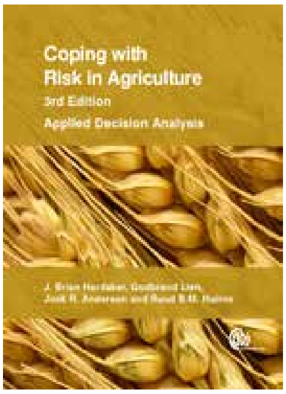
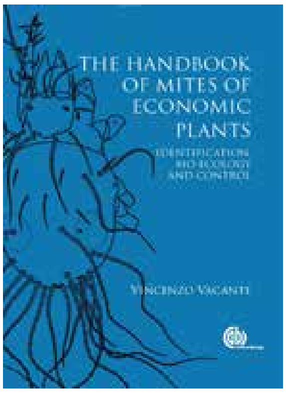
CABI in review 15

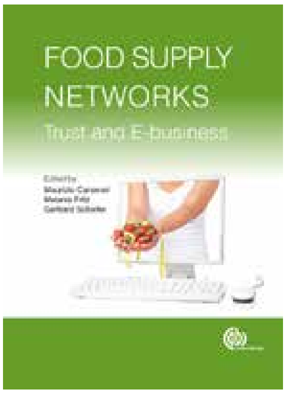
Selected book chapters

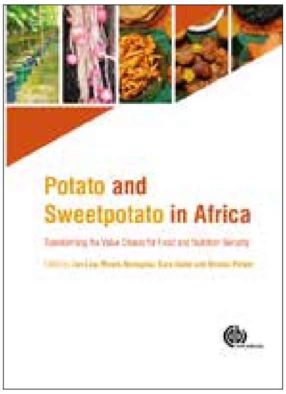
For our annual review this year, we have made available selected chapters from CABI books in a CABI in Review 2015 eBook.

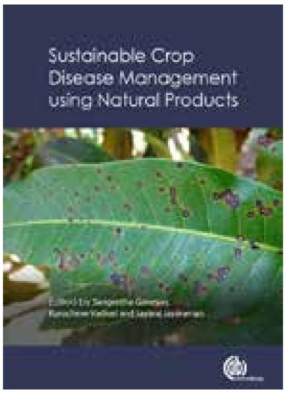
The chapters have been taken from the following books (click on the book to take you directly to that chapter).

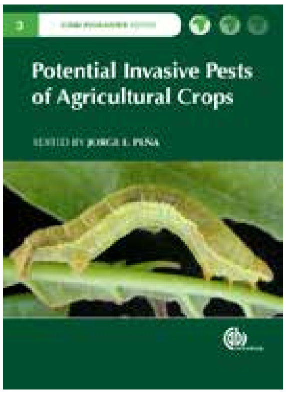


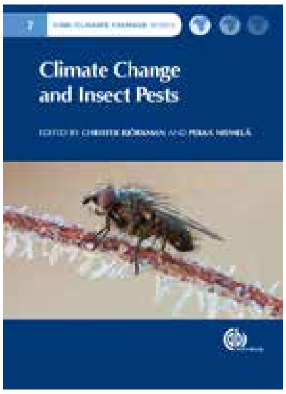












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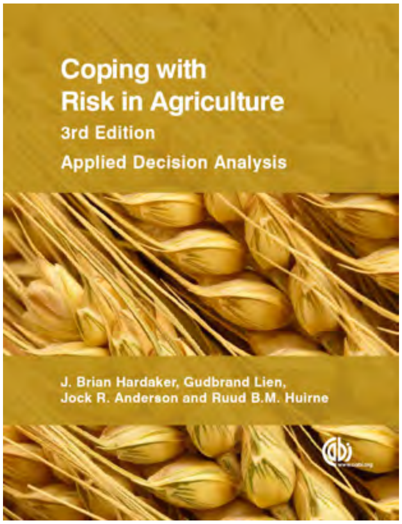

Coping with Risk in Agriculture: Applied Decision Analysis, 3rd Edition

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Preface to the Third Edition

The purpose of this edition of the book is the same as for earlier editions. Our aim is to support better agricultural decision making by explaining what can be done nowadays in risk analysis and risk management. As before, the intended readership includes senior undergraduate or graduate students of agricultural and rural resource management, agricultural research workers, people involved in advising farmers, such as extension workers, financial advisers and veterinarians, some farmers themselves, and policy makers.

Methods of risk analysis and management are evolving rapidly. In this third edition we have included some recent advances in both theory and methods of analysis. New material includes sections on state-contingent versus stochastic production functions and an introduction to the use of copulas for modelling stochastic dependency.

Improvements in available software continue to expand the scope to better represent and model real-world risky choices, and we have updated our advice concerning use of contemporary software.

We wish to thank Priscilla Sharland for her editorial input. Thanks are also due to Claire Parfitt, our commissioning editor, and to other staff at CABI, especially to Alexandra Lainsbury and Lauren Povey, for their professional work and encouragement in the production of this third edition.

Note

Dollar signs are used throughout to indicate money units but are not specific to any particular currency.

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Ruud B.M. Huirne

13

Risk Considerations in Agricultural Policy Making

Introduction

Our illustrations in earlier chapters demonstrate that the type and severity of risks confronting farmers vary greatly with the farming system and with the climatic, policy and institutional setting. This is the case in both more developed countries (MDCs) and less developed countries (LDCs). Nevertheless, agricultural risks are prevalent throughout the world and, arguably, have increased over time, as is suggested by the food, fuel and finance crises that have beset the world since 2007. Moreover, climate change appears to be creating more risk for agriculture in many locations. These prevalent and prospective agricultural risks have naturally attracted the attention of many governments – groups of DMs who have so far received little focus in our discussion. In this chapter we address analysis of risk management from this rather different point of view.

In our treatment we deal first with government interventions that have risk implications. Governments should realize that they are an important source of risk, as explained in earlier chapters, in particular when interventions negatively affect the asset base of farms. Potentially successful interventions are not those that merely reduce variance or volatility, but those that increase risk efficiency and resilience (to shocks, such as occasions of severely reduced access to food in LDCs, or extreme weather conditions). In many cases, this means increasing the expected value rather than decreasing the variance. In regard to specific instruments whereby farmers can share risk with others, we argue below that only in the case of market failure is there any reason for government involvement. Market failure is most severe in the case of so-called '*in-between risks*' or *catastrophic risks*. As explained later, in-between risks are risks that, by their nature, cannot be insured or hedged. Catastrophic risks are risks with low probabilities of occurrence but severe consequences. In this chapter we address issues in developing policies to manage these difficult risks as well as the management of some emerging risks, such as extreme weather, food-price spikes, food safety, epidemic pests and animal diseases, and environmental risks.

Government Intervention and Farm-level Risk

Background

Governments tend to want to intervene when they perceive that market mechanisms will not deliver economically efficient, socially desirable, environmentally sustainable or politically expedient outcomes. Such situations can be broadly conceived as forms of market failure. Unfortunately, however, it is not

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necessarily the case that all market failures can be fixed by government intervention. First, economic, social, environmental and political goals are often conflicting. Consequently, measures to improve the attainment of one goal will often have unintended and possibly seriously deleterious consequences in terms of other goals. So, for example, subsidies designed to support farmers' incomes may induce serious economic distortions and may lead to undesirable intensification of farming systems, thereby possibly harming the environment. In this chapter, we leave political considerations to the politicians and focus mainly on economic efficiency with some consideration given to social welfare and the environment.

Second, while markets certainly do fail in some situations, it is by no means always the case that government intervention will make things better. Sometimes, the information needed to design an effective policy may be too difficult and expensive to collect, or may even be unobtainable. Then the administrative costs of intervention may be high and unjustifiable relative to the likely benefits. Moreover, market failures have to be balanced against administrative failures. Some policy measures, especially those of a 'command and control' nature, may be too difficult to implement effectively. Even a well-designed policy may fail if the public servants responsible for its implementation are incompetent or corrupt, inappropriately trained and experienced, or inadequately supervised and resourced.

Experience shows that policy intervention in agriculture is a tricky business, to the extent that decisions about such interventions fall clearly into the category of risky choice. Evidently, policy analysts could well use some of the previously described methods of decision analysis to better account for the uncertainty of (often multi-attributed) outcomes that proposed interventions are intended to achieve.

Any government intervention that affects farmers' costs and returns will also affect their risk efficiency. As illustrated in Fig. 12.1 in Chapter 12, it is a mistake to think of policies relating to risk in agriculture solely in terms of measures to reduce volatility of production, prices or incomes. Of course, such measures are certainly important and are addressed later in this chapter. On the other hand, as is also clear from Fig. 12.1, any intervention that has the effect of shifting the CDF of a farmer's uncertain income to the right will be risk efficient in the sense that it will be utility increasing for any farmer who prefers more income to less, regardless of attitude to risk. Even when the intervention does not produce a stochastically dominant improvement in farmers' returns in the sense of Fig. 12.1, the result may still be risk efficient for moderately risk-averse farmers, as discussed in relation to Fig. 12.2. Moreover, the converse is also true. An intervention that reduces the volatility of farmers' returns at the cost of a leftward shift in the CDF may well decrease risk efficiency – a point that we believe is not universally well understood.

Decision analysis and policy making

Dealing with risk in public choice, in principle, merely involves application of the ideas set out in agricultural management contexts in earlier chapters. Such decisions always embody risks. Recognizing these systematically sets the scene for their better management by policy analysts and DMs. Documenting deliberated mechanisms for protecting against specific downside risky outcomes, and for dealing with them if and when they emerge, means that decision analysts have probably done their job properly. Decision analysts working on policy issues also need to alert implementers to their obligations to limit exposure to risk, to monitor progress and prospects, and to respond in an appropriate and timely manner when things go wrong. Our discussion of the virtues of flexibility (Chapter 12) in project design is naturally highly relevant to this theme. Needless to say, due accounting for downside risks should enter any *ex ante* assessment of the expected returns from a given choice in order not to send wrong signals to those making decisions about the acceptability of available options.

The need for a proper *ex ante* appraisal of such public choices raises the issues of what probabilities and what utility function should be used in such analyses. We have presented some ideas on how the formation of 'public' probabilities for risky policy analysis might be addressed in Chapter 3. In regard to choice of utility function, we consider first the case where all the consequences of the policy choice are adequately measured in money units via some form of cost–benefit analysis leading to a probability distribution of a measure of worth to society such as net present value. What degree of risk aversion is applicable to the appraisal of such a distribution?

Arrow and Lind (1970), in a seminal analysis of public investment under uncertainty, argued that society is usually able to pool its risks effectively by means of the large numbers of people sharing the risks, so that society as a whole is, to all intents and purposes, neutral towards risk. Cases that these authors say are unusual or exceptional do, however, occur. They are concentrated on project appraisal in LDCs and deserve brief comment here. The classic analysis is that of Little and Mirrlees (1974, p. 316), who outlined when something other than the maximization of expected net present value would be appropriate. Briefly, when a public project is large relative to national income, or highly correlated with such income, or a particular disadvantaged group is involved, there is a strong case for explicit accounting for riskiness of alternative actions, or equivalently, for explicitly taking account of social risk aversion through use of an appropriate social utility function. Simplified methods of accounting for such risk adjustments have been suggested by Anderson (1989) and are described in Chapter 5, this volume (see Eqn 5.25).

The issues are somewhat less clear when the nature of the public choice requires the evaluation of multi-attributed consequences. Whose preferences are then to be used to assess attribute utility functions and weights? There is no simple answer to these questions. Some analysts have been able to gain access to the DMs themselves (or their senior advisers) to undertake the needed assessments. Others have used sample surveys of members of the affected groups or representative panels thereof. These latter approaches raise hard theoretical problems about the legitimacy of combining utility functions in the face of Arrow's so-called 'Impossibility Theorem' which asserts that such interpersonal utility comparisons are invalid (Arrow, 1963). Perhaps it is not surprising, therefore, that some analysts have sought to dodge these tricky questions by recourse to some arbitrary rating methods. Similarly, some economists have sought to assign money values to intangibles to extend conventional cost–benefit analysis. Unfortunately, all such methods imply the adoption of an underlying utility function, so the problem has been implicitly hidden rather than really solved. We do not expect a solution to this puzzle to be found in the near future.

Interventions to improve farm productivity and incomes

Policies that governments can and often do adopt to achieve desirable shifts in farm incomes and risk efficiency include measures to improve farm productivity and measures to improve farmers' domestic terms of trade.

Because of the public-good nature of much productivity-improving research in agriculture, it is likely that there will be too little investment in research if it is left entirely to the private sector. For this reason, most governments fund agricultural research programmes and many also fund extension programmes to help pass on research findings to farmers.

Policies to improve farmers' human capital may also be expected to improve farm productivity and risk management. Human capital improvement is usually addressed by measures to upgrade rural education and health services. Of course, such interventions have broader objectives and benefits than merely improving farmers' risk management.

Policies that improve farmers' domestic terms of trade can be effective in increasing farm incomes. The most obvious way these risk-reducing benefits can be attained is by governments investing in improved rural infrastructure, such as better farm-to-market roads. Such public goods will not be provided by the private sector, so this is a clear responsibility of governments. Governments can also reform marketing arrangements to promote efficiency improvements through greater competition.

Finally, some public investments in agriculture can be both productivity increasing and income stabilizing. An example can be the provision of irrigation water via public schemes.

Interventions that affect farmers' property rights

A major source of risk for many farmers is insecurity of property rights. In LDCs this risk typically relates to insecurity of access to land, with many farm families being tenants or share croppers who may find themselves dispossessed of their access to land at any time, perhaps with no recourse to legal redress. Particularly in MDCs, governments may act unpredictably to change property rights. Thus, growing concern among the general public may lead governments to act to curtail farmers' rights to use land in particular ways. In Australia, in order to try to protect biodiversity and endangered species, measures have been introduced to prevent farmers from clearing their land without special permission. In general, the affected farmers are not compensated for the loss of what was previously a property right. Evidently, governments, particularly those in LDCs, can reduce farmers' risk exposure by codifying and enforcing reasonable property rights, while those in MDCs might at least think carefully about measures introduced for environmental or other reasons that may seriously curtail pre-existing property rights of farmers to an extent that may threaten the viability of their operations.

Interventions for risk prevention and abatement

Just as farmers need to review measures to prevent or reduce the chances of bad events happening, so do governments, in those areas where they have main responsibility. Usually it is government responsibility to try to maintain quarantine and other border protection measures to prevent the importation of potentially disastrous pests, diseases and weeds. The reason is that such problems entail significant market failure in the form of externalities – those who by their negligence introduce or spread the problem seldom bear the cost of their actions. Partly for the same reason, it is also usually government responsibility to deal with and try to minimize the impacts of outbreaks of such exotic infestations when they occur. That means having plans in place to limit any outbreaks that happen, and making sure that there are resources available to implement those plans speedily and effectively.

The operation of such programmes often raises difficult questions about who pays for the costs of controlling an epidemic. If the levels of subsidy to affected farmers are inappropriately set, they create undesirable incentives. For example, if the compensation to a farmer whose animals are compulsorily slaughtered is set too high, there may be an incentive not to take all precautions to avoid an outbreak among animals on that farm, especially if farm profitability is being harmed by restrictions such as movement bans. On the other hand, setting compensation too low may incite some farmers to hide the existence of animals with disease symptoms in the hope of avoiding having all stock slaughtered.

There are other areas where government actions to avoid and abate risks affecting agriculture (and often other sectors) are important. Governments can do little to prevent extreme weather events but they can plan to reduce their impacts by, for example, making appropriate investments in such public goods as levees to contain swollen rivers or providing fire breaks in forested areas to limit the spread of wildfires. Warnings of impending disasters, such as floods, can help to avoid or limit their impacts, as can government disaster management systems that swing into operation quickly and effectively when such disasters strike.

Interventions to deal with the casualties of risk

The nature of risk means that sometimes things go wrong, perhaps very wrong, so that individual farmers or, more often, groups of farmers, experience serious losses. For family farms, this can mean significant economic distress. Living standards may have to be cut and, in the extreme, even the basic necessities may not be affordable. While family, friends or charities may help, there may also be a need for government help.

Disaster relief

Most governments will try to help if there is a disaster leading to human suffering. There can be little argument about the need for such assistance. The problems begin when the definition of a disaster is broadened to encompass more modest falls in incomes, perhaps even merely rather bad outcomes lying well within the typical dispersion of outcomes. Such ‘disaster relief’ policy, or sometimes the lack of it, represents a significant opportunity for analysis of potential public intervention (e.g. Anderson and Woodrow, 1989). There has been a tendency for emotion and public outcry to drive a process that leads governments to intervene in ways that, with the wisdom of hindsight, are demonstrably ineffective and distorting of individual incentives to plan more carefully for what in many situations are inevitable occasional bad outcomes. Such planning would naturally include prudent management of finances and selective purchase of risk-sharing contracts such as insurance, as discussed in Chapter 12. Hence the routine provision of disaster relief will have predictable negative consequences for broad participation in formal insurance markets. If governments rush to bail people out of the effects of otherwise-insurable natural disaster risks whenever there is clamour to do so, development of commercial insurance markets will be fatally compromised.

Poverty relief and social welfare

In most MDCs, safety nets exist to support those in society who strike hard times. For example, it is common for income support payments to be made to families on low incomes. In principle, the same support payments might be available to help farm families whose incomes are low owing to falls in production or prices. The availability of such payments would reduce, perhaps eliminate, the need for expensive special schemes of farm income support, such as subsidized farm revenue insurance.

A problem with this solution is that social welfare payments are often subject to both income and asset eligibility tests. Farmers, especially owner occupiers, are typically asset rich but income poor. Under some social security schemes, they might be required to sell the farm and live off the proceeds before they could be entitled to support. That makes little sense if the fall in income is temporary and if the farm can continue to generate a reasonable income once the current crisis is over. The problem can be solved by appropriate revision of eligibility rules. Equity considerations suggest that the same revised rules should apply to all self-employed people in similar situations, not just farmers.

In LDCs, the payment of income supplements can seldom be afforded, but it may still be possible for governments to implement measures to deal with short-term poverty via such means as food-for-work schemes and other safety-net schemes such as schemes to transfer cash to targeted recipients, perhaps conditional on them qualifying in some socially determined way such as maintaining attendance of children in school. In cases of serious downturn in farm production, international agencies may come in with famine relief, although disillusion with many past interventions has led to a shift towards making resilience a focus.

