	References	318
11	Mitigating invasive insect species: eradication, long-term management, and the importance of sampling and monitoring <i>Amy Morey, University of Minnesota, USA; and Robert Venette, USDA Forest Service, USA</i>	325
1	Introduction	325
2	Overview of invasive species management	328

3	Eradication of invasive insects	330
4	Long-term management of invasive insects	340
5	Conclusion	346
6	Future trends	347
7	Acknowledgements	348
8	Where to look for further information	348
9	References	350
	Index	365

Introduction

Insect pests remain a major threat to crop production primarily because of their ability to inflict severe damage on crop yields, as well as their role as key vectors of disease. Early identification of pests is critical to the success of integrated pest management (IPM) programmes and essential for the development of phytosanitary/quarantine regimes to prevent the introduction of invasive insect pests to new environments.

This volume reviews the wealth of research on techniques to monitor and thus prevent threats from both native and invasive insect pests. The book is split into three parts: Part 1 chapters draw attention to detection methods for crop insect pests, focusing specifically on techniques to trap and monitor them as well as developments in sampling and survey design, detection techniques and ways to monitor airborne movement of crop insect pests. Chapters in Part 2 focus on identification, modelling and risk assessment, highlighting advances in image-based identification and analysis, population growth models and pest risk assessment techniques. Part 3 chapters review invasive species and how their potential economic impact can be assessed, including the development of effective phytosanitary measures to prevent invasive insect pests and successful IPM programmes to control or eradicate them.

Part 1 Detection

The first chapter of the book draws attention to advances in techniques for trapping crop insect pests. Chapter 1 begins by describing the basic components of an insect trap. It then moves on to discuss methods to make traps more attractive for an insect, emphasising the use of methods such as visual and olfactory cues. The chapter also highlights common trap types for catching insect pests, focusing specifically on water traps, sticky traps, suction traps, interception traps and funnel and cone traps. Case studies of their usage and an evaluation of their merits and limitations are also included. Automated traps for insect pests are also reviewed, such as time-sorting traps, automated counting and identification and automated visual identification.

The next chapter reviews current insect pest monitoring systems for native and invasive pest species of corn, soybean, and cotton in the U.S. Chapter 2 presents case studies of European corn borer, corn earworm, western bean cutworm and western (*Diabrotica virgifera* LeConte) corn rootworm as pests of corn; soybean aphid, stink bugs, and Japanese beetle as pests of soybean; and tobacco thrips, plant bugs and bollworm as pests of cotton. It discusses how new technology has driven recent improvements in monitoring of these pests

from the lab, field and areawide levels. It also discusses recent trends and tools for insect resistance management.

The subject of Chapter 3 is interpreting data from insect pest trap networks. The chapter begins by highlighting models to analyse trap networks, focusing primarily on the development of the TrapGrid network. TrapGrid can be used to quantify the probability of capturing insects instantaneously or over time using a function that relates distance from a given trap to probability of capture and two models of insect dispersal. Brief descriptions of other modeling approaches to these questions, some of which have seen application outside of research, are discussed followed by ideas for the application of TrapGrid, including a way to determine trap attraction (the parameter λ in the model) and how to compare alternative trap layouts on a landscape scale. A working example is also provided, comparing two alternative trap layouts in a 1 km² area via quantification of capture probability instantaneously and over 30 days.

Chapter 4 focuses on developments in crop insect pest detection techniques. The chapter first discusses the use of camera systems for pest detection at micro-scale ranges, then moves on to review how drone/camera systems can be used at meso-scale detection ranges. This is followed by an overview of the use of Landsat systems for pest detection and macro-scale detection ranges. A section on sound- and vibration-sensors is also included. The chapter provides a case study focused on augmenting traditional pest detection and biological control with nanoscale- and micro-scale sensor technologies, before concluding with an overview of future goals and developments for insect pest detection technologies in crops.

The final chapter of Part 1 explores monitoring airborne movement of crop insect pests and beneficials. Chapter 5 highlights the importance of trapping methods when it comes to monitoring specimens. This is then followed by a review of the visual observation of insects and a discussion of various forms of radar that can be used, such as scanning entomological radars, vertical-looking and weather surveillance radars. A section on optoelectronics is also provided, focusing specifically on short-range and long-range monitoring as well as imagers and the strengths, limitations and prospects of these devices. The chapter also provides a review of radiotelemetry and harmonic radar as well as a case study on moths over a cotton crop.