Resilience, according to the Organisation for Economic Co-operation and Development (OECD, in some 2013 advice to its Members), is most often defined as the ability of individuals, communities and states and their institutions to absorb and recover from shocks, while positively adapting and transforming their structures and means for living in the face of long-term changes and uncertainty. In a variety of development agencies, resilience has emerged not so much as a new conceptual construct but rather as an organizing framework that facilitates integration of humanitarian and development efforts. As an organizing framework, there seems scope for refinement into practical interventions in the diverse risky situations of the developing world. Efforts to mitigate and adapt to climate change constitute one important example. Using resilience as an organizing framework may facilitate more effective integration of both adaptation to risk and risk mitigation into broader development efforts. Work on strengthening informal and formal collective action, including work on governance, can also become better integrated into broader development efforts (Constas *et al.*, 2014).

Programmes designed to limit or prevent human suffering should, in principle, be well justified as well as meritorious. If implemented effectively, they should ideally somewhat reduce the need for other forms of government intervention in agricultural risk management.

Market Failure for Risk

In the ideal world sometimes assumed by economists, a full range of ‘contingency’ markets would exist that would enable economic agents to neutralize risks. In such a world, a risk-averse DM would be able to ‘offload’ as much risk as desired, no doubt sacrificing some reduction in expected income in consequence. In reality, not all such contingency markets exist and some of those that do are not fully effective in enabling farmers and others to share risks.

Individuals such as farmers would be able to smooth consumption flows to a large degree if the financial system were perfect. As discussed in Chapter 11, if farmers had access to a perfect finance system so that they could save in good times and borrow when times were hard, they could afford to make decisions on the basis of maximizing expected returns. Of course, no perfect finance market exists. In MDCs, where finance markets are relatively well developed, saving is easy enough, but credit may not always be available when needed. Even when available, it is offered at a higher interest rate than is available on deposits. Moreover, a prolonged spell of hard times, such as a long drought, could leave a farmer with an unsustainable level of debt. In LDCs the position is often worse. Many farmers have limited access to formal credit and may face usurious interest rates on informal credit. While improvements in farmers' access to financial services may ameliorate the situation, there may still be a need for other risk-sharing mechanisms.

Especially in MDCs, many mechanisms exist for risk sharing, but they are neither costless nor as widely available as might be thought desirable. Key questions are the extent to which there is market failure for risk in agriculture, how serious that failure is, and what can sensibly be done about it. The answers to these questions provide a basis for evaluating the need for, and merit of, government intervention in making risk markets more complete.

In thinking about markets for risk it is important always to recall that not all risks are the same. There is a spectrum of risks that can afflict farmers. At one end of this spectrum there are *independent risks* that are not appreciably correlated across farms. For example, the risk of theft of farm property usually strikes only one or two farms in an area at one time. Independent risks of this type are usually insurable, subject to some conditions that we shall examine below. At the other end of the spectrum are risks associated with falls in commodity prices, interest rate hikes or changes in exchange rates that have highly correlated impacts on many farmers at the same time. For example, a commodity price fall will affect all farmers who produce that commodity, just as all farmers in debt will be affected if interest rates rise. These kinds of risk can be called *covariate risks* because they affect most farmers operating in a particular market system. Risks of this kind are not usually insurable because insurers are not able to pool them. On the other hand, at least some covariate risks can be managed through derivative markets.

Many of the risks that confront farmers and others in agriculture lie on the spectrum of types of risks between covariate risks at one extreme and independent risks at the other. Following Skees and Barnett (1999), we call these *in-between risks.* They are neither independent nor highly correlated. Yet they can, on occasions, lead to high losses for insurers. For this and other reasons, discussed below, such risks can seldom be insured at affordable costs to farmers. On the other hand, since these risks are only moderately correlated, they generally cannot be managed through (traditional) derivative markets. It is therefore for these kinds of risk that there has usually been greatest pressure for government intervention. We examine these risks further below.

Derivative markets for agriculture

As far as covariate risk is concerned, it can be expected that these markets will evolve and develop as financial and risk markets deepen. It is of some concern, however, that, to date, rather few futures and related derivative products exist in agriculture. Exchanges that trade agricultural derivative products are located primarily in the USA, but also exist in Australia and Europe. Some agricultural derivatives trade on very thin markets. For others, trading was so limited that the derivatives were discontinued. Such outcomes seem at variance with the supposed need for farmers to be able to hedge risks. The reasons why so few farmers use these products to hedge risk were discussed in Chapter 12. They include the possibility that farmers are not as risk averse as is widely presumed.

Insurance markets for agriculture

In order to understand why there may be market failure in insurance markets for agriculture, we first need to consider the requirements for a risk to be insurable.

Conditions for risks to be insurable

The following are the ideal conditions for a risk to be insurable (adapted from Rejda, 2003):

1. A large number of homogeneous insured clients facing independent risks – necessary for the insurer to be able to pool the risk.
2. Accidental and unintentional losses – insurance can be problematic if losses are influenced by the management of the insured.
3. Determinable and measurable losses – the amount of loss and the extent to which it was caused by an insured event need to be unambiguous for proper loss assessment.
4. No catastrophic losses – the losses must be sufficiently independent and individually constrained so that there is an acceptably low risk of total losses so large as to threaten the solvency of the insurer.
5. Calculable chance of loss – necessary for the insurer to be able to rate the risk to set a premium, which may be problematic for low frequency, catastrophic loss events.
6. Economically feasible premium – if the premiums are too high, as would be required for high frequency but non-catastrophic events, clients will find it more profitable to retain the risk and absorb it as part of normal operating expenses.

When all these conditions are reasonably well met, insurance products are likely to be available, albeit at premiums that will be somewhat above the expected value of the risk by a margin for the insurer's normal administrative costs and profit. In so far as some conditions are not met, the cost of insurance will be higher, or only partial, or no cover at all may be available.

Reasons for failure of insurance markets for agriculture

Asymmetric information

A main source of failure in risk and related markets arises because of *informational asymmetry* between parties to potential contracts. Such asymmetry occurs when one of the parties has more or better information about a risky outcome than the other. As a result, it can be difficult or impossible for the parties to strike an effective contract. For instance, the market for many factors of production (such as farm finance or rented land) is somewhat imperfect because farm operators invariably know the operating environment and its risks better than potential providers of such services.

In decision making under uncertainty, informational asymmetry causes two main problems (Milgrom and Roberts, 1992): *adverse selection* and *moral hazard*.

Adverse selection is a problem of pre-contractual opportunism related to unobserved or hidden characteristics of a good or service traded, as in the productive services example. In the insurance industry adverse selection is the tendency of those who face higher risks of experiencing an insurable loss to buy insurance cover to a greater extent than those with average or lower expectations of loss. Adverse selection therefore represents a breach of the first condition listed above for risks to be insurable. Yet insurance may still be feasible if less effective. Faced with substantial adverse selection the insurer must set a higher premium (or face a loss) if informational asymmetry makes it impossible to identify the clients with higher risk and to rate policies differentially.

To manage adverse selection, many insurance contracts include a duty of disclosure clause making the contract invalid if the insured party fails to inform the insurer about any adverse circumstances affecting the insured risk. Insurers can also discriminate against clients who make frequent claims by loading premiums, but such measures may not completely solve the problem.

The second cause of market failure owing to informational asymmetry, moral hazard, refers to unobserved or hidden actions by one of the parties to a contract to the detriment of the other party. Moral hazard is a form of post-contractual opportunism. In the insurance industry the term is used to describe the tendency of people with insurance to change their behaviour in ways that lead to larger or more frequent claims against the insurer. For example, a farmer with crop insurance may choose to neglect a poor crop, knowing that the insurer will pay for any shortfall in yield below the insured level. Such behaviour is a breach of the second condition set out above for risks to be insurable. Moral hazard impairs the ability of parties to make mutually beneficial agreements and so limits the effectiveness of markets for risk. Overcoming moral hazard problems by monitoring behaviour is often impossible or at least too costly. Problems may sometimes be reduced by including an appropriate incentive in the contract. For example, an insurance contract may be written with a substantial deductible, meaning that the insured party has to bear the first part of any loss.

Moral hazard and adverse selection problems are not confined to insurance products. They can also be important in other actual or potential markets for risk. It can be argued, for example, that credit institutions, which offer loans at high interest rates, may induce adverse selection of clients, since those who do not plan to repay may be more likely to borrow. High interest rates may also induce moral hazard if borrowers then start to take more risks to try to meet the loan costs. Some ill-conceived government interventions in markets also suffer from problems of informational asymmetry. For example, as noted above, the routine provision of disaster payments to farmers in hard times is likely to encourage greater risk taking, leading to more frequent 'disasters'.

Although both adverse selection and moral hazard are often present for many kinds of risks, it may still be possible to develop a feasible insurance scheme using tools such as deductibles and premium differentiation. For example, optional motor vehicle insurance can be vulnerable to both adverse selection and moral hazard, yet insurance companies have been able to offer policies by being able to rate clients differentially to deal with adverse selection and by the use of deductibles and the like to control moral hazard.

Catastrophic risks

The fourth condition (i.e. no catastrophic losses) usually means that such risks as floods, droughts, hurricanes, all-risk crop yield losses and livestock epidemics have, until recently, seldom been commercially insurable. The reason is that insurers need to hold much larger reserves, or buy expensive reinsurance.

Insurers also confront a problem in rating catastrophic risks because such events are, by their nature, both rare and highly variable in scope and impact. Indeed, the next catastrophe may well be far worse than anything experienced in recorded history. Faced with such imperfect knowledge, insurers are generally obliged to inflate premiums considerably, in case a really bad outcome eventuates.

Despite the problems, the insurance market for catastrophic risks has been growing as a consequence of developments in capital markets, such as the increasing 'securitization' of reinsurance. We discuss the scope for such further growth for catastrophic risks in agriculture below.

In-between risks

In-between risks violate at least some of the ideal conditions for insurability given above. Many in-between risks embody aspects of adverse selection and moral hazard. Crop yield or crop revenue insurance are a good examples. Farmers whose farm conditions, such a soil type, aspect, etc. make them more vulnerable to crop failure than their neighbours are more likely to purchase such insurance. Yet the insurer may not be able to garner the information about such fine differences between farms, or it would be very expensive to do so. Moreover, there is an obvious moral hazard aspect in that yields tend to depend to a considerable extent on crop management. Further, if many farmers in a region were to purchase such insurance and the season was particularly adverse, the insurer could be confronted with catastrophic indemnity payments.

The problems with many in-between risks in agriculture may not prevent the development of products for farmers to share these risks with others, but the violations increase the cost of providing such products and reduce the supply. The result may be failed markets since the socially optimal amount of risk sharing cannot occur.

Other risks that have some of the characteristics of in-between risks for which anxieties about market failure are gaining new prominence include environmental risks, food safety and associated public health issues. However, for many such risks it seems likely that the best approach to remedy perceived problems will not lie in developing new insurance products, since, in many cases, these are likely to be too costly to be economic. Rather, solutions are more likely to lie in better management of the risks themselves.

The Possible Role of Government in the Market for Risks in Agriculture

Understandably, the development of derivative products is proceeding more quickly in those countries where, and for those products for which, government interference is least. For example, there can be no effective futures market for farm products that have prices subject to government manipulation through minimum price schemes. So, if governments want to see farmers offered good commercial opportunities to hedge commodity price risks, they should get out of the price formation process. Governments can encourage the development of derivative products for agriculture by ensuring that the appropriate legal and regulatory frameworks are in place to promote fair trade in such products. Then it is more likely that entrepreneurs will be encouraged to develop and launch new and innovative products to face the test of market acceptability.

Similarly, there would seem to be little need for governments to concern themselves about the market for insurable risks, except again to ensure that appropriate market rules are in place and are enforced. Such supervision should extend to requiring companies to follow sound prudential practices to make sure that funds are available to pay indemnities. When governments step in with more heavy-handed regulation, the results are often unfortunate. Political pressures mean that premiums are typically set too low and indemnity payments are made too generous, so that, sooner or later, a gap in funding opens up and governments may then have to pay for the shortfalls their actions have created.

Only in the case of in-between risks does there seem to be a reasonable case to be made for government to participate actively. The central policy problem in regard to these kinds of risks is that the markets for transferring them, if they exist at all, tend to clear at less than socially optimal quantities of risk sharing. Such failure raises the questions of whether and how governments might intervene to improve the situation. Unfortunately, however, the very reasons that make these risks hard to share through market arrangements also make it hard for policy makers to find ways to protect people (including farmers) from losses suffered owing to in-between risks.

One possible form of intervention that may have some merit is for governments to take a share of the reinsurance of in-between risks. Such reinsurance could be at commercial or subsidized rates, although experience discussed later in the chapter shows that subsidized agricultural insurance has had a rather bleak history. However, there are some arguments in favour of a limited government subsidy for this type of reinsurance, summarized below.

1. Many governments already provide disaster relief. Providing assistance through reinsurance may be more efficient because disaster relief tends to be ad hoc and often involves problems regarding who gets paid and when. For example, it is rare for relief to be paid if only a few farmers suffer severe losses, whereas cover could be individual, or at least local, under an insurance scheme. There are also considerable administrative costs incurred in setting up special agencies to deliver disaster relief. By providing reinsurance, governments can use the experience and capacity of insurance companies in handling large numbers of claims as well as in dealing with moral hazard and adverse selection problems.
2. In some parts of the world, governments already provide continuous payments to farmers (e.g. through price support). Providing assistance through reinsurance seems likely to be more effective, because governments provide assistance when and only when farmers' incomes are low and income enhancement is therefore most needed. The cost to the exchequer (or to consumers) is also much less that way.
3. Having the government financially involved may address a moral hazard problem in government behaviour: many catastrophes (e.g. losses from floods) can be either prevented or magnified by government policies, or lack thereof. Having governments financially responsible for some losses might be an incentive for them to put in place appropriate hazard management measures.
4. Financial involvement of a government in reinsurance may reduce political pressure to provide distorting and often capricious ad hoc disaster relief.
5. Governments can potentially provide reinsurance more economically than can commercial reinsurers. Governments have advantages because of their deep credit capacity and their unique position as the largest social entity in a country. These advantages enable them to spread risks broadly.

While more research is warranted to get a better understanding of the economic, social and practical advantages and disadvantages of government involvement to cover in-between risks, two critical factors in dealing appropriately with in-between risks can be listed. First, government participation, such as providing reinsurance, should be carefully designed with respect to exposure to adverse selection and moral hazard. Otherwise, both farmers and commercial insurers will seek to off-load their losses onto the government. Second, transaction costs, including monitoring and administrative costs, must be kept low if the insurance products developed are to be attractive to potential buyers.

While in principle such public–private partnership for insurance might appear to be rather straightforward, we shall see in the next section that practical results to date have generally been discouraging.

Experience with Public Risk-management Instruments

Given the diversity of their nature, and their proliferation over time and geopolitical boundaries, the experience of risk-intervention policies is, not surprisingly, diverse and varied. A significant focus of the profession of agricultural economics has been on dealing with the instability inherent in the sector, both in MDCs and LDCs. The generalizations presented below represent a synthesis of some relevant studies in the field.

The emphasis here on public intervention reflects the situation that has prevailed in agriculture in most countries. Yet this emphasis on intervention is in stark contrast to the fundamental importance and success of the private sector in overall risk management around the world, such as underpins international trade in agricultural and other products. For instance, the insurance industry, which supports such trade and deals with a diversity of inherent political and other risks, is vital to commerce in general and to the globalization of agriculture. This industry is almost completely private. The importance of the private sector in risk markets is expanding and spreading with globalization. On the other hand, of course, increasing globalization does not yet mean that producers all around the globe have ready access to insurance or other markets, so the many cases in rural areas where such access is absent must be considered.

Price stabilization

Price uncertainty in traded agricultural commodities has long been seen as a significant problem for everyone concerned, from small-scale producer to statutory marketing authority. Price stabilization is the major 'traditional' intervention in the agricultural sector. Various mechanisms have been used to pursue such stabilization objectives, with varying degrees of success and many failures. Probably the most common, and certainly the most significant in terms of the production inefficiencies and distortions to world trade they have caused, have been various forms of guaranteed price schemes for farmers. Because it seems that at last some serious efforts are being made to eliminate or at least scale back these schemes, we shall not dwell on them here. However, the proposed phasing out of such support under World Trade Organization (WTO) agreements has focused interest on other measures that might be used to stabilize farmers' prices. In the past, buffer stocks, buffer funds, variable tariffs and the like have been among the most popular alternatives to guaranteed prices.

The theoretical justification for price stabilization measures has been explored in detail in a number of studies (e.g. Newbery and Stiglitz, 1981). An important frequent finding, however, is that the welfare gains that are possible from price stabilization are relatively small. Moreover, the practical implementation of stabilization schemes raises many thorny problems to be overcome by programme administrators. These include the difficult-to-assess supply responsiveness to induced stability.

Among the important reasons for taking a cautious approach to farm price stabilization schemes is the tendency for political forces to intrude into the management of schemes virtuously put in place, and to modify the rules (e.g. concerning parameters such as trigger prices) in ways that benefit particular groups and inevitably bankrupt the scheme itself, or cause it to be such a drain on the public purse that it becomes impossible to sustain.

Government insurance schemes

Insuring farmers' yields, revenues or incomes has long attracted the attention of governments. As discussed above, these are in-between risks for which covariances of losses are fairly high, aggregate losses often large, and for which there are big problems of adverse selection and moral hazard to be confronted. Naturally, few commercial insurers have ventured into this potential minefield, but the problems have not dissuaded many governments from getting involved. Many schemes have been tried with few successes.

Crop yield insurance

For reasons of asymmetric information, full crop yield insurance has seldom been provided by commercial insurers, although specific risk cover is often available for such defined events as fire and hail damage. There are some recent exceptions to this generalization, but it is still largely true, in both MDCs and LDCs, that such full yield insurance schemes as exist are provided or supported by governments. The motivation for such programmes often originates in political concern about catastrophic risks such as drought, or the desire to reduce the incidence of loan defaults to banks (e.g. see the critical analysis of Hazell *et al.*, 2001).

With few exceptions, the financial performance of public crop insurers has been ruinous (Hazell, 1992). To be financially viable without government subsidies, an insurer needs to keep the average value of annual outgoings – indemnities plus administration costs – below the average value of the premiums collected from farmers. In practice, many of the larger all-risks crop-insurance programmes pay out \$2 or more for every dollar of premium they collect from farmers, with the difference being paid by governments. Even at these high levels of subsidy, many farmers are still reluctant to purchase insurance. As a result, some public crop-insurance programmes have been made compulsory, either for all farmers growing specified crops (e.g. Japan), or for those who borrow from agricultural banks (e.g. Mexico). On the face of it, such compulsory schemes cannot be utility increasing for farmers reluctantly forced to join.

The primary reason for the high cost of public crop-insurance schemes is that they invariably attempt to insure risks that, as noted above, are prone to severe informational asymmetry problems in terms of both adverse selection and moral hazard.

Another overwhelming factor is the moral hazard problem that arises in the contract between government and private insurer if the government establishes a pattern of guaranteeing the financial viability of an insurance provider. If commercial insurers know that any losses will automatically be covered by the government, they have little incentive to pursue sound insurance practices when setting premiums and assessing losses. In fact, they may even find it profitable to collude with farmers in filing exaggerated or falsified claims.

Yet another common reason for failure has been that governments undermine public insurers for political reasons. In Mexico, the total indemnities paid have borne a strong statistical relationship with the electoral cycle, increasing sharply immediately before and during election years, and falling off thereafter. In the USA, the government has repeatedly undermined the national crop insurer by providing direct assistance to producers in 'disaster' areas. Why should farmers purchase crop insurance against major calamities (including drought) if they know that farm lobbies can usually apply the necessary political pressure to obtain direct assistance for them in times of need at no financial cost?

Income and revenue insurance

For farmers, insuring their whole-farm income is likely to be more attractive (i.e. closer to optimizing the welfare of the farm family) than insuring separate components of the income, such as the revenue for a particular commodity. From a commercial insurer's point of view, however, insuring whole-farm incomes is not attractive at all. It includes aspects such as farm operating costs and inventories, which are strongly influenced and easily manipulated by an insured farmer. As a result, severe problems of moral hazard are likely, and adverse selection will also be a problem because farmers usually know more about their future income prospects than do insurers.

Even insuring the revenue (price × yield) for a particular commodity is not a simple task. For instance, in order to rate such a policy an insurer would need information on the stochastic dependency between prices and yields. If the correlation is negative (i.e. lower yields result in higher prices, and vice versa) revenue insurance should be less expensive than insurance for yields only. The correlation may change over time, for example as a result of market liberalization, requiring rate adjustments. Also, insurers need to make forecasts of the price levels at harvest or sale time, yet the volatile nature of agricultural prices means that simple projection using historic information will be unreliable.

These and other problems have not stopped some governments from introducing subsidized farm revenue insurance schemes. The motivation for the introduction of revenue insurance comes from the need for governments to desist from paying subsidies based on farm production under recent WTO agreements. Disaster relief is exempt from these provisions (subject to certain restrictions) and several governments have seized on this loophole to be able to continue subsidizing farmers as a means of retaining their political support.

The best documented of these interventions are the schemes in the USA. After being introduced experimentally in 1996, the US Federal gross revenue insurance scheme quickly grew to a national programme covering an increasingly wide range of products. The level of subsidy support for the scheme has also been growing rapidly.

Skees (1999), in a critique of the schemes at that stage, noted many problems. First, subsidized insurance does not take the risk out of farming. The availability of subsidized revenue insurance is likely to encourage farmers to take more risk in other aspects of their business operations. Second, the value of the subsidized protection, like other farming subsidies, quickly becomes capitalized into land values, making land owners richer, but doing nothing for tenant farmers or new entrants. Third, Skees documented some unfortunate unintended consequences of the schemes. He found that those farmers with the highest risk and those in the higher risk regions gained most from the subsidies. This effect has induced a shift in production of major crops away from the most stable and productive areas to more marginal areas. Moreover, because the subsidies are not 'decoupled' from production, they induce a positive supply response that has a negative effect on market prices. The price declines hurt the producers who are most productive yet for whom insurance is unattractive. The distribution of the benefits among farmers is also inequitable. These subsidies, paid under the guise of revenue insurance, like all such subsidies that are linked to the level of output, go mainly to the better-off farmers who produce most of the insured production, the very ones who least need subsidized support. Perhaps most importantly, Skees concluded that, but for the existence of subsidized insurance, there is no reason why commercial multi-peril crop yield and revenue insurance products could not be developed, as well as a range of other products that would help farmers better manage their risks without the distorting effects of the present schemes.

Evidently, governments might be better advised to look at how they might facilitate the evolution of new and effective insurance products, rather than stepping in with ill-conceived subsidized agricultural insurance schemes that may do more harm than good.

Where governments are encouraging innovation rather than impeding it by provision of competing subsidized products, some commercial solutions to sharing farming risks are emerging. Some of these developments are discussed in the next section.

Continuing Issues in Risk Management

Index-based crop insurance and derivatives

In agriculture, analysts have long had the idea of eliminating moral hazard and adverse selection problems that have bedevilled crop insurance so persistently by insuring, instead of an individual's crop and its performance, some more objectively measured index that is less subject to the unplanned-for influence of the insured. One such index that has been proposed is crop yield assessed over a local area so as to avoid the moral hazards of insuring yields on an individual farm or field basis. However, recently there has been a growing interest in products based on weather indexes.

The original idea of index products for transferring risks was published in the middle of the last century (Halcrow, 1949). With the deepening of financial and insurance markets in the 1990s, it got renewed attention. With index insurance products, payment of an indemnity depends on an objective index based, for example, on observations of rainfall or temperature. To avoid problems of informational asymmetry, the index should be independent and reliable – thus beyond control of both insured and insurer. If the index falls below (or rises above) an agreed threshold value, then indemnities are paid by the insurance company. Because there is a (single) objective index, which is easy to measure at low cost, it is usually relatively easy to calculate the probability that indemnities are due. Index products have the potential, therefore, to be cost-efficient and easy to administer – although climate change, especially change that increases the frequency of extreme weather events, adds an extra degree of difficulty.

It is essential that there is a high correlation between the index (such as amount of rainfall at a specified recording station and in a specified time interval) and the losses suffered by the insured farmers. To the extent that the index is not perfectly correlated with the insured property (for instance, crop yield), the insured is left with a basis risk. The lower the basis risk the higher the effectiveness and the efficiency of the risk transfer. The disadvantage of the basis risk, which will always be present though varying in size, may be more than compensated for by the cost advantages of an index product in terms of lower premium and administration costs.

This idea has been vigorously pursued in various ways, and has been under experimental implementation in a few countries (Greatrex *et al*., 2015). The general idea is that specifically defined perils are insured, such as failure to reach a defined fraction of normal rainfall at agreed recording stations. Insurance policies consist of standard contracts for each unit at a fixed price for a defined region and there are no limits to the number of units an individual can purchase. Even with these simplifications relative to conventional crop-insurance contracts presently used in agriculture, there are implementation issues yet to be ironed out, so it is still premature to declare that such index insurance instruments will necessarily meet the test of the market.

There are also emerging derivative products tied to similar indexes. So, there are reports of what are in effect weather futures being traded that are also based on some objective weather index. Some deals in innovative instruments are commercial in confidence, so it is not easy to assess the current extent of market developments, but it is likely that many more innovative products will be launched in coming years. Some may pass the test of market acceptability and some will no doubt fail. Those that survive will surely broaden the scope for farmers and agribusinesses to share risks in more cost-effective ways.

Food safety and public health

Risks relating to food safety and public health have recently become of increasing concern. These risks are usually caused by hazards in food such as microbial (e.g. aflatoxins and *Salmonella*), chemical (e.g. dioxin, antibiotics, herbicides or insecticides) or physical (e.g. pieces of glass or metal) contamination. The emergence of new pathogens, changes in the food system, and increased trade in food products have all led to more attention being given to food safety issues. A number of countries have updated their food safety regulations, such as the European Union (EU) Food Safety Law of 2002. The food industry is increasing its efforts to certify food safety and reassure consumers. Consumers' confidence in the safety of food has been affected by a number of major food-related crises, such as bovine spongiform encephalopathy (BSE) in beef, dioxin in beverages, melamine in Chinese milk products, formalin in Bangladeshi fish and vegetables and *Escherichia coli* in hamburgers. Although many experts believe that food has never been as safe as it is now, that is not the perception of consumers. The risk of food contamination is an 'imposed' risk for consumers – something over which they have no control. Hence, as discussed by Gardener (2008), they are likely to over-estimate the importance of the risk.

While food may indeed be safer than ever, the risks of widespread problems have also increased. Because food ingredients are increasingly traded worldwide, and it is impossible to check all these ingredients for potential contamination, there is always a risk that something harmful will end up in the food chain. In contrast to earlier years, affected consumers more often try to sue food suppliers for harm they suffer caused by unsafe food. The increased scale of food production and processing means that many consumers can be affected by a single contamination event, raising the prospect of potentially crippling class actions against suppliers of unsafe food. Analysis of the BSE problem showed that, in the worst case, almost all consumers in the UK could have been infected by eating beef or beef products. Similarly, if there were to be an undetected dioxin contamination on a farm producing milk, the processing of this milk into pasteurized milk and milk products (yoghurt, cheese, etc.) could endanger a whole population.

The scale of food safety issues was illustrated by a survey by Buzby *et al*. (1998), which revealed that between 6.5 and 33 million people/year in the USA fall ill from microbial pathogens in their food and, of these, up to 9000 die. In addition, between 2% and 3% of people falling ill following *Salmonella* infections develop secondary illnesses or complications such as arthritis. According to Buzby *et al.*, in the summer of 1997, 25 million lb (about 11,440 t) of hamburger meat was recalled because of potential *E. coli* problems.

The basic problem with food safety is that consumers do not know the level of food-borne-illness risk – contaminants, especially pathogens, cannot usually be identified by visual inspection of the product. Because food suppliers usually have more and better information about the ingredients used and about production and handling, there is informational asymmetry between buyer (consumer) and seller (producer or supplier), implying market failure. The result can be unsatisfactory levels of contamination of food supplied with associated excessive risks to human health. Evidently, in such circumstances public health and social welfare are affected, indicating that intervention by governments may be appropriate.

Most governments do intervene via food safety regulation, and also often through criminal law, so that people who supply unsafe food may face heavy fines or jail sentences. Moreover, as food supply chains nowadays get better organized, using techniques such as electronic tracing and tracking, at least in MDCs, it is growing more likely that blame for a food-borne illness can be traced back to those responsible. Food producers may therefore face large and perhaps catastrophic damages claims. Most therefore seek to protect themselves against such risks by the purchase of product liability insurance that indemnifies them against such claims (though not against criminal penalties). Unfortunately, such insurance cover may create moral hazard problems, to the possible disadvantage not only of the insurer but also of consumers. Partial solutions to this problem, at least for insurers, may be sought through deductibles and co-payments.

Choosing the right mix of measures to improve the safety of food products is itself a risky decision problem. Most such measures are costly and the benefits are usually uncertain. Both for a private business concerned with profitability and financial sustainability, and for a government, concerned about economic and social costs and benefits, the required analyses are challenging. The methods of decision analysis described in this book should surely be relevant to such choices, yet apparently rather little work has been done along these lines. Instead, much of the public debate on these issues seems to be about 'making food safe', which is impossible if taken literally. Even aiming for a near zero risk of any contamination across all products would be impossibly expensive. Therefore it is important to focus on the main risks and to find ways to reduce them that are as effective as possible in terms of the actual and opportunity costs incurred. On the other hand, proper analysis will confront some tricky issues about priorities, valuation of human health and life, and willingness of consumers to pay for products that may be safer but not perceptibly so when offered for sale.

Epidemic pest and animal diseases

Outbreaks of epidemic animal diseases such as swine fever (affecting pigs), foot-and-mouth disease (affecting all cloven-hoofed animals including cows, pigs, sheep and goats), avian influenza (affecting poultry and humans) and BSE (affecting cattle and humans) have shown that such diseases can have devastating social impacts. These impacts derive from the costs (in all forms) of:

1. the typical (e.g. EU) stamping-out strategy of killing and destroying infected, suspected and contact stock (resulting in loss of assets and animal welfare concerns);
2. the limitations on exports (resulting in lost export markets and extremely low domestic producer prices); and
3. limitations on the movement of animals and people in certain regions (resulting in inconvenience, lost incomes from tourism, etc.).

In terms of animal welfare, economics, personal anguish and societal outcry, the 'losses' can be large indeed. Society has grown increasingly concerned about these issues to the point that many people now think that such losses can no longer be borne. Therefore, it seems inevitable that more attention will be given to preventing such outbreaks and to managing them better when they occur. In the past, some farmers, officials and governments have been seen to be too slow to react to new outbreaks.

Epidemic pests in crops can also have large effects on economics and trade, although the ethical factor that is present in animal disease control (killing and destroying 'healthy' animals) is not usually significant in crop epidemic control.

In some countries, in particular those that have experienced outbreaks of contagious diseases, there is an increasing interest in reviewing the current regulations and practices, including the option to apply emergency vaccination, where available. The choice of preventive and control strategies for a contagious animal disease is a complicated one that should be based on the best available information and a sound trade-off of all aspects – evidently a case requiring decision analysis with multiple objectives (Chapter 10, this volume). Moreover, the issue is inevitably one fraught with uncertainty, so a proper risk analysis needs to be undertaken in reaching a decision about the best control strategies to use.

In formulating policies to try to prevent and control epidemic pests in crops, a similar approach is needed. Epidemiological objectives need to be balanced with economic (damage to affected crops, export consequences) and environmental (including use of chemical control agents) objectives. Again, choosing the best strategy is a risky choice, so here too a multi-objective decision analysis is indicated, at both policy and individual farm levels.

Growing concerns with environmental risks in agriculture

One emerging aspect of agriculture that is riddled with uncertainties is 'the environment'. Most of the agricultural risk literature has been concerned with the production and economic risks facing farmers. Since agricultural activities may often have uncertain but significant impacts on natural resources and the environment through negative and positive externalities, resource depletion, and reduction of environmental amenities, these risks should also be taken into account in farm-level and society-level planning. There is a growing perception among policy makers and the population at large that some of the environmental threats created by modern farming methods may be unacceptable.

The complexities that confuse this topic are intense, and range from the biological, through the physical and chemical, to the social and economic. The phenomena of concern are diverse and include, for instance: (i) loss of biological diversity at the genetic, species and ecosystem levels; (ii) threats to critical ecosystem goods and services; (iii) agricultural contributions to global warming; and (iv) agricultural responses to the resulting changing but yet uncertain agronomic circumstances. Solutions being advanced include integrated pest management, organic farming, and various approaches to sustainable agriculture and sustainability. Risk plays many parts in influencing environmental outcomes of agricultural producers' decisions. Through changes induced in, say, cropping practices or livestock farming intensity, risk policy itself may have environmental consequences.

In the past, debates about environmental policies have been bedevilled by the polarization of positions by 'greenies' and 'developers'. A decision-analytic framework suggests that such differences can be dissected into different beliefs about the (risky) consequences of alternative actions, and different preferences for those consequences. People of good will should be able at least to narrow differences in beliefs about consequences by gathering and sharing more information. When good will is lacking, however, there is a tendency for both sides to make exaggerated claims that are not consistent with the evidence. Resolution of such problems is not aided when so-called experts retained by the opposing sides present as 'facts' conclusions they have reached about fundamentally uncertain phenomena. The role of policy analysis in this process, therefore, should be to strike a balance between the opposing views being advanced and to make the best possible assessment of the probability distributions of the uncertain events and consequences of concern and ultimately reach the best decision possible.

It is less clear how differences in preferences for consequences can be resolved. The polar viewpoints can be characterized as 'ecocentric' and 'anthropocentric', meaning focused primarily on ecological values and on human values, respectively. The view that all living organisms are sacred, for example, is a legitimate position for someone to take, but problems loom when believers seek to impose their views on the rest of society, including many people with different values. It is, of course, a matter for politicians to resolve such irreconcilable views, accounting, at least in a democracy, for the impact of the stance they take on the support they will receive at the next election.

Concluding Comment

Risk management for most farmers is a challenging task that relates to almost all decisions they make, ranging from the everyday to once-in-a-lifetime investment decisions. As argued above, policy makers and governments often have a big impact on farm-level risk management, both directly, by providing (or not providing) certain instruments, and indirectly, such as by creating an enabling environment for competitive farming. Institutional risk has been categorized in Chapter 1 as one of the main sources of risk for farming. This additional risk within the rural sector is a result of policy interventions that have uncertain outcomes, or which are subject to frequent and unpredictable changes in their design and implementation. Evidently, policy makers and governments have a special responsibility with respect to farmers' risk management. They should not always take it for granted that their decisions or projects are technically sound and that their interventions will be effectively implemented. But since risks pervading agriculture are not going away, policy makers must continue to be alert to the challenges of farm communities to manage their risks successfully, and to identify interventions that are actually helpful and defensible.

Selected Additional Reading

General overviews of the roles of government in promoting farm productivity growth have been provided by many authors including Lee and Barrett (2001), Pardey (2001) and Runge *et al*. (2003). Ways of reducing farmers' transaction costs are discussed, for example, by Gabre-Madhin *et al*. (2003).

A general overview of risk-management instruments available to farmers in the USA is given by Harwood *et al*. (1999), while Barry (1984) deals with many of these from a more theoretical standpoint. Fafchamps (2003) covers similar ground but from a development perspective.

Policy issues relating to risk in US agriculture are discussed by, for example, Glauber and Collins (2001). Several contemporary views are reported in the publication edited by Buschena and Taylor (2003).

For reading on derivatives in agriculture we recommend Carter (1999), Harwood *et al*. (1999), Williams (2001), Garcia and Leuthold (2004) and Geman (2005).

The OECD has published a number of reports on the policy aspect of risk in agriculture. These are not cited individually but interested readers can see what is available and in most cases download the documents at: http://www.oecd.org/tad/agricultural-policies/risk-management-agriculture.htm (accessed 2 June 2014).

An overview of the economics of crop insurance has been provided by Hueth and Furtan (1994) with more recent events covered in some several publications by Skees and his collaborators (e.g. Skees and Barnett, 1999; Skees, 2000; Skees *et al*., 2001). Advantages of using market-based instruments for risk management have been argued by many, including Varangis *et al*. (2002). Analyses of the risks associated with sharp spikes in food prices have been assembled by Barrett (2013) and Chavas *et al*. (2015).