Part 2 Identification, modelling and risk assessment

Part 2 opens with a chapter that reviews progress in developing automated image-based systems for identifying crop insect pests. Chapter 6 identifies the challenges in distinguishing insect pests in field conditions and ways they can be addressed. The chapter outlines key steps in image-based identification (image capture, processing, segmentation, feature extraction and classification)

and the growing use of artificial intelligence to increase accuracy and reliability. It also provides examples of commercially-available systems and considers future developments. The chapter is aimed at practitioners and scientists new to the topic and as a useful reference on the pros and cons of different monitoring strategies for those already in the field.

Chapter 7 looks at advances in insect pest monitoring using pest population growth and geospatial data for pest risk management. The chapter reviews approaches and provides case studies of current advances that are in development or have been applied in operational IPM systems. It first analyses incorporating knowledge of expected pest population growth to adjust economic thresholds for use in applying remedial IPM tactics to individual fields. The chapter then turns to principles and advancements in using spatial data, including spatially-referenced pest, crop and remote sensing data. Spatial data linked to insect pest monitoring may improve strategic use of remedial IPM tactics at the field level and use of preventive IPM tactics at larger scales.

The subject of Chapter 8 is advances in pest risk assessment techniques focusing on invertebrate pests of European outdoor crops. The chapter breaks down the processes and tools available to undertake a pest risk assessment, first focusing on the ways to assess the likelihood and hazard of pest infestations. It then highlights the potential influence of the perception of risk on decision making and how risk can be reduced. The chapter also provides a worked example for a priority pest in wheat.

Part 3 Invasive species

Chapter 9 addresses the potential economic impact of invasive plant pests. The chapter evaluates techniques such as partial budgeting, partial equilibrium models, input-output models and computable general equilibrium models in terms of their economic concepts, scope and required data and skill. This is then followed by a general reflection on the question of how to choose the most appropriate technique whilst considering the trade-off between completeness in economic scope and required resources. The chapter concludes with two case studies to illustrate the potential of the methods that are most often applied.

The subject of Chapter 10 is developing effective phytosanitary measures to prevent the introduction of invasive insect pests. The chapter provides a definition of phytosanitary measures, why they are needed, how standards for phytosanitary measures developed through international cooperation and how they relate to international agreements. This chapter then explains how policy decision making and the management of invasive insect pests using phytosanitary measures is supported by the structured framework of pest risk analysis which follows international standards. Outlines of some of the more

commonly used phytosanitary measures used to manage pest risk are provided. Case studies are used to illustrate the impact of phytosanitary measures. The chapter closes by identifying some of the key challenges the industry faces to inhibit the introduction and spread of invasive insect pests with the aim of stimulating future research.

The final chapter of the book is focused on mitigating invasive insect species, focusing specifically on eradication, long-term management and also highlights the importance of sampling and monitoring. Chapter 11 introduces major concepts associated with the management of invasive insects. It then focuses more deeply on eradication and long-term management, especially IPM, describing common factors associated with successful programmes and potential challenges of each strategy. Brief case studies are provided to illustrate applications of eradication and IPM to various invasive insects in different regions. Lastly, the chapter summarises recent research and technology that have progressed effective management of invasive insects and highlight areas where further research is needed.

Chapter 1

Advances in techniques for trapping crop insect pests

Archie K. Murchie, Agri-Food & Biosciences Institute, UK

- 1 Introduction
- 2 Basic trapping elements
- 3 Making the trap attractive
- 4 Common trap types for collecting pest insects
- 5 Automated traps
- 6 Conclusion
- 7 Future trends in research
- 8 Where to look for further information
- 9 Acknowledgements
- 10 References

1 Introduction

Monitoring of insect pests is an essential component of integrated pest management. To determine whether pest densities justify an intervention, such as an insecticide application or other control measures, their numbers need to be assessed and compared to economic thresholds (Pedigo and Buntin, 1994; Ramsden et al., 2017; Stern, 1973). Such assessments can be done by physical sampling of the crop and visual inspection or passively using traps. The method used will depend on the biology of the pest species, the ease of assessment, the availability of labour and the relationship between the stage monitored and the damage done. For example, traps may monitor the adults, whilst the damaging stage is the larva. The closer the temporal and spatial association between the monitored stage and the damaging stage, the more accurate the assessment but the less advanced the warning provided.