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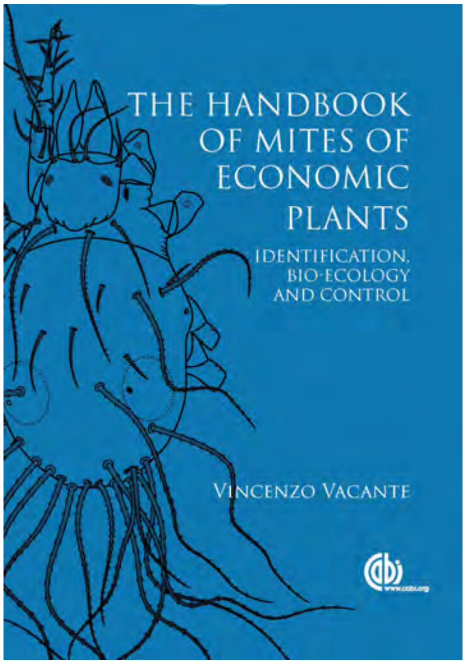

The Handbook of Mites of Economic Plants: Identification, Bio-Ecology and Control

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In honour of Edgard Van Daele, acarologist of Gand University, Belgium, who patiently introduced me to Acarology

7 Mites and Plant Damage

Pest mites *sensu stricto* belong to the Tetranychoidea and Eriophyoidea, both of which have mouthparts that are able to pierce plant tissues and suck out their contents. Other mite groups (Acaridae, Erythraeidae, Penthaleidae, etc.) have different mouthparts that are not strictly adapted to phytophagy, but are nevertheless also able to cause severe damage. The feeding mechanism, together with the plant response, determine the damage typology. Plant damage by mite pests has been extensively investigated in the Tetranychoidea and Eriophyoidea, but less so in the Tarsonemidae and other minor phytophagous groups. Sometimes, the symptoms can be easily taken for boron deficiency, or they may be confused with virus symptoms or even with herbicide action, such as on the new leaves of papaya infested by the broad mite, *Polyphagotarsonemus latus* (Banks).

The main part of this chapter is devoted to an account of the damage to plants that is caused by the main phytophagous groups of mites (Tetranychoidea, Eriophyoidea) and others (Tarsonemidae, minor groups), with details of the feeding mechanisms that they use, the symptoms caused by feeding and the resulting plant damage. The last part of the chapter discusses the transmission of plant diseases – mainly plant virus diseases – by mites.

Tetranychoidea

The Tetranychoidea include two important families of pest mites, the Tetranychidae and the Tenuipalpidae. This family includes 1275 described species in about 77 genera and represents the most important family of pest mites, together with the Eriophyoidea, which are described next (Bolland *et al*., 1998; Migeon and Dorkeld, 2006–2013). They have a worldwide distribution and association with higher plants, including economic species, and often cause severe injury or the death of the host plant. The role of the Tetranychoidea in the transmission of plant viruses has been largely investigated in American citriculture, and most of the reported work on the damage caused concerns the Tetranychidae, except for a few tenuipalpids.

Feeding mechanism

The morphological and physiological adaptations of the Tetranychidae to plant feeding are very similar to those of the Tenuipalpidae (discussed by Beard *et al*., 2012) and Tuckerellidae. The feeding mechanism involves actively the stylophore, the chelicerae (Fig. 2.6H, I)[a] and the palpi (Fig. 2.7B, E)[b]. The stylophore is mobile (retractable and extrudable) and lies on the dorsomedial surface of the infracapitulum; it consists of the bases of the chelicerae fused together, curves ventrally and is divided by a median and vertical septum and into two basal cheliceral compartments, each of which hosts a stylet that is attached at the base to a cheliceral lever that activates it in a vertical plane. The chelicerae have a uniformly long and thick digitus mobilis, except at the distal end, where it is sharpened and slightly notched, and if this is protracted and juxtaposed with the one from the other side, it forms an empty tube. The stylophore pushes the chelicerae into plant tissues and when it is retracted usually leaves an opening through which the plant's cellular fluids may be pushed out by the turgor pressure of the cell. Immediately behind the stylets, the palpi press the plant surface and the pharyngeal pump located on the distal side sucks in the cellular contents. The stylets penetrate to a depth of between 70 and 120 μm, and once they are inserted into the plant tissue they push and withdraw continuously, thereby causing mechanical damage. As soon as a mite has consumed the part of the tissue fist attacked, it moves and looks for a site that has not yet been attacked. The depth of damage depends on the length of stylets, the feeding time and the mite population density (Jeppson *et al*., 1975; Sances *et al*., 1979a; Mothes and Seitz, 1982; André and Remacle, 1984; Lindquist, 1985). At a microscopic level, a significant volume of the plant's cellular contents passes through the intestinal tract of mites, which was estimated by McEnroe (1963) to be 1.2×10^{-2} ml h^{-2} per mite, which corresponds to approximately 50% of the mass of an adult female of *Tetranychus urticae* Koch. The mite can empty 100 photosynthetically active foliar cells within 1 min (Leisering, 1960). After feeding, thylakoid granules, derived from thylakoid grana in the plant cell and made up of 45–50% protein, 50–55% lipid and small amounts of RNA and DNA, are found in the mite intestinal tract (Mothes and Seitz, 1981b; Noggle, 1983). Water and other small quantities of substances are excreted directly (McEnroe, 1963). On the plant, it is sometimes difficult to separate the influence of mechanical damage caused by the mite from that caused by local toxins (Jeppson *et al*., 1975).

Symptoms of feeding

The main feeding activity of tetranychids usually occurs on the leaves of the plant, but it can also involve other plant organs, such as the cotyledons, fruits, flowers, shoot tips, etc. The symptoms caused result from the removal of the contents of the cells of the palisade tissue and of the disappearance of the chloroplasts. Coalescence of the cell residues leads to the appearance of small amber-coloured masses. Only the punctured cells of the palisade layer are damaged, with the surrounding cells left undamaged along with the leaf ribs. The small punctures are light in colour and after exposure for some time assume the appearance of irregular white or greyish spots. The density of the punctures is a function of the size and duration of the attack and of the injurious species. The density of punctures on the leaf surface can be high, e.g. *Eutetranychus banksi* (McGregor) produced 873 feeding punctures cm^{-2} on the leaves of Valencia orange (Hall and Simms, 2003).

Tetranychoid mites give variable symptoms as a result of feeding, according to the species, anatomical structure of the infested organ, the weather (during or after the infestation) and the reaction of the host plant to the attack. The symptoms of feeding are most common on the leaves, particularly on the lower surface, although some mite species may feed on both leaf surfaces. On citrus, colonies of the two-spotted spider mite, *T. urticae*, usually develop on a well-defined surface of the lower leaves and fruits. The oriental red mite, *Eutetranychus orientalis* (Klein), the red citrus mite, *Panonychus citri* (McGregor), and the yellow citrus mite, *E. cendanai* Rimando, may develop on both leaf surfaces, but they usually prefer the upper leaf surface (Jeppson *et al*., 1975). The resulting colour often characterizes the mite attack, and there may be leaf curling and necrosis of young leaves, stems and growing tips. High levels of attack may induce defoliation. On citrus, the damaged areas can be yellowish (*T. urticae*), grey (*E. orientalis*, *Meyernychus emeticae* (Meyer), *Schizotetranychus baltazari* Rimando) or yellow bronze (*Oligonychus coffeae* (Nietner)). Necrosis of young leaves (*M. emeticae*, *E. sexmaculatus* (Riley)) and of stalks and shoots (*E. orientalis*, *E. yumensis* (McGregor)), or even leaf burning and defoliation (*E. africanus* (Tucker), *E. orientalis*, *E. sexmaculatus*, *E. yumensis*, *O. coffeae*) and/or fruit drop (*E. yumensis*) (Vacante, 2010) can occur. Different tetranychids (*P. citri*, *E. lewisi* McGregor, *E. yumensis*) and tenuipalpids (*Brevipalpus californicus* (Banks), *B. obovatus* Donnadieu, *B. phoenicis* (Geijskes)) cause citrus russets. The same pest mite can cause symptoms that differ in severity on different host plants, e.g. *Tetranychus pacificus* McGregor on pear, apple, grape, etc.

Although silk production in tetranychid mites has different functions (Gerson, 1985b), webbing may be an aspect of the symptomatology of mite attack (see Chapter 5, 'Webbing and Life Types').

Damage

Jeppson *et al*. (1975) used the phrase 'plant disease' rather than 'plant damage' and noted that 'the term plant disease in its broadest meaning includes all injuries or abnormalities generated from sources outside the plant regardless of the cause'. In the case of mites, there is a link between mites and the diseases that they sometimes transmit, and the damage that they cause can either be defined, or local, or wider, or more general in character and involve the entire plant as a result of the injection of systemic or persistent toxins and/or viruses. The reaction of the plant to mite attack therefore consists of a range of external symptoms resulting from mechanical damage (colour changes, alterations in shape, reductions in growth and loss of flowers and production) and internal alterations or changes involving biochemical mechanisms. Understanding these reactions requires the analysis of the mutual interaction between the host plant and the pest (Tomczyk and Kropczyńska, 1985).

With the exception of some tenuipalpids, e.g. *B. phoenicis*, which transmits the virus disease known as 'lepra explosiva' or 'leprosis' (Childers *et al*., 2001; Childers and Rodrigues, 2011), plant damage caused by the Tetranychoidea is basically due to feeding activity – stylet penetration into plant tissues and the sucking out of the cells contents, often associated with the injection of saliva. The length of the stylets, feeding time and the density of the attack, as well as the host plant, determine the depth at which the damage occurs (Sances *et al*., 1979a; Mothes and Seitz, 1982). The damage involves morphological, histological and cytological aspects, as well as chemical and physiological changes and the associated impact on growth, flowering and cropping (Tomczyk and Kropczyńska, 1985).

Cytological and histological aspects

The mechanism by which the stylets penetrate the epidermis and the mesophyll layers is partially known. On young fruit trees, *Panonychus ulmi* (Koch) may pass the stylets between cells (Avery and Briggs, 1968a), while in leaves of the apple, *Tetranychus mcdanieli* McGregor inserts the stylets through the walls of the epidermal cells (Tanigoshi and Davis, 1978). Damage may occur on the epidermal cells, which may show punctures (Summers and Stocking, 1972), or appear flattened or deformed, as a result of the punctures or osmotic effects. Damage to the spongy parenchyma may lead to destruction of the stomatal apparatus (Sances *et al*., 1979a). Mite feeding reduces the number of cells and infested leaves may show a reduced thickness, which on bean plants may be as much as 50% (Mothes and Seitz, 1982) and on apple up to 35–55% (Tanigoshi and Davis, 1978).

On strawberry leaves, a low density of two-spotted spider mite causes fundamental damage to the spongy mesophyll tissue, but little damage to the lowest parenchyma cell layer, while a high density of the mites causes severe damage to the palisade parenchyma (Sances *et al*., 1979a; Kielkiewicz, 1981). When *Bryobia rubrioculus* (Scheuten) feeds on the upper side of almond leaves, symptoms of damage may occur in the first two layers of the palisade parenchyma, and the cells of the spongy parenchyma may be undamaged (Summers and Stocking, 1972).

Damage may also involve both directly punctured cells and adjacent cells. The damaged cells are deformed, lack protoplasts and their walls are smaller. Starch grains are sometimes observed within damaged cells, as well as the walls being broken and the spaces containing air. Amber-coloured protoplasts or dense material, and other structural changes, are observed within the cells or in the intercellular spaces that separate them. These modifications may depend on the breakdown of tonoplasts and the resulting contact between the vacuolar sap and the cytoplasm (Tanigoshi and Davis, 1978). According to the time of feeding, the surrounding cells may present various types of damage (coagulation of the cytoplasm, destruction of the nucleus, modification of the wall structure, degeneration of the chloroplasts) (Mothes and Seitz, 1982).

The effects of feeding by *T. urticae* and *Eotetranychus carpini* (Oudemans) on red raspberry (cv. Meeker) physiology were investigated under greenhouse conditions by comparing the chlorophyll fluorescence and chlorophyll content of infested leaves with those of the most recently expanded and uninfested leaves of infested plants. The results show that cellular injury occurs before the appearance of damage and that the primary site of injury in spider mite feeding may be the plastoquinone pool (and within that, QA, the primary quinone receptor of photosystem II), which plays a major role in electron transport during photosynthesis (Bounfour *et al.*, 2002).

Cytological alterations resulting from feeding by *Oligonychus biharensis* (Hirst) on cassava leaves were examined using transmission electron microscopy (TEM). The severity of damage to the cassava leaves is directly related to the feeding intensity of the mites and is a function of time. Infested cassava leaves show a reduction in thickness as a result of the disruption and reduction of the mesophyll layers. Cells exhibit coagulated protoplasts, a reduction in the number of cells and chloroplasts, alterations in cell structure, increased space in the spongy layer, extensive disruption of the mesophyll cells and even a reduction of chloroplasts in adjacent unpunctured cells (Kaimal *et al.*, 2011).

The importance of the mechanical action of the stylets versus that of the saliva injected before the sucking out of the cellular contents is not really known. However, the process involves both the host plant and pest mite. The mite saliva could cause changes in the adjacent cells that are not damaged directly by feeding. The cells that are damaged by stylets may also induce changes in the water balance of the mesophyll, and uninjured cells may be separated by damaged cells, which make empty spaces between them. In addition, the destruction of liposome membranes may cause autolysis. According to Mothes and Seitz (1982), tetranychid damage could be due to other factors as well, such as the formation of a vacuum which induces the cells to burst, the influence of mite saliva on adjacent undamaged cells and damaged plant tissue influencing the undamaged cells.

Effects of saliva

The role of saliva injected by mites into plant tissues is complex and sometimes unclear. Unfortunately, the small size of mites does not allow an adequate amount of saliva to be obtained for chemical analysis, so indirect investigations have to be made, focusing mainly on the damaged organs and the plant reactions. Studies on *T. urticae* by Sances *et al.* (1979a) show that damage to strawberry plants is by mechanical means and that no toxic substances are involved in the feeding action of the mite. However, Mothes and Seitz (1981a), in a study of the prosomal glands of *T. urticae*, found that the salivary glands take part in the feeding action and in the digestive process. The salivary secretions contain mucous substances, glycoproteins and a liquid component. The use of various markers, such as $^{14}CO_2$ or ^{32}P, has highlighted that during mite feeding, injected substances are translocated to various parts of the plant, such as the roots and young shoots of plum and apple fed on by *Panonychus ulmi* (Avery and Briggs, 1968a) and the growing parts of bean plants infested by spider mites (*T. urticae*) (Storms, 1971). The saliva injected by mites into plant tissues may contain proteolytic enzymes and plays a fundamental role in the degradation of plant cell contents. Moreover, the saliva also could contain plant hormone-type substances that could cause a specific reaction in the host plant. A high hormone content could stimulate physiological processes in the plant that would compensate for the losses caused by mite damage (Avery and Briggs, 1968a; Storms, 1971). Increases of gibberellin-like substances have been found in leaves infested by *P. ulmi*, associated with decreases of auxin-like substances, with the exception of indole-3-acetic acid (IAA), which is higher in damaged leaves. This process may involve monophenolic substances (Avery and Briggs, 1968a). Overall, phenolic compounds increase in strawberry leaves infested by the two-spotted spider mite, decreasing in palisade parenchyma and increasing in the upper and lower epidermis and in the leaf veins. This may interfere in the host plant–mite pest relationship (Kielkiewicz, 1981).

Chemical and physiological changes

Mite feeding causes changes in the chemical composition of the host plant, including both organic and inorganic compounds. The contents of nitrogen and phosphorus decrease after a long period of *P. ulmi* feeding on apple, but only small changes or none have been observed in potassium, calcium and magnesium contents (Herbert and Butler, 1973a; Golik, 1975). Decreases in potassium, nitrogen and phosphorus have been found on chrysanthemum infested by *T. urticae*. The exact contribution of uptake by the roots from the soil and the role of damaged cells in the decrease in the mineral contents is largely unknown. The process has been little investigated and could also involve other factors, such as the ageing process of the cells and changes in their potassium content (Tomczyk and Kropczyńska, 1985). The main organic compounds involved in mite feeding activity are proteins, carbohydrates and chlorophyll. The organic compounds of saliva have been briefly mentioned above. Changes in the amounts of these compounds could affect plant physiology. A reduction of protein contents and decrease of activity of amylase and proteolytic enzymes have been reported in cotton plants infested with the red spider mite, *Tetranychus telarius* (L.) (Zukova, 1963), as well as an increase in amino acids and soluble sugars in chrysanthemum (Kolodziej *et al.*, 1975). Changes in chlorophyll concentration have also been documented (van de Vrie *et al.*, 1972). Further studies show that any reduction in chlorophyll content depends on the length of feeding activity and the number of mites feeding (Tomczyk and van de Vrie, 1982; De Angelis *et al.*, 1983b). However, other studies have reported minor changes (Sances *et al.*, 1979b, 1982a; Kolodziej *et al.*, 1979). Any reduction in chlorophyll content probably results from mechanical damage of the chloroplasts during feeding, and will vary according to the mite and host plant species. Feeding on the upper side of the leaf causes palisade damage and the greatest reduction in chlorophyll content (Summers and Stocking, 1972; Sances *et al.*, 1982b), whereas feeding on the underside causes damage to the spongy mesophyll, which usually has fewer chloroplasts (Sances *et al.*, 1979b).

Infested plants may exhibit significant changes in transpiration and photosynthesis. Damaged plants lose water by transpiration, which increases up to a certain level and then decreases (Sances *et al*., 1979b, 1982a), depending on the damage to the protective surface of the leaf and disturbance to the stomatal openings (Sances *et al*., 1979a). During the day, the transpiration is stomatal whereas during the night it is cuticular (De Angelis *et al*., 1982). Severe infestations of *Panonychus citri* lead to substantial changes in the transpiration and photosynthesis of plants. In particular, transpiration increases during high-density attacks and decreases with lower mite density, and the quantity of chlorophyll may be reduced to 60% (Wedding *et al*., 1958). Heavy infestations of the oriental red mite, *Eutetranychus orientalis*, associated with poor irrigation, drought and strong ventilation, may induce defoliation (Jeppson *et al*., 1975). Water stress may increase the metabolic changes, such as hydrolytic processes and the degradation of starch to simple sugars and of proteins to amino acids (De Angelis *et al*., 1983a). Mite density and the length of feeding affect the assimilation of CO_2, which is correlated with the chlorophyll content of the leaves. However, this correlation is sometimes unclear (Hall and Ferree, 1975; Sances *et al*., 1979b;), and other factors may also be involved in the decrease in CO_2 assimilation (Tomczyk and Kropczyńska, 1985). The use of ^{14}C markers has assisted in studying carbon metabolism in photosynthesis and highlighted significant changes in the synthesis of soluble sugars, amino acids, organic acids and starch in chrysanthemum and apple infested by mites (Kolodziej *et al*., 1975; Borichenko and Manolov, 1982).

Impact on growth, flowering and cropping

Damaged plant tissues and anomalies in physiological processes in mite-infested plants may cause changes in growth, flowering and yield. However, although retardation of the growth of the damaged organs is common (Tomczyk and Kropczyńska, 1985), infested plants do not always show a growth reduction (Zwick *et al*., 1976; Hoyt and Tanigoshi, 1983). A low mite population density and a short feeding time may conversely stimulate plant growth (Avery and Briggs, 1968b; Storms, 1971) according to their effects on the level of growth regulators and the compensatory capacity of the plants (Tomczyk and Kropczyńska, 1985). Infested plants usually have a reduced total leaf area as a result of the decrease in leaf area growth rate (Avery, 1962; Avery and Briggs, 1968b; Summers and Stocking, 1972) and the number of leaves per plant (Avery, 1962). Shoots have reduced dry matter and so may be shorter (van de Vrie *et al*., 1972). Mite feeding may also affect the roots, which appear reduced, and there may be fewer branches and less dry matter (Avery and Briggs, 1968b). Infestations on fruit trees may induce a reduction of flowering or fruiting of 75% in the following year (Golik, 1975). Damage may occur at the early stage of fruit development, and the early dropping of immature or ripening fruits has been reported (van de Vrie *et al*., 1972; Golik, 1975; Hoyt and Tanigoshi, 1983). The effects on fruiting may appear after 2 or 3 years and at various intensities, depending on the plant species. A low density of *P. ulmi* causes yield losses on pear (Hoyt and Tanigoshi, 1983), whereas on strawberry the numbers and size of the fruits increase (Oatman *et al*., 1982). The storage quality of apples from infested plants is lower (Zwick *et al*., 1976) but grapes from plants that had or had not been attacked by *T. pacificus* had the same sugar contents (Laing *et al*., 1972). The fruits of damaged plants are sometimes more coloured (Golik, 1975). In Iraq, *Oligonychus afrasiaticus* (McGregor) caused 50–80% yield loss of dates in years of dry, dusty and stormy weather (Al-Jboory and Al-Suaide, 2010).

Eriophyoidea

The Eriophyidae is the most economically important family of the Eriophyoidea and the second family of the most severe plant pests after the Tetranychidae (Lindquist and Amrine, 1996). Leaf vagrants and gall formers cause different morphological alterations to infested plants (Jeppson *et al*., 1975; Keifer *et al*., 1982). According to Amrine (see Huang, 2008), the leaf vagrants include 43.6% of all eriophyoid species (1618 vagrant species out of a total of 3708), while the gall formers make up 15.8%, the erineum formers 11.4% and the bud mites 8.9%. However, altogether, the gall, erineum and bud mites – which may be referred to as refuge-creating mites – make up 36.1% of the eriophyoids, which is almost as great a proportion as the vagrants. Other assessments have noted that the Eriophyoidea include 2263 vagrants, 462 refuge-seeking and 941 refuge-inducing species; moreover, at least half of the species adopt the vagrant life strategy and the other half the refuge-creating or refuge-seeking strategy (Skoracka *et al*., 2010). The damage caused by these mites is due to the mechanical action of their mouthparts and to the injection of saliva containing various biochemical agents. In addition, various eriophyoid species are vectors of viruses causing severe diseases (see the last part of this chapter on the transmission of plant diseases).

Some of the species of this important group of phytophagous mites are very injurious, e.g. *Phyllocoptruta oleivora* (Ashmead), *Aculops lycopersici* (Tryon) and others. In several species, the damage is less and understanding it requires appropriate ecological analysis, e.g. the citrus bud mite, *Aceria sheldoni* (Ewing). This citrus pest has long been feared worldwide, but the results of the research on lemon carried out in Italy by the author have shown that the citrus bud mite does not negatively influence the lemon harvest and that the interaction between the mite populations and the host plant takes the form of a mutual symbiosis in which the mite uses the buds as a resource and repays the host plant positively by regulating its production system. The case is not unique in this mite group, and its ecological study represents a serious challenge that is largely underestimated by eriophyoid specialists in the Mediterranean region.

Feeding mechanism

The feeding mechanism of the Eriophyoidea involves the subcapitulum or rostrum, the palps and the cheliceral stylets. The cheliceral complex is placed in a subcapitular groove, covered by the free edges of the cheliceral sheath. The cheliceral stylets are connected to the underlying motivator, which provides basal support (see Fig. 16.3). They are rigid, separated from each other for their entire length and do not form a food channel; they provide only an alternative longitudinal movement. On the sides of the cheliceral stylets there are two auxiliary stylets of uncertain function. In addition, a single long stylet, called the labrum and conformed below as a gutter, is connected to the pharynx and propelled by strong muscles (Lindquist, 1996; Nuzzaci and Alberti, 1996; Westphal and Manson, 1996). After selecting a suitable site for feeding, the mite stops, puts its rostrum on to the host surface and contracts the telescopic segments of the palps, which allows the protrusion of cheliceral stylets over a short distance. In a few seconds, the stylets mechanically penetrate the epidermal cells (Keifer, 1959a; Shevtchenko and Silvere, 1968; Krantz, 1973; McCoy and Albrigo, 1975; Hislop and Jeppson, 1976; Nuzzaci, 1976; Westphal *et al*., 1990; Westphal and Manson, 1996). At the same time, three glands (two paired and one unpaired) produce secretions (Nuzzaci and Alberti, 1996). Of these, the paired glands are probably salivary glands (Thomsen, 1988; Nuzzaci and Alberti, 1996), while the function of the unpaired gland is unclear. The saliva is injected into the plant cell through the cheliceral stylets and the labrum, and the cell contents are sucked up through a canal formed by the infracapitular stylets (see Fig. 16.3) and the labrum (Nuzzaci and Alberti, 1996). It is difficult for the mite to maintain its cheliceral stylets within the wound, given that they do not participate in the establishment of a food tube. It is possible that they go backwards and that the action of the terminal segments of the palp allow the consumption of food from the plant. The mechanism of movement of the food in the gnathosoma has not been definitively clarified, but it is possible that the labrum is adapted in the hole in the plant cell wall and acts as a funnel carrying food along its ventral gutter to the pharynx. The regular contractions of the pharyngeal pump allow active ingestion (Westphal *et al*., 1990; Westphal and Manson, 1996).

There is no agreement on the mechanism of insertion of the cheliceral stylets into the cell wall. One hypothesis is that the cheliceral stylets are inserted into the cell during the action of feeding (Jeppson *et al*., 1975; Nuzzaci, 1979); another is that the stylets are inserted into the cell wall after it has been perforated and then the labrum is fixed to the hole in the cell wall to actively suck out the cell contents (Westphal and Manson, 1996). It seems that the limited time that is available to the mite does not allow the saliva that is excreted to dissolve the cell wall enzymatically, only to notch it. The eriophyoid first ejects the saliva on to the leaf surface to digest the plant cuticle and the cellulose of the cell wall enzymatically, and after that pierces the site with its chelicerae and sucks out the cell contents within 10–20 min (Thomsen, 1988). However, the process of probing and cell penetration needs only a few seconds, and so the saliva ejected on to the plant surface may not have time to be effective in its action on the cell wall before the chelicerae are inserted (Westphal and Manson, 1996).

The feeding mechanisms and mouthparts of the different families of the Eriophyoidea vary. In the Eriophyidae and Phytoptidae, the mouthparts are 7–30 µm long (Keifer, 1959a; Jeppson *et al*., 1975; McCoy and Albrigo, 1975; Krantz, 1978, 2009a; Westphal, 1983; Easterbrook and Fuller, 1986; Royalty, 1987) and not penetrate the epidermis of plant leaves and fruits as far as the parenchyma. The mouthparts of the Diptilomiopidae can be 50–70 µm long and are capable of reaching the mesophyll tissue but do not cause clear damage to the host plant (Keifer, 1959b; Jeppson *et al*., 1975; Krantz, 1978, 2009a).

The cheliceral stylets of eriophyid gall mites penetrate only the cell wall, to a depth of about 2 µm (Westphal, 1972, 1977a). On fruits of *Citrus sinensis* (L.) Osbeck, feeding adults of the pink citrus rust mite, the eriophyid *Aculops pelekassi* (Keifer), produce about 20 punctures, each approximately 1 µm in diameter in the epidermal cells (which are 10 µm long and 7 µm wide). The depth of penetration is about 20 µm and reaches as far as the second and third layer of the fruit epidermis (Tagaki, 1981).

Symptoms of feeding

The eriophyoid mites are highly specific and live only on susceptible host plants with which they are closely associated (Jeppson *et al*., 1975). Their feeding activity is strictly related to the host plants and causes a great variety of symptoms. The leaf vagrant and gall former species induce different morphological alterations (Jeppson *et al*., 1975; Keifer *et al*., 1982). Common feeding symptoms of eriophyoid mites include various types of 'galls' and 'distortions' (Westphal, 1992; Westphal and Manson, 1996). Plant galls are abnormal structures characterized by various shapes, size, colours, etc. Among the mites, only eriophyoids and some tropical tenuipalpids (Oldfield, 2005) are gall formers. Eriophyoids induce galls with a typical form that are placed on a specific green organ of the plant (stems, leaves, petioles, buds, flowers, fruits and seeds), but not on the roots (Westphal, 1992). The different effects caused by species living on the same host plant (Boczek and Griffiths, 1994) suggests that gall morphology is determined by the pest mites rather than the host plant (Kane *et al*., 1997). It has been observed that *Cecidophyopsis* spp. cause the same type of galls on different *Ribes* spp. (Amrine *et al*., 1994); likewise, three *Aceria* spp. induce similar galls on different maple leaves (Rančić and Petanović, 2008). However, the same eriophyoid may cause different symptoms on different plant species or on different developmental stages of the same host plant (Westphal, 1980; Oldfield, 1984; Soika and Kielkiewicz, 2004).

A single gravid female (sometimes also the immatures) may induce the development of a gall (Westphal *et al*., 1990). The galls are a localized growth reaction exhibited by the host plant, although the feeding activity of the eriophyoid can also severely affect the growth patterns of the host plant via morphogenetic mechanisms. The gall-forming process generally develops in two steps, first there is local inhibition of the growth and differentiation of the infested plant organ, and next the adjacent tissues grow to shelter the mites in their gall, associated with the formation of nutritive tissues (Němec, 1924; Westphal, 1977a).

According to their morphology, Küster (1911) classified the galls caused by various organisms as 'organoid galls' and 'histoid galls', respectively. Organoid galls are abnormal modifications of plant organs and histoid galls have more complex arrangements of the internal tissues. The histoid galls are divided into the 'kataplasmas', which are usually less differentiated, and the 'prosoplasmas', which are more complex. The recent description of gall typology by Larew (1982) includes among eriophyoid galls both 'simple' and 'complex' kataplasmas, which are subcategorized by the thickness of the nutritive layer at gall maturity or the alignment and general type of nutritive cells. Galls may also be divided according to the adaptation of the mites to live externally to the epidermis or inside the plant tissues (Mani, 1964). A further classification based on the plant organ that is infested and the degree of damage complexity classifies galls as 'leaf galls', 'stem galls', 'bud galls', 'fruit galls' and 'other distortions' (which include other distortive and non-distortive alterations and toxaemias) (Westphal, 1992; Westphal and Manson, 1996). The structure of the various types of galls are described by Jeppson *et al*. (1975) and by Keifer *et al*. (1982), and the latter authors published a number of very interesting pictures of eriophyoid feeding symptoms.

Leaf galls

Leaf galls include 'erinea', 'blister galls', 'roll galls', 'vein galls' and 'pouch galls'.

ERINEA. The erinea are felt-like masses consisting of an unusual development of plant hairs or 'trichomes'. According to the eriophyoid species, these hairs may be unicellular or multicellular, elongate, globular, lobate or ramified (Fig. 7.1). The erinea may be set either on the lower or upper leaf surface. They have various sizes and sometimes occupy the whole leaf, or cause distortions, and may exhibit a characteristic coloration (Westphal, 1977a). Abnormal hairs may be associated with leaf rolling, pouch galls, witches' brooms or inflorescence galls. Erinea may or may not be associated with other leaf modifications, such as leaf bulging, convex swellings on both sides of the leaves, different colours, etc. (Westphal and Manson, 1996). The grape mite, *Colomerus vitis* (Pagenstecher), causes erinea that are associated with leaf bulging.

BLISTER GALLS OR POCKET GALLS. Some eriophyoid mites reach the internal leaf tissues through a stomatal aperture either in the lower or the upper leaf surface. Their feeding activity induces abnormal growth of the mesophyll tissues associated with an increase of the lacunae and swellings of the leaf lamina (Westphal and Manson, 1996). The pear leaf blister mite, *Eriophyes pyri* (Pagenstecher), causes blister galls.

ROLL GALLS. The feeding activity of some eriophyoid mites on the leaf margin may cause rolling of various size and shapes (Fig. 7.2A), depending on the species, and consist of a well-defined serration or affect the entire length of the leaf margin. Roll galls can develop upwards or downwards, be thickened or not and have one or more windings (Westphal and Manson, 1996). *Aceria stefanii* (Nalepa) causes roll galls on pistachio leaves.

VEIN GALLS. The feeding activity of *Aceria macrotrichus* (Nalepa) on the lateral veins on the upper leaf surface of the European hornbeam (*Carpinus betulus* L.) causes a vein elongation forming sinuous prominent galls (Westphal and Manson, 1996).

POUCH GALLS. These are very common galls of various sizes (from a few to over 10 mm wide), shapes (nail, bladder, spindle or finger, woolly bead, rounded, etc.) and colours (red, yellow, green, etc.) (Fig. 7.2B). Depending on the species, they develop on both leaf surfaces or on only one leaf surface (Westphal and Manson, 1996). *Aceria brachytarsa* (Keifer) causes pouch galls on walnut.

Stem galls

Few eriophyoids cause stem galls. Their formation involves the mite penetrating into the bark of young twigs through lenticels or splits near the insertion of bud scales, as in Norway maple (*Acer platanoides* L.) infested by *Aceria heteronyx* (Nalepa). The feeding activity of the mite causes outgrowth of the internal tissues, with a central cavity covered by nutritive tissues. These galls are usually small, close and coalescing. They persist in time, becoming woody and turning brown (Westphal and Manson, 1996). *Acalitus phloeocoptes* (Nalepa) causes stem galls on plum twigs.

Bud galls

Bud galls include 'big buds', 'bud proliferation and witches' brooms' and 'inflorescence galls'.

BIG BUDS. The feeding activity of some eriophyoid mites induces the infested buds to develop to several times their normal size. These buds consist of thickened scales containing fleshy nutritive excrescences and may host hundreds of mites. The buds remain closed and fail to develop leaves (Westphal and Manson, 1996). The filbert bud mite, *Phytoptus avellanae* Nalepa, on hazelnut (*Corylus maxima* Mill.) (Fig. 7.2C) and *Cecidophyopsis ribis* (Westwood) on blackcurrants are typical examples.

BUD PROLIFERATION AND WITCHES' BROOMS. Some eriophyoid mites infest buds causing anomalies of growth pattern in different parts of the plant (Figs 7.2E–F, 7.3A–C). The feeding activity of these mites induces the proliferation of adventive buds or the development of dormant buds, accompanied by other symptoms, such as leaf reduction and short internodes, inducing the formation of cauliflower-like galls, such as the stunted twigs with crowded buds caused by *Aceria mangiferae* Sayed on young mango trees. Further formation of branchlets, usually short and thin, produces a typical malformation, called witches' brooms. These witches' brooms may be typical, such as those caused by *Aceria celtis* (Kendall) on *Celtis occidentalis* L., or cause a different kind of damage, such as that on the common chrysanthemum infested by *Paraphytoptus chrysanthemi* Keifer in North America and the British Isles (Westphal and Manson, 1996).