For traps, cost and ease of use are important practical elements for in-crop sampling. For all trapping systems, the processing times and costs are major considerations. Some flight interception traps such as Malaise traps catch a

wide variety of flying insects, with several thousand specimens collected over a trapping period (Skvarla et al., 2021). For biodiversity assessment, non-selective traps like this are ideal; however, for monitoring crop pests, selective traps are usually required that produce as targeted a sample as possible with little bycatch. This makes for speedy and accurate processing, as well as minimising impacts on non-target species. In-crop trapping systems therefore aim to be attractive to the target pest species but not to other insects within the crop. The exceptions to this may be where two species interact, such as, two pest species [e.g. cabbage seed weevil, *Ceutorhynchus obstrictus* (Marsham), and brassica pod midge, *Dasineura brassicae* (Winnertz)] (Smart et al., 1992), or where there is an opportunity to monitor a pest and its natural enemy at the same time (Murchie et al., 1997).

The first challenge in successful pest monitoring is to produce a cheap, selective trap that is highly attractive to the pest species. The second challenge is that the trap must be effective enough to provide an accurate population assessment. The third challenge is to reduce the trap sample processing time. Correspondingly, there is increasing interest in automatic methods of sorting and identification of trap catches. The fourth challenge is to reduce the environmental impact of trapping. Indiscriminate traps such as sticky traps are notorious for their large bycatch, even including small birds, bats and lizards, whilst water traps catch beneficial insects such as bees, hoverflies, lacewings and parasitoids. There is also the difficulty of disposal. Sticky traps are awkward to handle and invariably made of plastic, which once contaminated by the sticky glue cannot be easily recycled (Solorzano et al., 2015). The handling and disposal of any chemical preservative involved also needs to be considered.

2 Basic trapping elements

There are four basic components to an insect trap. The first is a method to make the trap attractive to the pest. This is commonly achieved using an attractive colour, light (for nocturnal insects) or more selectively volatile chemicals, in particular pheromone lures. Combinations of colour and chemical attractants are common, and trap design can use both visual and olfactory cues to enhance collection (Blight and Smart, 1999). An exception to this requirement would be where the trap is intended to sample specifically background insect populations, for example with suction traps, pitfall traps or clear flight interception traps. The second component is a mechanism to retain the catch. Insects may be retained on sticky glue, water with a dash of detergent to break the surface tension, or caught into a preservative such as alcohol. Some traps may be run for the purposes of live capture, particularly for biodiversity assessment (e.g. moth trapping) or to collect specimens for further work. In such cases, the design of the trap will allow entry but minimise the likelihood

of exit. Often traps will be left for several days or longer before being emptied, so some method of preserving the catch must be used, if identification of specimens is required. Common preservatives are alcohol, if evaporation can be minimised, and ethylene or propylene glycol (anti-freeze), where the trap is more open to the elements. Alternatively, some traps operate dry and use insecticides to rapidly kill the catch. Lastly, the trap must be mounted in such a way as to maximise catch. Often for flying crop pests, this is at the crop canopy height and unobscured by plant foliage, which changes as the crop grows; therefore, height mounts for the trap are adjustable.

3 Making the trap attractive

3.1 Visual cues - colour and light

Colour is the simplest method of increasing trap attractiveness. Insects have diverse and highly developed colour vision, with some species having up to six different spectral receptors and a visual range of <300 nm [ultraviolet (UV)] to >700 nm (Briscoe and Chittka, 2001; Fennell et al., 2019). Specific wavelengths are attractive to certain insect species. Yellow in particular has been used for attracting phytophagous insects and has been recommended for monitoring glasshouse pests since the 1920s (Lloyd, 1922). This may be because the peak colour reflectance of plants is in the yellow band at 500–580 nm (Prokopy and Owens, 1983), due to brightness/intensity effects (Döring and Chittka, 2007) or attraction of phytophagous insects to stressed/diseased plants (Hodge et al., 2011). However, other colours have also proven attractive depending on the specific pest. For example, Kirk (1984) demonstrated that within the thrips species caught in coloured pan traps in an English sports-field, there were strong species-specific colour preferences for yellow, white, or blue, but there were also some grass-feeding thrips that were caught equally in all colours. The author suggested that yellow was in general the most attractive for non-grass foliage feeders, dark colours (black or red) for biting flies and wood borers, and white or blue for predators and parasites not associated with foliage. Responses to colour are therefore specific to the ecology of the pest species and can be subtle. For example, the contrast between the trap colour and background can affect the response of insects to traps, as can the sex and physiological state of the insect (Blackshaw, 1983; Košťál and Finch, 1996; Murchie et al., 2018). Due to the sensitivity of insects to colour, when conducting choice experiments to aid in designing traps, spectral reflectance measurements in visible and UV using spectrophotometers are preferable to human-vision assessment of colour hues.

Light trapping is used extensively for monitoring flying nocturnal insects. Many species have strong attractions towards artificial light sources particularly

Index

- Additional Declaration 299
- Aerial plankton 16
- AI. *see* Artificial Intelligence (AI)
 - algorithms
- Airborne movement monitoring
 - moths over cotton crop 170-174
 - optoelectronics 162
 - imagers 165-166
 - long-range monitoring 163-165
 - short-range monitoring 163
 - strengths limitations and prospects 166-167
 - overview 147-150
 - radar 155-156
 - scanning entomological radars 156-158
 - strengths, limitations, and prospects 160-161
 - vertical-looking radars 158-159
 - weather surveillance radars 159-160
 - radiotelemetry and harmonic radar 167-170
 - trapping 150-154
 - visual observation 154-155
- Anoplophora glabripennis* 306, 348
- APLC. *see* Australian Plague Locust Commission
- ArcMap 228
- Artificial Intelligence (AI) algorithms 251
- Artificial lighting 202
- Astronomical telescopes 163
- Australian Plague Locust Commission (APLC) 159

- Baited traps 247
- Bird cherry-oat aphid 255
- Blacklight traps 50, 51
- Black pyramid trap 64, 65
- BMSB. *see* Brown marmorated stink bug (BMSB)
- Boll weevil trap capture 234
- Broad-spectrum insecticides 330
- Brown marmorated stink bug (BMSB) 64
- Bucket trap 21

- Cactoblastis cactorum* 337-338
- Canadian Food Inspection Agency 339
- CBC. *see* Conservation Biological Control (CBC)
- CBD. *see* Convention on Biological Diversity (CBD)
- CEW. *see* Corn earworm (CEW)
- Chortoicetes terminifera* 159
- Clean trap catches 30
- Climate change 316
- Combining radar observations 176
- Conservation Biological Control (CBC) 252, 258
- Convention on Biological Diversity (CBD) 296
- Corn earworm (CEW) 53-56, 72-74
- Corn rootworm (CRW) 57-61
- Cost-benefit analysis 280
- Cotton agroecosystems 225
- Cotton fleahopper 233
- Crop insect pest detection techniques
 - camera systems, at micro-scale ranges 123-124
 - drone/camera systems, at mesoscale detection ranges 124-125
 - future trends 131
 - Landsat systems, at macro-scale ranges 125
 - locations by region 132
 - nano-scale-and microscale-sensor technologies, biological control with 128-130
 - overview 117-123
 - sound-and vibration-sensors 125-128
- CRW, Corn rootworm (CRW)

- Dasineura brassicae* 19-20
- Decision support systems (DSSs) 16, 31, 244, 248, 249, 254, 256
- Density-based economic thresholds 222
- Diaboloacatantops axillaris* 161
- Diamond-back moth monitoring network 249
- Diaphorini citri* 128, 129
- Direction-finders 169