INFLORESCENCE GALLS. Some plants infested by eriophyoid mites show typical inflorescence galls. The phenomenon is due to the feeding activity of the mites, which inhibits the differentiation of the floral organs and induces the modification of various parts of the host plant into curving and rolling leaf-like formations. *Aceria peucedani* (Canestrini) causes this type of gall on

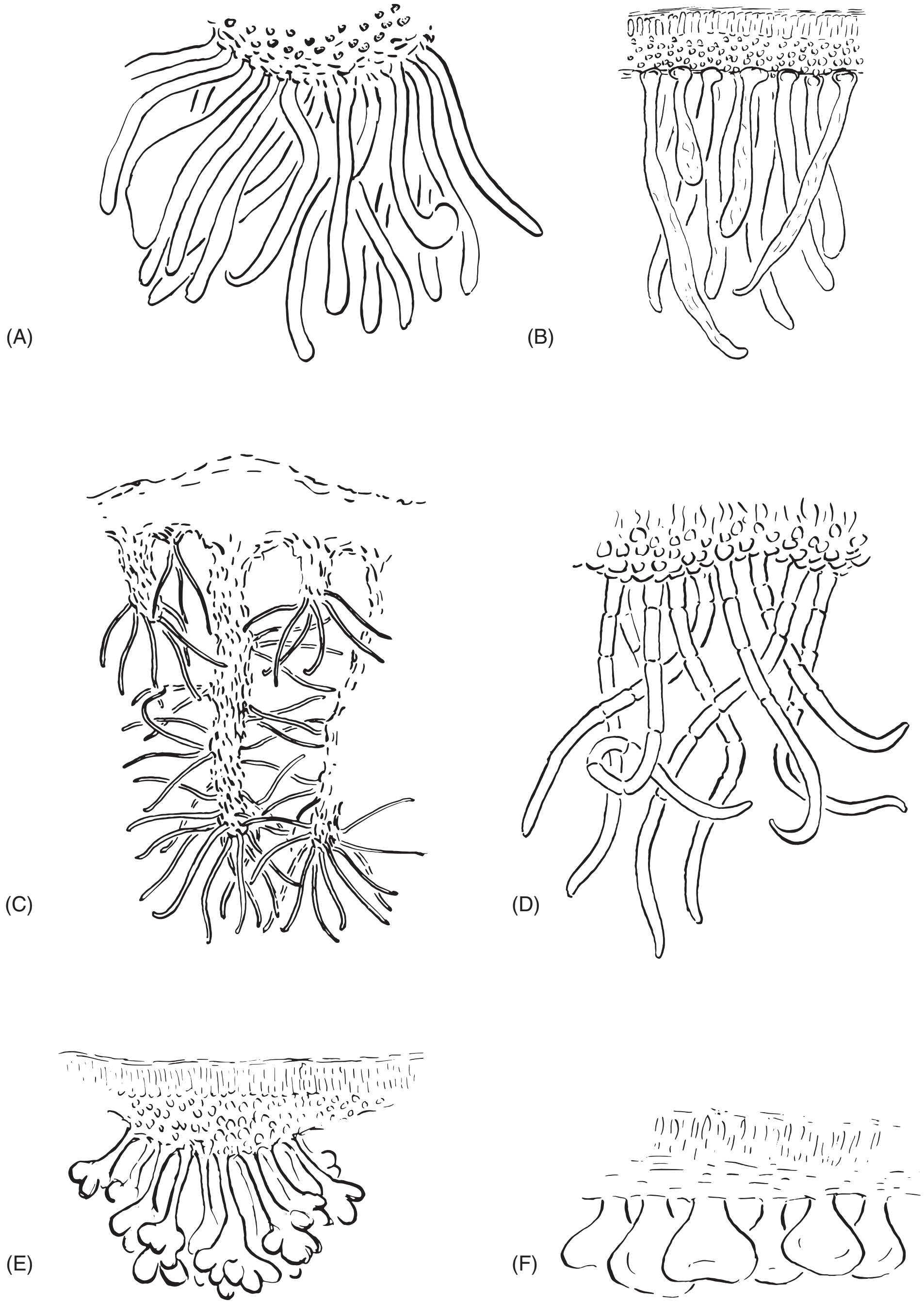


Fig. 7.1. (A) Unicellular hair-like erineum on petiole gall caused by *Aceria caulis* (Cook) on *Juglans nigra* L.; (B) unicellular erineum caused by *Phyllocoptes calisorbi* Keifer on *Sorbus* leaves; (C) erineum caused by *Aceria erinea* (Nalepa) on English walnut; (D) multicellular hair-like erineum on litchi leaf caused by *Aceria litchii* (Keifer); (E) compound capitate erineum on alder leaf caused by *Acalitus brevitarsus* (Fockeu); and (F) simple capitate erineum on sugar maple caused by *Aceria modesta* (Hodgkiss) (from Jeppson *et al*., 1975).

carrot and pimpinella (*Pimpinella saxifraga* Linnaeus), and *Aceria fraxinivora* (Nalepa) causes inflorescence galls consisting of masses of small leaves on *Fraxinus* spp., which are easily visible and pendulous on the tree during the winter. *Aceria aloinis* (Keifer) damages the leaves and flowers of *Aloe* sp. (Denmark and Keifer, 1979).

Fruit galls

These anomalies are uncommon and are produced by *Trisetacus quadrisetus* (Thomas), which causes 'berry' galls on junipers (Fig. 7.2D). The feeding activity of the mite induces slight swelling and hypertrophy of internal tissues of the female cones,

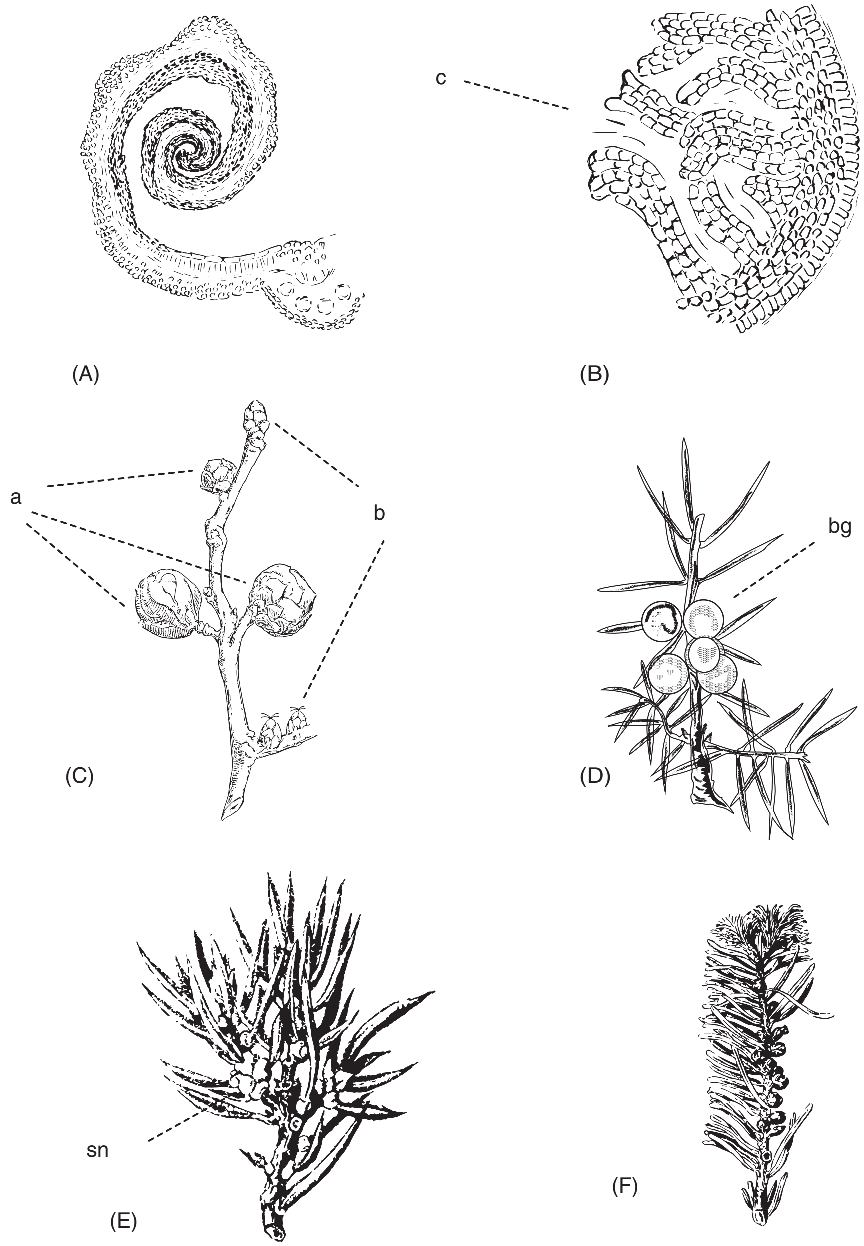


Fig. 7.2. (A) Cross section of leaf roll gall on pistachio caused by *Aceria stefanii* (Nalepa); and (B) interior of pouch gall caused by *Aceria brachytarsa* (Keifer) on walnut (from Jeppson *et al*., 1975). (C) Big buds and normal buds caused by *Phytoptus avellanae* (Nalepa) on a hazelnut branch (from Targioni Tozzetti, in Berlese, 1925). (D) Berry galls on juniper caused by *Trisetacus quadrisetus* (Thomas); and (E) swellings of needles on juniper caused by *Trisetacus juniperinus* (Nalepa) (from Houard, 1903, and Schlechtendal, 1911). (F) Alterations caused by *Trisetacus floricolus* (Trotter *et* Cecconi) (from Houard, 1903). Key: a, big buds; b, normal buds; bg, berry galls; c, inside; sn, swelling of needles.

hindering the fusion of the different parts of the cones with the formation of an opening at the top of the berry (Westphal and Manson, 1996).

Other distortions

In addition to the symptoms or malformations discussed above, other different distortions are associated with the feeding activity of eriophyoids. Some malformations have a short-lasting effect on plant development, causing the death of the mites and not impeding plant growth (Westphal *et al*., 1996). Other malformations may have a more long-lasting effect. Usually, this phenomenon characterizes free-living eriophyoids that are not confined within galls and are dispersed on the host plant. These species cause distortions of various organs, but do not induce the formation of new morphological structures. The symptoms usually

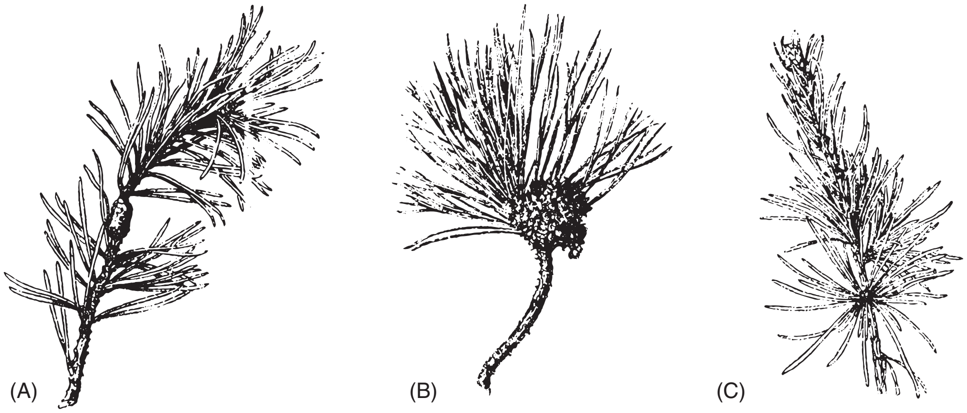


Fig. 7.3. (A) Knots on a pine twig caused by *Trisetacus pini* (Nalepa) (from Schlechtendal, 1911). (B) Bud proliferation on pine caused by *Trisetacus cembrae* (Tubeuf); and (C) alterations on pine caused by *Trisetacus laricis* (Tubeuf) (C) (from Tubeuf, 1910).

involve changes in the appearance of the epidermis of green leaves, young fruits, young stems or bud bracts and are referred to as rust, russeting, browning, bronzing, silvering, chlorotic spots, reddening, etc. These symptoms could be primarily described as a discoloration of the plant organs, but they may also be associated with other symptoms. Petanović and Kielkiewicz (2010b) reported a comprehensive list of these distortions, which included 'brown scarification and necrosis of infested buds, mortality of buds, witches' broom or multiple branching owing to the death of primary growing points, distortion of veins, chlorotic spots, concentric ring blotch, mottle effects, hairless spots on the lower surfaces of attacked leaves, hardening and late ripening, irregular streaks, defoliation (if the collapse of lower leaf mesophyll follows extensive epidermal damage), lignifications, yellowish white areas, stunting, twisting, curling, desiccation of terminal buds or whole terminal shoots, distorted fruits, and premature drop'.

The most common non-distortive effects are 'toxaemias' and 'other non-distortive' feeding effects, which are usually considered to be specific and distinct types of alterations (Oldfield, 1996b). In addition, Petanović and Kielkiewicz (2010b) reported a series of 'complex and mixed symptoms'.

TOXAEMIAS. Toxaemias are macroscopic visual changes on plant epidermal tissues caused by agents in the saliva injected by some eriophyoids during their feeding activity. The short cheliceral stylets of these mites do not reach the cells of the tissues located below the epidermal layer, and the alterations of the tissues underlying the epidermal cells that result suggests that toxaemias are caused by a transfer of a toxicogenic agent(s). The alterations appear on leaves as chlorotic areas associated or not with veins and sometimes with distorted effects, such as wrinkling of the leaf surface, etc. On fruits, toxaemias may cause striking colour changes. Eriophyoid species causing distortions (leaf, bud, stem galls) do not produce toxaemias or other non-distortive effects on plants (Oldfield, 1996b).

Several eriophyoids cause toxaemias. *Aculus fockeui* (Nalepa *et* Trouessart) induces toxaemias on developing green tissues and russeting on the epidermal tissue of mature leaves (Oldfield, 1996b). *Calepitrimerus vitis* (Nalepa) causes brown scarification and necrosis on the winter buds of grapes, death of the buds and witches' broom, and the leaves turn yellow and drop (Carmona, 1973). *Phyllocoptes gracilis* (Nalepa) produces leaf blotches of chlorotic spots or rings on tayberry (Jones *et al.*, 1984). The feeding activity of *Aceria medicaginis* (Keifer) on young leaves of *Trifolium* spp. induces toxaemias (Ridland and Halloran, 1980a). *Aceria tulipae* (Keifer) causes 'kernel red streak' on maize (Nault *et al.*, 1967), leaf stunting, twisting and curling of tulip bulbs, onions and garlic (Conijn *et al.*, 1996; Perring, 1996), and premature bud drop or 'bull head' blooms on *Camellia japonica* L. (Subirats and Self, 1972). Toxaemias may include 'red berry disease', caused by the feeding activity of *Acalitus essigi* (Hassan), in which the ripening of the drupelets of blackberry (*Rubus* spp.) is prevented (Hamilton, 1948). Further details on toxaemias are given in the discussions of single eriophyoid species (see Chapters 16–18).

OTHER NON-DISTORTING FEEDING EFFECTS. The feeding activity of leaf vagrant species on leaves and other green plant organs may cause non-distortive feeding symptoms, such as russeting, bronzing, silvering and discoloration of leaves, stems and fruits.

The citrus grey mite, *Calacarus citrifolii* Keifer, causes 'concentric rings blotch' on citrus foliage. The symptoms consist of minute chlorotic or necrotic spots which gradually coalesce at the mid-veins. The production of resin gives these blotched areas a dark brown colour associated with darkish rings of resinous tissues. In addition, the mite secretes white wax on the upper side of the leaves (Doidge, 1925; Dippenaar, 1958a,b,c).

The tomato russet mite, *Aculops lycopersici*, lives on various solanaceous plants, and its feeding symptoms vary according to the host plant. Thus, it causes severe russeting on the leaves and stems of tomato, while on potato stems it produces little bronzing, with leaf symptoms similar to those of the tomato. Leaves of the aubergine show slight russeting and crinkling. Infested tomatillo plants do not have russeting, while *Convolvulus* leaves become silvery (Rice and Strong, 1962).

The citrus rust mite, *Phyllocoptruta oleivora*, feeds on the leaves and fruits of different species of citrus. Its cheliceral stylets are about 7 μm long and infestation affects the epidermal cells at a depth of 6–12 μm (McCoy and Albrigo, 1975). The mite destroys the stomatal guard cells on the lower leaf surface, inducing uncontrolled water loss. The epidermal cells turn brown and sometimes the lower leaf surface shows collapse of the mesophyll tissue, associated with yellow chlorotic patches which gradually become necrotic spots. The leaf drying may induce leaf abscission. On leaves that are severely infested, the upper leaf surface is slightly shiny and appears rough and dull bronze (McCoy, 1976). The fruits are usually more rusty than the leaves. Fruit damage first occurs on the epidermal layer, and afterwards also on cells of the underlying layer. It involves both the oil glands and parenchymatous structures, and appears as dark groups of cells surrounded by clear and healthy cells. The browned cells contain lignin but not lipid, callose or tannin. Ethylene emission has been observed. Some cells are punctured up to 26 times (McCoy and Albrigo, 1975). Bronzing and peel shrinkage occur on 'Valencia' orange fruits infested late in the season, and they have less juice, more soluble solids and acids, and higher concentrations of acetaldehydes and ethanol (McCoy *et al.*, 1976a).

The apple rust mite, *Aculus schlechtendali* (Nalepa), damages the leaves and fruits of apple. The mite feeds on the upper and lower leaf surfaces, damaging mesophyll tissue and causing callus tissue to form over the parenchyma in regions where the epidermis is destroyed. The hypodermal layer undergoes accelerated cell division, resulting in the formation and subsequent rupturing of periderm tissue (Easterbrook and Fuller, 1986; Royalty and Perring, 1996). The feeding activity of *A. schlechtendali* on the lower leaf surface causes epidermal cell collapse and the rupture of cell walls and the plasmalemma; this induces the degeneration of the cells of the spongy parenchyma associated with the thickening of cell walls and intercellular deposition of lignin-like compounds (Kozlowski and Zielinska, 1997; Kozlowski, 1998). Leaf damage appears as browning or rusting of the undersides during the summer, and is most obvious on leaves of the last shoots. High levels of attack may cause premature leaf fall. Damage is most severe on young trees in nurseries and in newly planted orchards (Easterbrook, 1996). In spring, the feeding activity of the apple russet mite on developing fruitlets causes russeting (Ciampolini *et al.*, 1976; Easterbrook and Fuller, 1986). The damage occurs from full bud until early July. Cells of the epidermal layer are damaged and cork gradually formed with russeting of the fruit. The lignification of the thickened cell walls is in the regions adjacent to the epidermal cells destroyed by the feeding activity of the eriophyoid on the leaves and fruits. Besides lignin formation, phellogen or 'cork cambium' forms within the attacked tissues (Easterbrook and Fuller, 1986; Kozlowski, 1998).

The coconut flower and nut mite, *Aceria guerreronis* Keifer, lives on coconut flowers and feeds on young nutlets. The green surface of the young nutlets shows triangular, pale yellowish white or whitish marks located at tightly adpressed bracts when the nuts are about 5 cm long. An increase of infestation enlarges the blemishes, which become brown and corky, sometimes forming deep fissures with exudate of gum. Irregular growth of the fruit causes cracking; damage is usually only to a part of the fruit and the kernel is partially reduced in size. Nuts about 20 cm long host a low density of mites under the bracts (Hall and Espinosa, 1981). Infested fruits turn brown and corky in appearance with sometimes extensive cracking reaching deep into the mesocarp. Fruits may be small and deformed as a result (Mariau, 1986; Schliesske, 1988; Howard and Moore, 2008).

Oxycenus maxwelli (Keifer) causes silvering of leaves and premature leaf drop on olive trees (Hatzinikolis, 1982). The feeding activity of *Calacarus carinatus* (Green) produces bronzing on tea leaves, followed at a high density of attack by desiccation and premature leaf drop (Shiao, 1976).

COMPLEX AND MIXED EFFECTS. Symptoms that are difficult to separate from those of pathogens transmitted by eriophyoids or by mixed infestation and/or infection can be attributed to eriophyoids. Several other symptoms (chlorosis, phyllody, flower virescence, internode shortening, enations, fasciation, axillary bud growth, necrotic spots, wart-like structures, blastomania, witches' brooms, stunting, multiple inflorescences and vegetative and floral malformations) may be confused with those caused by other agents (thrips, fungi, viruses, phytoplasmas, microelement deficiency). Toxaemias and non-distortive feeding effects are only known from the macroscopic visual changes of the host plant infested by the mites. Eriophyoid mites can be either vectors of diseases or prefer infested/infected plants, but many such symptoms have been proved to be caused exclusively by eriophyoid mites (Oldfield, 1996b). Petanović and Kielkiewicz (2010b) treat the topic extensively.