- Direct visual assessment 26
 Direct visual counts 218
Drosophila suzukii 199
 DSSs. *see* Decision support systems (DSSs)
- EAGs. *see* Electroantennograms (EAGs)
 Early detection and rapid response (EDRR) 329, 330
 ECB. *see* European corn borer (ECB)
 ECB sex pheromone 51
 Economic injury level (EIL) 52, 220, 341
 Economic threshold (ET) 52, 341
 Economic threshold concept 215, 216, 219, 220
 EDRR. *see* Early detection and rapid response (EDRR)
 Effective attraction radius 99
 Effective phytosanitary measures, prevent invasive insect pests
 case study
 against *Anoplophora chinensis*, EU 309-311
 against *Bemisia tabaci* and *Liriomyza huidobrensis*, UK 307-309
 challenges 313-316
 within framework of pest risk analysis 298-299
 international agreements and trade intervention 294-297
 overview 293-294
 pest-free area 303-304
 pest-free countries 299-303
 pest-free place of production 304
 pest-free production site 304
 phytosanitary treatments 304-306
 systems approach 311-313, 316
 Effective sampling area (ESA) 99
 EIL. *see* Economic injury level (EIL)
 E-isomer 50
 Electroantennograms (EAGs) 118
 Electroretinograms (ERGs) 120
 Entomological radar 155
 Eradication programme 306
 ERGs. *see* Electroretinograms (ERGs)
 ESA. *see* Effective sampling area (ESA)
 ET. *see* Economic threshold (ET)
 European corn borer (ECB) 49-53
 EUROPHYT database 310
 E-Z hybrid 50
- FarmSense device 126
 Flight boundary layer (FBL) 149, 153
 Forecast systems 248
- Gas chromatography 7
 General surveillance 303
 Geographic information systems (GIS) 223, 224, 227, 229
 GERDA. *see* Global Eradication and Response Database (GERDA)
 GIS. *see* Geographic information systems (GIS)
 Global arthropod eradication programs 333, 334
 Global Eradication and Response Database (GERDA) 333, 335
- HAD. *see* Host-associated differentiation (HAD)
Halyomorpha halys 344-346
 Harmonic insect detectors 169
 Harmonic radar 169
Helicoverpa spp., 171
 Host-associated differentiation (HAD) 130
 Host plant resistance 220
 Host plant tolerance 220
- Image analysis algorithms 27
 Image-based identification and analysis
 automated and semi-automated
 image-based insect identification 205-206
 automated image-based insect identification 199-202
 commercially available systems 206-211
 machine vision image-based insect identification 202
 classification 204
 feature extraction 203-204
 image capture 202
 image processing 203
 segmentation 203
 overview 197-198
- Insect pests monitoring, United States corn (*Zea mays* L.)
 corn earworm (CEW) 53-56
 corn rootworm (CRW) 57-61
 European corn borer (ECB) 49-53
 western bean cutworm (WBC) 56-57
 cotton (*Gossypium* spp. L.) 47
 bollworm (corn earworm) 72-75
 plant bugs 71-72
 tobacco thrips 69-71
 future trends 74-75
 overview 47-48
 primary crops 48-49
 soybean (*Glycine max* [L.] Merr) 47

- Japanese beetle 65-69
- soybean aphid (SBA) 61-62
- stink bugs 62-65
- Insect pest trap networks, quantifying
 - captures from
 - applications
 - large area surveillance 103-105
 - trap attraction estimation 100-103
 - other models 98-100
 - overview 91-94
 - practicum 106-111
 - TrapGrid model 94-98
- Insect sampling 231
- Instantaneous capture probability 96
- Integrated Pest Information Platform
 - for Extension and Education (iPiPE) 234-236
- Integrated pest management (IPM) 48, 117, 148, 215, 236, 245, 253
- International Plant Protection Convention (IPPC) 295, 298
- Internet of things (IoT) technology 120
- Invasive plant pests, potential economic impact
 - case study
 - pine wood nematode (*B. xylophilus*) 281-283
 - Xylella fastidiosa* 283-288
 - complexity level selection
 - appropriate assessment method 276-279
 - context setting economic impact assessment 275-276
 - economic analyses, support pest risk management 279-280
 - future trends 288-289
 - methods
 - computable general equilibrium modeling 274-275
 - input-output (I-O) analysis 273-274
 - partial budgeting 268-270
 - partial equilibrium modeling 270-273
 - overview 267-268
- IoT. *see* Internet of things (IoT) technology
- I-O tables 273, 274
- iPiPE. *see* Integrated Pest Information Platform for Extension and Education (iPiPE)
- IPM. *see* Integrated pest management (IPM)
- IPPC. *see* International Plant Protection Convention (IPPC)
- Isothiocyanates lures 19
- ISPM 15, 305
- Johnson-Taylor suction trap 14, 25
- Kairomones 7
- LeafByte 68
- LEDs. *see* Light-emitting diodes (LEDs)
- Lepidoptera 7
- Lidars 164
- Light-emitting diodes (LEDs) 6, 122
- Light trapping 5, 6, 218
- Lindgren funnel trap 21, 22
- Live trapping mechanism 209
- Live traps 201
- Lymantria dispar dispar* 342-343
- Lysiphlebus testaceipes* 226
- Machine learning 27
- Malaise trap 17, 18
- Male annihilation (MAT) 92
- Market equilibrium 270, 271
- Mark-Release-Recapture (MRR) 100, 102, 106
- MAT. *see* Male annihilation (MAT)
- McPhail trap 23, 28, 199
- Meso-scale technology 120
- Methyl bromide 314
- Microsoft Premonition project 31
- Migratory behaviour 149
- Mitigating invasive insect species eradication
 - campaigns in agriculture 333-340
 - challenges 332-333
 - concepts 330-332
 - factors 332
 - future trends 347-348
 - invasive species management 328-330
 - long-term management
 - integrated pest management 340-341
 - managed through integrated pest management 342-346
 - overview 325-328
- Molecular identification techniques 328
- MRR. *see* Mark-Release-Recapture (MRR)
- Multiple data layers 223
- Multiple image processing algorithms 125
- Multispectral imaging 202
- Nano-scale technology 120
- National Plant Protection Organizations (NPPOs) 295, 299, 303, 305, 315
- NDVI. *see* Normalized vegetation index (NDVI)
- Near-infrared (nIR) illumination 155, 163, 164

- Night-vision goggles 155
- Non-conspicuous delta trap 13
- Normalized vegetation index (NDVI) 227
- Northern Irish trap 16
- NPPOs. *see* National Plant Protection Organizations (NPPOs)
- Nylon-mesh traps 54, 55
- Orange wheat blossom midge (OWBM) 250
- PAM. *see* Portable passive acoustic monitoring (PAM)
- Partial equilibrium 277-279
- PCNs. *see* Potato cyst nematodes (PCNs)
- PCs. *see* Phytosanitary certificates (PCs)
- Pectinophora gossypiella* 335-336
- Pest-free area (PFA) 303-304
- Pest-free place of production (PFPP) 304
- Pest-free production site (PFPS) 304
- Pest population growth and geospatial data
- basics and economic threshold
 - adjustments, pest monitoring 217-219
 - crops exhibiting plant resistance 220-221
 - pest population growth into economic thresholds 219-220
 - sugarcane aphid as pest of sorghum 221-223
 - case studies
 - cotton pests spatial variability, pest monitoring and management 231-234
 - GIS to create pest risk maps, in-field use 227-231
 - pest information networks, regional pest risk assessment 234-235
 - spatial pest risk assessment, cotton production region 234
 - future trends 235-237
 - geospatial data, pest risk assessment 223-224
 - spatial variation within and between fields 224-227
 - overview 215-217
- Pest risk analysis (PRA) 297-299
- Pest risk assessment techniques, invertebrate pests, European outdoor crops
- barley yellow dwarf virus (BYDV), winter wheat
 - assessing abundance 256
 - barley yellow dwarf virus load 256-257
 - hazard an infestation represents to crop performance 256
 - likelihood of infestation 256
 - pest priority 255
 - preventing/mitigating for 257
 - future trends 258
 - hazard of pest infestations 250-251
 - remote sensing and image-recognition technology 251-252
 - likelihood of pest infestations 245-246
 - on field monitoring 246-247
 - on forecast models 248-249
 - on observation networks 249-250
 - overview 243-245
 - risk reduction
 - managing infestations 252-253
 - preventing infestations 252
 - risk vs. perception of risk 253-254
 - steps 254-255
- PFA. *see* Pest-free area (PFA)
- PFPP. *see* Pest-free place of production (PFPP)
- PFPS. *see* Pest-free production site (PFPS)
- Pherobase 7
- Pheromone-baited delta traps 12
- Pheromone baited traps 335
- Pheromones 118
- Pheromone traps 7, 51, 52, 54
- Phytophagous insects 9
- Phytosanitary certificates (PCs) 299
- Pine wood nematode (PWN) 281-283
- Pitfall traps 8
- Plan position indicator (PPI) 157
- Platygaster subuliformis* 20
- Portable passive acoustic monitoring (PAM) 125
- Potato cyst nematodes (PCNs) 246, 247
- PPI. *see* Plan position indicator (PPI)
- PRA. *see* Pest risk analysis (PRA)
- Probability density function 98
- Push-pull strategies 129
- Quantifying capture probability 91
- Radio-frequency identification (RFID) 169
- Random point sampling 231
- Regional pest risk assessment 216
- Reliable forecast systems 249
- Remote sensing 149
- Remote-sensing observations 175