Damage

Eriophyoids feed on young and tender tissues, frequently on meristems, because of the high nutritional value of their cells. This adaptation forces them to inhabit particular plant organs, such as buds, sheaths, leaf veins, fruit calyxes, etc. Moreover, these microhabitats provide protection from natural enemies (Royalty and Perring, 1996). The feeding activity causes cellular and histological effects, which may or may not be associated with chemical and physiological disorders. Depending on the species and the mite population density, the attack can lead to slowdown in growth, leaf, flower and fruit drop, and death of branches or whole plants. The various responses do not have a general pattern and the long-term effects of eriophyoid infestation on host plants range from tolerance (without visible damage) to total damage (with plant death). The feeding activities of leaf vagrants and gall formers result in different morphological alterations (Jeppson *et al.*, 1975; Keifer *et al.*, 1982).

Cytological and histological effects induced by vagrant species

The small size of the mouthparts of eriophyoids forces them to feed on epidermal tissues. The vagrant species attack a single cell and leave shortly afterwards to search for another cell. At a high mite density, this behaviour causes the destruction of epidermal tissue. In the areas where the epidermal cells are destroyed, a layer of callous tissue rich in lignin is formed above the parenchyma. Russeting, bronzing, silvering or discoloration due to the feeding activity of mites arises from an oxidation process within the layer of injured cells. The destruction of individual epidermal cells requires multiple punctures by many mites or continuous feeding by a single mite. Commonly, the surrounding cells do not undergo any damage, but in some cases the changes that occur involve cells that are not directly damaged by mites (Jeppson *et al.*, 1975; McCoy and Albrigo, 1975; Westphal, 1977a,b; Royalty and Perring, 1988, 1996).

Depending on the vagrant and host plant species, the plant tissues that are damaged vary. *Phyllocoptruta oleivora* and *Aculus schlechtendali* are both leaf vagrants and damage mesophyll tissue. However, on citrus, *P. oleivora* does not feed directly on mesophyll cells, rather, the damage that it causes to epidermal cells on the abaxial leaf surfaces causes the mesophyll cells to collapse (McCoy and Albrigo, 1975), resulting in leaf drop (McCoy, 1976) and fruit abscission (Ismail, 1971). On apple, the feeding activity of *A. schlechtendali* causes the formation of callus tissue over the parenchyma where the epidermis is destroyed. The hypodermal cells increase their division, and formation and rupturing of the periderm tissue occurs (Easterbrook and Fuller, 1986). Massive feeding of *A. schlechtendali* on the lower leaf surface leads to the degeneration of the cells of parenchyma accompanied by the thickening of the cell walls and intercellular formation of lignin-like compounds (Kozlowski and Zielinska, 1997; Kozlowski, 1998). Other leaf vagrant eriophyoids do not damage mesophyll cells, e.g. *Aculops lycopersici* (Royalty and Perring, 1988) and the grass rust mite, *Abacarus hystrix* (Nalepa) (Gibson, 1974). Both of these species generally feed in depressions around the veins on the upper leaf surface. In these areas, they find a suitable microhabitat that is characterized by greater nutritional content. After the destruction of the cells around the veins, both mite species move and feed on exposed leaf surfaces. Parenchymal cells are not attacked and the water loss through the destroyed epidermis causes desiccation and plant death (Royalty and Perring, 1996). Recently, Pećinar *et al.* (2007) found that *Leipothrix dipsacivagus* Petanović *et* Rector caused significant cellular damage and changes in the mesophyll organization of the curled flower-stem leaves of *Dipsacus laciniatus* L. Infested leaves have hypertrophied epidermal cells and a mesophyll consisting of two to three layers of palisade parenchyma and several layers of non-differentiated parenchyma.

Cytological and histological effects induced by gall-forming species

Cecidogenesis – the process of gall formation – has been extensively investigated in the gall mite *Aceria lycopersici* (Wolffenstein), and in the rust mite *Thamnacus solani* Boczek *et* Michalska, both reared on woody nightshade (*Solanum dulcamara* L.). The feeding activity of these two eriophyoids stimulates a different reaction on this host plant, and comparison of their behaviour has allowed an understanding of the process. On susceptible plants, *A. lycopersici* induces a 'compatible interaction' which is characterized by the formation of witches' brooms, while on resistant plants, it causes an 'incompatible interaction' or hypersensitive response (HR), which is associated with small necrotic lesions and leads to the death of the mite. As a result, the mite develops only on plant varieties upon which it can induce galls. In resistant plants, callose (1,3-β-glucan) does not appear around the mite puncture wounds and the damaged cells collapse within 45 min. The neighbouring epidermal and mesophyll cells do not show hyperplasia, their nuclei shrink and they become plasmolysed. The cells may collapse and form a necrotic spot, but no erinea form and the mite population does not develop (Westphal *et al.*, 1981, 1989, 1990). The hypersensitive response and the absence of galls are associated with the production of several novel proteins referred to as pathogenesis-related proteins (Bronner *et al.*, 1991a). *T. solani* exhibits a compatible interaction with *S. dulcamara*, causing vein russeting and the withering of leaves. The mite kills only the punctured cell, which turns brown and dies, and does not damage the surrounding cells. It then moves on from this cell and seeks a new cell to attack, which exhibits the same limited damage. Severe damage to the host plant depends on there being a high density of populations. This compatible interaction gradually causes leaf russeting as a cumulative effect of severe attack (Westphal and Manson, 1996).

Unlike the rust mites, the gall-forming eriophyoids feed on one epidermal cell for a long time (hours or days). The damaged cell often dies and the neighbouring epidermal and parenchymal cells show morphological alterations that result in various abnormalities (galls, erinea, witches' brooms, etc.). After the penetration of the stylets, a cone-shaped cell wall thickening, called a 'feeding puncture', forms around the puncture, which has been reported for several gall mites (Němec, 1924; Westphal, 1977a; Thomsen, 1988). This has a callosed disc-like structure and appears 10–20 min after stylet penetration (Bronner and Westphal 1987; Bronner *et al.*, 1989). Callose deposition is a widespread phenomenon and is not specific to stylet penetration; for example, it also occurs following superficial mechanical wounding caused by microinjections (Nims *et al.*, 1967) or by the action of fungi (Aist, 1976). The vacuoles of the epidermal and palisade cells surrounding the attacked cells become smaller and the pH inside the vacuoles increases, as does that of the vacuoles of the damaged cells which exhibit a clear alkalinization (pH > 8) within 30 min that is associated with alterations in membrane permeability (Westphal, 1982) and nuclear structure (Bronner *et al.*, 1989). The nucleus swells, occupies a central position and shows progressive DNA-denaturation, with a lower contrast and appearing to be optically empty. The nuclei and nucleoli of the neighbouring cells swell and mitosis increases, thereby providing more cells for mite feeding (Westphal *et al.*, 1981). In infestation by *A. lycopersici*, this mechanism results in erinea or witches' brooms (Westphal *et al.*, 1981, 1990). Hyperplasia of the glandular trichomes and epidermal hairs has also been observed (Westphal, 1985), and forms a favourable microhabitat for mites.

Callose formation plays an important role in cecidogenesis. The suction cone and the nucleus are characterized by chitosan accumulation. The chitosan may be introduced into the cell by the chitinous cheliceral stylets of the mite, because higher plants do not synthesize this derivative of chitin (Bronner *et al.*, 1989), and it seems that it may trigger a modification of cell permeability and alterations in the nuclear DNA. The high affinity of chitosan for DNA molecules and polygalacturonate in plant–pathogen interactions (Hadwiger, 1999) suggests that its accumulation within the nucleus and in feeding punctures on the walls stimulates the activity of neighbouring cells. Callose is involved in the formation of the callosic disc-like feeding punctures of the compatible interaction (Thomsen, 1988), and is probably also used in the regeneration of the pierced plasmalemma of attacked cells and in other cellular functions. The cellular biochemistry and metabolic responses induced in mite-injured plants have been extensively discussed by Petanović and Kielkiewicz (2010a).

Like callose, the layers of nutritive tissues used by gall mites for feeding are important (Thomsen, 1975; Westphal *et al.*, 1981; Bronner and Westphal, 1987; Bronner *et al.*, 1989). The punctured cells undergo a similar process to that of injured epidermal cells and die, but the maintenance of nutritive tissues (for the mite) and the formation of galls require continuous puncturing (Mani, 1964; Westphal and Manson, 1996). If gall formers are removed, the nutritive tissue turns into regular parenchyma cells (Rohfritsch, 1975). For example, when *Eriophyes tiliae* (Pagenstecher) is removed from the leaves of *Tilia platyphylla* Scopoli and gall formation stops, the gall cells transform into epidermal cells with stomata and mesophyll cells containing chloroplasts (Thomsen, 1975); the epidermal cells also contain anthocyanins.

The macro-morphology of the gall is specific to the mite species. Conversely, the micro-morphology of galls is very similar. It begins with repeated anticlinal and periclinal divisions of the lower epidermal cells, which lead to the formation of both nutritive and mesophyll tissues, but no differentiation into palisade and spongy tissues. The hypertrophied parenchyma cells and nutritive tissue contain starch and proteins, but not lipids. The vascular bundles of the galls relate to those of the healthy leaf surface, but there is no direct connection between the bundles and the nutritive tissue. Fibres and tannins have been observed in gall phloem and in the lignified vascular bundle sheaths. Many unicellular and cylindrical hairs may grow on the gall surface (Petanović and Kielkiewicz, 2010a). Other cytological and histological features of the gall include hyperplasia of the epidermal and parenchymal cells adjacent to the damaged cells (Anthony *et al.*, 1983). Hypertrophy of the nuclei and nucleoli associated with hyperplasia of the epidermal cells has also been reported (Moha, 1969), as well as hypertrophy and hyperplasia of the epidermal and mesophyll cells and polyploidy in the nuclei of the nutritive cells of the galls (Wcislo, 1977). Polyploidy and multiple nuclei have been observed in the epidermal cells of galls too (Kendall, 1930; Hesse, 1971; Westphal, 1974). Different gall mites induce fragmentation of the vacuoles, increased amounts of endoplasmic reticulum, increased numbers of mitochondria and ribosomes, and plasmid alteration (Westphal, 1970, 1977a).

Some gall mites induce the formation of different gall types, such as *Eriophyes goniothorax* (Nalepa) (Boczek and Griffiths, 1994), and *Phytoptus tetratrichus* (Nalepa), which causes edge rollings on the small-leaved linden (*Tilia cordata* Mill.) and warty galls on the upper sides and erinea on the undersides of the leaves of the silver linden (*Tilia tomentosa* Moench.) (Soika and Kielkiewicz, 2004).

The feeding activity of eriophyoid mites modifies the quality of plant tissues and affects the behaviour of other herbivorous arthropods that feed successively on the same host plants. Thus, severe infestation of *Aculus schlechtendali* on apple trees inhibits the development of the European red spider mite, *Panonychus ulmi* (Croft and Hoying, 1977). In other compatible interactions, e.g. between *T. solani*, *P. oleivora*, *Aculops lycopersici* and susceptible host plants, the quality of the food resource within infested organs favours further development of the mites (Royalty and Perring, 1996; Westphal and Manson, 1996; Westphal *et al.*, 1996). Infestations of *Aceria cladophthirus* (Nalepa) trigger the incompatible interaction (or HR) in resistant *S. dulcamara* plants, which induces the death of *A. cladophthirus* and, successively, increases the mortality of *T. solani* (Westphal *et al.*, 1991). Curiously, the HR does not protect *S. dulcamara* plants from later infestation by the two-spotted spider mite, *T. urticae* (Westphal *et al.*, 1992).

Chemical and physiological changes

The feeding activity of eriophyoid mites may induce changes in the physiological processes of the host plants, but the effects of both vagrant and non-vagrant eriophyoids on the metabolism of the host plants are variable. Alterations in photosynthesis, concentrations of plant hormones and hormone regulators, and nutrient contents are well known. However, most of the data concern leaf vagrant mites, because the effects of gall-forming mites have not been extensively investigated. The topic is very complex, involving various factors, such as eriophyoid genotypes (or strains), mite population density and period of feeding, and host plant species, cultivar, organ age and environmental conditions (Petanović and Kielkiewicz, 2010a).

The feeding activity of leaf vagrant eriophyoids may reduce leaf gas exchange and thereby affect physiological processes. On peach (*Prunus persica* (L.) Stokes), 3000 *Aculus fockeui* feeding days per leaf reduce the CO_2 assimilation rate and stomatal conductance by about 20%, and there is a negative relationship between gas exchange and damage to the epidermis of the adaxial leaf surface (Andersen and Mizell, 1987). A high density of *A. fockeui* on *Prunus cerasifera* L. reduces photosynthesis by more than 70% and respiration by more than 50% (Zawadzki, 1975). On tomato, 450 *Aculops lycopersici* days cm^{-2} reduce leaflet net photosynthesis by 50% (Royalty and Perring, 1989). On apple, a density of *A. schlechtendali* of 4000–5000 mites per leaf causes direct damage to the leaf epidermis and indirect damage that is mainly correlated with changes in the mesophyll cells of leaves and reduction of the net CO_2 exchange by as much as 65%. Furthermore, the stomata are partially open and affect the transpiration process, causing a decrease of guard cell turgor and the desiccation of epidermal and parenchyma cells (Spieser *et al.*, 1998).

Galled leaves within a heavily galled portion of *Prunus americana* Marsh. infested by *Phytoptus emarginatae* (Keifer) reduce the photosynthetic surface of the nearby leaves as a result of the reallocation of resources within the infested shoot (Wilson and O'Dowd, 1990). Galls induced by *Phytoptus cerasicrumena* Walsh reduce the photosynthetic rate of galled leaves of *Prunus serotina* Poit. *et* Turpin by 47% and the photosynthesis of nearby ungalled leaves within the same shoot by 24% (Larson, 1998).

The presence of hormonal substances in the saliva of eriophyoid mites has been discussed by various authors (Jeppson *et al.*, 1975; Westphal, 1992; Boczek and Griffiths, 1994).

Lipophobic substances have been reported to be secreted by the mouthparts of *Aceria caulobia* (Nalepa), along with IAA and cytokinin-like compounds, suggesting the presence of plant growth regulatory substances in the mite saliva (de Lillo and Monfreda 2002, 2004). The feeding activity of eriophyoids may cause alterations in the concentrations of plant hormones and hormone regulators, usually associated with galling, growth abnormalities and damage. The introduction into the host plants of auxin 'protectors' (*o*-dihydroxyphenols, coumarins, polyphenols, gibberellins) that bind with peroxidase and IAA oxidase (indole-acetic-acid-oxidase), which usually degrades IAA, suggested that there was an abnormal accumulation of IAA in the damaged cells that was stimulating unusual growth and gall formation. Research on *Ziziphus jujuba* Lamk. and *Z. Mauritania* Lamk. infested by *Aceria cernuus* (Massee) highlighted IAA regulation in the galls (Purohit *et al.*, 1979; Tandon and Arya, 1980, 1982; Tandon, 1982). The citrus bud mite, *Aceria sheldoni*, induces auxin regulation and plant growth abnormalities in the buds of lemon, *Citrus limon* (L.) Burman. The feeding activity of the mite stimulates an increase in the level of phenols in the bud tissues with a simultaneous decline in auxin activity, with alterations in ribonuclease (RNase) activity. Infested tissues do not show any inhibition of IAA-oxidizing enzymes, but the auxin produced is oxidized, inducing inhibition of growth. The increase of polyphenol oxidase that is found is probably due to the conversion of polyphenols to quinones (Ishaaya and Sternlicht, 1969, 1971), which react with proteins to form melanin and other tannins, which are typically brown, as are the lemon buds damaged by the mite. On the apple cultivar 'Pioneer', a density of *A. schlechtendali* of 22–27 cm^{-2} of leaf surface induces an increase in the ratio of total phenolic compounds to carbohydrates from 3:1 in control to 5:1, and a decrease in the palatability of the injured host plant to mites (Kozlowski, 1998). On blackberry, a density of *Epitrimerus gibbosus* (Nalepa) of 600–1000 per leaf changes the nutritional value and palatability of the infested leaves after 3 weeks (Shi and Tomczyk, 2001). In the leaves of a 'Thornfree' blackberry cultivar, an increase in the concentration of phenolics is associated with decreases in carbohydrate concentration, whereas in leaves of a 'Thornless' evergreen cultivar, an increase was found in the soluble protein concentration. As an appropriate balance between feeding inhibitors and stimulators is a very important factor in the eriophyoid–plant interaction, it is believed that a rise in the ratio of total phenolics to total carbohydrates/proteins in infested blackberry leaves results in a decrease in successful mite feeding.

The localized necrotic lesions caused by *Aceria lycopersici* are associated with an increase of peroxidase activity which is involved in the oxidative cross-linking of proline-rich proteins in cell walls (Bronner *et al.*, 1991b). This mechanism renders the cell walls indigestible to enzymes and characterizes the hypersensitive response of host plants to pathogens (Dixon *et al.*, 1994). Other enzyme proteins, such as chitinase or 1,3-β-glucanase, accumulate in response to the feeding activity of *A. lycopersici* (Bronner *et al.*, 1991a). Several enzymatic proteins are not only induced locally but also systemically in the leaves of tomato plants (*Solanum lycopersicum* L.), in response to short-term feeding by *A. lycopersici*. The local induction of peroxidase (POX, hydrogen peroxide (H_2O_2) oxidoreductase) activity was much more evident than the induction of polyphenol oxidase (PPO) or lipoxygenase (LOX) (Stout *et al.*, 1996).