- RFID. *see* Radio-frequency identification (RFID)
- RIS. *see* Rothamsted Insect Survey (RIS)
- Risk-averse approach 257
- Rothamsted Insect Survey (RIS) 15, 16
- SADIE. *see* Spatial Analyses by Distance IndicEs (SADIE)
- SASA. *see* Science and Advice for Scottish Agriculture (SASA)
- Scale dimension 276
- Scheimpflug lidar 165
- Science and Advice for Scottish Agriculture (SASA) 15, 16
- Scope dimension 275
- Scouting 197
- Semiochemical-baited traps 247
- Semiochemical lures 10
- SIT. *see* Sterile insect technique (SIT)
- Slugs 248
- Smart Palm system 128
- Sodium benzoate 9
- Soil sampling 218, 247
- South Texas cotton system 231
- Spatial Analyses by Distance IndicEs (SADIE) 72, 225, 226
- Speed scouting 61, 63, 75
- Spodoptera frugiperda* 128, 326
- SPS Agreement 295
- Sterile insect technique (SIT) 331, 335, 337
- Sticky traps 201
- Sugar-and protein-based baits 339
- Synthetic pesticides 244
- Teia anartoides* 336-337
- Telemetry 201
- Tephritid fruit flies 93
- TFI. *see* Treatment Frequency Index (TFI)
- Thrips Infestation Predictor 70
- Time dimension 276
- Transmitter tags 168
- Trap networks 92
- Trapping crop insect pests, techniques
 - attractive trap
 - colour and light, visual cues 5-6
 - semiochemicals, olfactory cues 6-8
 - automated traps
 - automated counting and identification 25-26
 - automated identification via wingbeat harmonics 27-29
 - automated visual identification 26-27
 - time-sorting traps 25
 - elements 4-5
 - funnel and cone traps 21-23
 - boll weevil monitoring 23-24
 - key challenges, pest monitoring 24
 - future trends 30-32
 - interception traps 17-19
 - cross-vane trap, *Dasineura brassicae* sampling 18, 19-20
 - key challenges, pest monitoring 20-21
 - overview 3-4
 - sticky traps 11-12
 - key challenges, pest monitoring 13
 - pea moth 12-13
 - suction traps 14-15
 - key challenges, pest monitoring 16-17
 - Rothamsted trap network 15-16, 29
 - water traps 8-9
 - aphids on potatoes 9-10
 - key challenges, pest monitoring 10-11
- Treatment Frequency Index (TFI) 245
- Trissolcus japonicus* 346
- Unmanned aerial systems (UAS) 227
- Unmanned aerial vehicle (UAV) 152
- Vertical-entomological radars 120
- Vespa mandarina* 338-340
- Volatile organic chemicals (VOCs) 118, 122, 129
- Western bean cutworm (WBC) 56-57
- Window traps 17
- Wind-tunnel tests 149
- Wingbeat frequency 27, 29
- Wing-style trap 56, 57
- Wire-mesh Hartstack trap 54
- Wood packaging materials (WPM) 305
- World Trade Organization (WTO) 294, 295
- WPM. *see* Wood packaging materials (WPM)
- WTO. *see* World Trade Organization (WTO)
- X-band 156
- Yellow sticky trap 59
- Yellow water traps 9
- Yield Enhancement Network 245
- Z-isomer 50
- ZLC configuration 158, 161