Alterations in the nutrient contents were observed in leaves of *P. cerasifera* infested by *A. fockeui*, e.g. a reduction in carbohydrate content and increased nitrogen, Ca^{2+}, Na^+, K^+ and chlorophyll contents (Zawadzki, 1975). Leaves of *Jasminum auriculatum* Vahl infested by *Aceria jasmini* ChannaBasavanna showed a reduction of carbohydrate to 21% less than in uninfested leaves, associated with a reduction of 31% of the soluble sugars, probably as a result of the inhibition of photosynthesis (Rajagopal *et al.*, 1970). The contents of nitrogen, PO_4^{2-}, and K^+ of the sheath leaves of sugarcane infested by *Abacarus sacchari* ChannaBasavanna were respectively 23, 16 and 37% greater than those of uninfested leaves (Sithanantham *et al.*, 1975). Studies on the effects of feeding by *Aceria acnisti* Keifer on *Acnistus cauliflorus* Schott. and by *Phyllocoptes bougainvilleae* Keifer on *Bougainvillea spectabilis* Willd. on the host plants show that *A. acnisti* induces the formation of galls on both leaf surfaces, with a tenfold increase in the number of galls associated with an increase of 50.6% in fresh weight and 55.63% in dry weight of the leaves. Moreover, the content of six macronutrients increased markedly, and potassium and phosphorus increased 299.37% and 105%, respectively. The micronutrients iron and copper increased 173% and 81.8%, respectively. These results indicate that plants invest large amounts of their resources in gall production, although it should be noted that the nutrient analyses do include the mites living on the plant tissues. In *Bougainville*a leaves infested by *P. bougainvilleae*, there was a negligible decrease in nitrogen content, a 19% decrease in calcium and a 9.8% decrease in manganese, but there were increases in the other elements analysed. In both of these latter cases, there was an increase in leaf copper contents: 81.8% in *A. cauliflorus* infested by *A. acnisti* and 100% in *B. spectabilis* infested by *P. bougainvilleae* (Flechtmann and Berti-Filho, 1994).

Gall mites may induce different changes in the metabolism of galled leaves of walnut, apple and pear trees. In walnut leaves, the walnut erineum mite, *Aceria tristriatus* (Nalepa), induces no changes in soluble proteins and a marked decrease in carbohydrate, with a slight decrease of carbohydrates in the morphologically unaltered leaf tissues surrounding the mite erinea. The concentration of phenolics remains almost unchanged. A slight increase in the concentration of these compounds occurs within the leaf tissue between the galls. The erinea occupy at most 15–20% of the total leaf surface, but a reduction of five times occurs in the rate of photosynthesis (Tomczyk and Boczek, 2006). On apple leaves, infestations of the apple leaf blister mite, *Eriophyes mali* (Nalepa), induce an increase in soluble protein associated with a lack of changes in total carbohydrates and an increase in phenolics (Tomczyk and Boczek, 2006). On pear leaves, the pear leaf blister mite, *E. pyri*, causes a large increase in soluble proteins in slightly galled leaves but a rapid decrease in strongly galled leaves (Tomczyk and Boczek, 2006). Leaves of the linden (*T. cordata*) galled by *E. tiliae* show a decrease in the content of carbohydrates, with a non-uniform distribution of ^{14}C among the leaf blade, midribs and galls (Boczek, 1974). Studies on the composition of carotenoids in the leaf blade of *T. cordata* and in galls caused by *E. tiliae* var. *rudis* Nalepa showed that seven carotenoids were present in the leaf blade but missing in the galls, whereas three carotenoids were located specifically within the galls. This indicates that the feeding activity of *E. tiliae* promotes the biosynthesis of some carotenoids and hinders that of others (Czeczuga, 1975).

Eriophyoid galls contain a variable amount of tannins. Within each gall type, apart from the nutritive tissue layers, there are numerous cells accumulating *o*-dihydroxyphenols, which are commonly considered to be plant defence compounds. The deterrent, antifeedant or toxic effects of condensed tannins on many arthropod herbivores are well known, as exemplified by the finding that differences in tannin content between alder genotypes at the early stages of gall formation can significantly delay gall development and differentiation of the defensive response. Another known function of tannins and phenolic compounds, especially those located in the outer layer of the galls, is protection of the gall formers from parasitoids, predators and pathogenic infections (Mound, 1994; Hartley, 1998). The gall and leaflet tissues of ash produced by *Aceria fraxini* (Garman) have few tannins, whereas the galls of willow caused by *Eriophyes aenigma* Walsh (= *Aculops aenigma* (Walsh)) and the galls of filbert caused by *Phytoptus avellanae* have many tanniferous cells in their walls, but their nutritive tissues have few tannins. The nutritive cells of very young alder galls induced by *Eriophyes laevis* (Nalepa) contain tannins, and the nutritive tissue accumulates more tannins as the alder gall matures. Week-old pouch galls induced by *E. laevis* on the leaves of European alder, *Alnus glutinosa* Gaertn., have the same structure as the galls on the leaves of *Alnus incana* (L.) Moench., but differ in the presence of tannins in the vascular bundle sheaths in undifferentiated cell layers. Tannin deposits did not appear within bundle sheaths and cells derived from the mesophyll until the galls of *A. incana* were 3 weeks old. Comparison of the internal structure of 3-week-old galls show that the galls of *A. incana* are more differentiated and have more tannin deposits than the galls of *A. glutinosa* (Kane *et al*., 1997).

Impact on growth, flowering and cropping

The feeding activity of several eriophyoids has impacts on the growth, flowering and cropping of economic plants.

On lemon, the extent of blossom and fruit abscission significantly increases with the distortion caused by the feeding of the citrus bud mite, *Aceria sheldoni*. Distortion of the fruit is significantly linked to that of the blossoms from which they develop. It is probable that the increase in blossom and fruit abscission may depend on a decrease in auxin activity and other biochemical changes in the axillary buds infested by the mite (Phillips and Walker, 1997). On navel orange, the mite causes a reduction in fruit size and the number of fruits (Schwartz, 1972).

The tomato russet mite, *Aculops lycopersici*, develops on the stems, leaves, flowers and fruits of tomato plants (and other plants). The stems become bronzed or russeted, and may crack longitudinally or check. The leaves become brown and paper like and usually wilt. Severe infestations cause leaf drop, even before the leaves change in colour. The flowers lose turgor, cease to develop, show russeting of the sepals and fall (Jeppson *et al*., 1975). Most yield loss is due to mite feeding on the flower stalks and pedicels, which dry and cause flower bud death (Kamau *et al*., 1992). Severely infested fruits do not develop, and gradually become russeted and roughened (Jeppson *et al*., 1975).

The pink citrus rust, *Aculops pelekassi*, develops on the leaves, green stems and fruits of citrus. Its feeding activity affects the diameter, volume and weight of citrus fruits, compromising their marketing as fresh fruit. The sugar content of the juice is higher in the damaged fruit, and the increased concentration of soluble solids most likely occurs through water loss caused by mite feeding (Tono *et al*., 1978). A density of 200 or more mites per leaf is destructive (Childers *et al*., 2007).

The citrus rust mite, *Phyllocoptruta oleivora*, feeds on the leaves and fruits of all citrus species. The result of infestations on the lower (abaxial) surfaces of the leaves differs from that on the upper (adaxial) side, and in citrus fruits; attacks on the upper side are confined to the epidermal cells and show symptoms similar to the russeting of immature fruit (Albrigo and McCoy, 1974). In severe attacks, the cuticle of the upper surface may lose its shine and become bronze with yellowish spots in areas that have been ‘degreened’ by the release of ethylene during the wounding process (McCoy and Albrigo, 1975), while on the lower surface the attack can lead to appreciable mesophyll collapse visible as degreened yellowish spots that later become necrotic (Albrigo and McCoy, 1974). Severe attack on the lower leaf surfaces can increase transpiration and stimulate defoliation (McCoy, 1976). Damage to fruits varies depending on the variety and stage of fruit development, and results in russeting or bronzing. A high density of the eriophyoid population causes reduced size of the fruits (Yothers and Mason, 1930; Schwartz, 1975a), fruit water loss (McCoy *et al*., 1976a; Allen, 1979), fruit drop (Allen, 1978) and alterations in juice quality (McCoy, 1976). Although the aesthetic damage that is caused has a commercial impact, the total content of soluble solids does not appear to be affected and the fruits that result can be used for industrial applications without any problem (Chandramani *et al*., 2004).

Severe attacks of the grape mite, *Colomerus vitis*, on grapevines significantly reduces the growth of shoots and canes and the number of dead buds increases (Smith and Schuster, 1963).

On peach trees, *Aculus fockeui* causes a reduction in the weight, sugar content and acidity of next year’s fruit. Severe injury to the peach leaves causes a reduction in the sugar content of fruits in the same year, and damaged trees show lower vigour as a result of postharvest defoliation, resulting in lower fruit quality in the next year (Kondo and Hiramatsu, 1999a).

On *Medicago sativa* L., infestations by the alfalfa bud mite, *Aceria medicaginis*, reduce the length of the petioles at each stem node, as well as the leaf surface, shoot weight and number of axillary shoots (Ridland and Halloran, 1980b, 1981).

The dry bulb mite, *Aceria tulipae*, infests shallots, onions, garlic and tulips. Severe infestations induce a mean weight reduction of 19%, and the chronic impact of mite infestation is more severe than the acute damage that occurs during a short infestation (Santos and Lima, 1976). Severely infested bulbs have a 20% reduction in emergence and a 23% yield reduction (Larraín, 1986).

The coconut flower and nut mite, *Aceria guerreronis*, lives on coconut flowers and feeds on the young nutlets. Infested fruits turn brown and corky in appearance, sometimes with extensive cracking reaching deep into the mesocarp. The fruits that result may be small and deformed (Mariau, 1986; Schliesske, 1988; Howard and Moore, 2008), and infestation may also affect copra yield, causing reductions of about 30% in American and African countries (Hernández Roque, 1977; Julia and Mariau, 1979a; Moore, 1986) and about 40% in India (Nair and Koshy, 2000; Muthiah and Bhaskaran, 2000). A later study in India (in Kerala) by Haq and Sobhal (2010) demonstrated that infestation by *A. guerreronis* reduced the weight of copra from highly infested coconuts by 32%, but showed that when mite infestation was low, the weight loss was only 7%. In Venezuela, early dropping of the coconuts induced a reduction in copra yield of about 70% (Doreste, 1968a), and in Tanzania and the African coastal islands of Mafia, Zanzibar and Pemba, the reduction in copra yield ranged from 10 to 100% (average 21%) (Seguni, 2002).

A density of 4000–5000 apple rust mites (*Aculus schlechtendali*) per leaf affects flower formation and the quality of apple yield. Fresh fruit weight, soluble carbohydrate content and skin colour intensity show a stronger decrease in the 'Jonagold' than in the 'Golden Delicious' variety, indicating the possibility that the latter cultivar is relatively resistant to the mite (Spieser *et al*., 1998). Easterbrook and Palmer (1996) found that according to the cultivar, the level of infestation affected flower formation and the quality of apple yield.

Tarsonemidae

Only a restricted number of the Tarsonemidae are feeders on higher plants, and they belong to five genera. Other tarsonemid species probably feed on fungi and/or algae; their mouth appendages seem to be unable to penetrate the tissues of higher plants (Jeppson *et al*., 1975).

Feeding mechanism

The feeding mechanism of the Tarsonemidae involves various mouthparts, including the stylophore, the gnathosomal capsule, the palpi, the chelicerae and the pharyngeal complex. The stylophore is formed by the fused cheliceral bases, and is integrated with the infracapitulum to form the gnathosomal capsule. This latter is usually ovoid, sometimes prolonged, and composed of modified cheliceral bases and rostral elements. The palpi are simple and are adapted to tactile function or in some cases to eating solid food particles – certain species are capable of swallowing whole fungal spores. The chelicerae are simple, stylet like, retractable and, according to the feeding habit, of various length (Fig. 2.7G). Each stylet is attached proximally to a 'cheliceral lever', which relates it to the retractor and protractor muscles. The pharyngeal complex lies in the ventral part of the gnathosomal capsule, and consists of sclerotized parts, muscular sheaths and a pair of gland-like structures, probably salivary glands. A great diversity of pharyngeal structures occurs among the various species of the family, which seem to be more suited to penetrating the cell walls of fungi and of soft tissues rather than ligneous tissues such as leaves and mature shoots (Jeppson *et al*., 1975; Lindquist, 1986; Nuzzaci *et al*., 2002).

Symptoms of feeding

The symptoms resulting from feeding by tarsonemids vary according to the species and are sometimes unclear or doubtful. Only a restricted number of species included in the genera *Steneotarsonemus* Beer, *Phytonemus* Lindquist, *Polyphagotarsonemus* Beer *et* Nucifora, *Hemitarsonemus* Ewing and *Tarsonemus* Canestrini *et* Fanzago are plant feeders. Some tarsonemid mites initiate fungal infection (*Steneotarsonemus* spp.).

The pineapple leathery pocket mite, *Steneotarsonemus ananas* (Tryon), causes brown spots on the white tissues at the base of the leaves of pineapple, especially in young plants (Meyer Smith, 1981a). In South Africa, the presence of the mite is associated with 'leathery pocket disease', in which there is hardening of the walls of the seed cavities and nectary ducts of the pineapple fruitlet (Petty, 1975). The hardening is probably due primarily to the fungus *Penicillium funiculosum* Thom (Rohrbach, 1979, in Meyer Smith, 1981a).

The feeding activity of the West Indian sugarcane mite, *Steneotarsonemus bancrofti* (Michael), causes transparent brown crater-like depressions on the young sugarcane stalk, and the plant tissues appear to be scabby or scarred. As the cane grows, these areas successively become opaque, brown and rough (Holloway, 1936; Butani, 1959).

Steneotarsonemus furcatus De Leon causes severe distortion of the leaves and shortened internodes on the ornamental grass *Paspalum* spp., and on *Maranta leuconeura* E. Morren, resulting in stunted plants (Jeppson *et al*., 1975).

The bulb scale mite, *Steneotarsonemus laticeps* (Halbert), feeds mainly on epidermal surfaces of the scales of bulbs of *Narcissus* and other Amaryllidaceae. On developing shoots, it causes distortion, stunting and death of leaves and flowers. Scar-like tissues on the leaves and flower stems cause bronze streaks and transverse cracks. Infested bulbs have yellowish brown areas (Doucette, 1936; Carmona, 1966; Jeppson *et al*., 1975).

The rice panicle mite, *Steneotarsonemus spinki* Smiley, has a probable Asian origin and was first described on the plant hopper, *Sogata orizicola* Muir, in Louisiana in 1960 (Smiley, 1967). It is a rice pest in China, the Philippines, Taiwan (Smiley *et al*., 1993), India, Kenya (Rao and Das, 1977), Cuba (Ramos and Rodríguez, 2001), the Dominican Republic (Ramos *et al*., 2001), Japan (Shikata *et al*., 1984), Korea (Schall, 2004), Haiti and Columbia (Ochoa, 2004, in NPAG, 2008). In addition, the rice panicle mite has been reported in Belize, Costa Rica, Guatemala, Haiti, Honduras, Nicaragua, Panama, the Philippines, Sri Lanka, Thailand (Návia *et al*., 2006a; EPICA, 2007; GPDD, 2007), the USA (Texas, Louisiana and Arkansas), Mexico (Arriaga, 2007) and Puerto Rico (USDA, 2007). Reports of the mite in the Americas regions have been recently discussed by Návia *et al*. (2010b). This tarsonemid feeds on rice (*Oryza sativa* L.), on the invasive *O. latifolia* Desv. and on other *Oryza* spp. (USDA NRCS, 2007). Symptoms, such as necrotic bands and spots, develop on the rice grains and leaf sheaths when populations are large, and populations greater than 450 mites cm^{-2} have been recorded (Ramos and Rodríguez, 2001).

Steneotarsonemus spirifex (Marchal) causes spiral malformations of the rachis, blind spikelets and incompletely emerged inflorescences of cereals (Evans *et al.*, 1961).

Phytonemus pallidus (Banks) infests various economic plants, such as strawberries and watercress, and many ornamental flowers and shrubs (Van Eyndhoven and Groenewold, 1959). On pikake, *Jasminum sambac* (L.) Aiton, the feeding activity of this mite results in fewer flowers per cluster and often severe abortion of the clusters and buds, poorly formed flowers, with twisted, distorted and smaller leaves. The shoots have elongated internodes (Boyle and Haramoto, 1956). Infested strawberry leaves have a roughened and wrinkled upper leaf surface, with irregular folding and fluting of the leaf margins. The veins bulge upward like blisters, and the petioles fail to elongate, and bear leaflets that fail to unfold completely. These small leaflets become pale yellowish green with a hard brittle texture and turn brown or silvered on exposure to the sun. The flowers and fruits become brown near the inner bases of the sepals, and may turn black and dry (Dustan and Matthewman, 1932).

The broad mite, *Polyphagotarsonemus latus* (Banks), feeds on tender tissues and is common on the young leaves, flowers and immature fruits of a large variety of crops in subtropical and tropical countries, and in the greenhouses of temperate regions. On *Gerbera*, the lower leaf surface becomes rigid and rolled under at the edges and turns bronze, and the flowers have distorted and discoloured rays. Overall, the feeding activity of the mite causes curling and crinkling of the leaves and patches of blisters. High mite population densities stop the plants growing and cause death (Smith, 1939a). On potato plants, feeding symptoms consist of blackish spots on the undersurfaces of young leaves, which turn gradually reddish. The plant becomes rosetted, showing prominent leaf hairs and leaves wrinkled at the edges. The plant withers and the buds are killed (Mann *et al.*, 1920). On pepper seedlings, the infestation prevents flower and fruit development, later causing the dropping of flowers and silvering of fruits (Kulkarni, 1923).

P. latus also damages young leaves and fruits of citrus, particularly of lemon. Its feeding activity causes distortions and curlings of the leaves, sometimes so pronounced as to prevent the development of the shoot. The lower surface of the young leaves can develop a shining and a silver colour. The fruits are infested as soon as they start to develop and until they reach the size of a walnut, and the mite populations develop more frequently on young fruits in the shade and inside the apical part of the canopy. The attack causes a silvering of the pericarp with irregular contours and sometimes over the entire fruit surface, and with the progress of the infestation and the development of the fruit, the pericarp develops russeting and an irregular shape, with a variable colour from white to silver to brown (Nucifora, 1961; Jeppson *et al.* 1975; Vacante, 2010).

On tomato, the stems of terminal shoots and the undersurfaces of the young leaves infested by the broad mite become shiny bronze or brownish. The first type of injury consists of browning of the epidermal cells, but later the cells of developing tissues collapse and die. The young expanding leaves become narrow, stiff, twisted or crumpled, fail to develop and dry up. The stem of the young plant becomes swollen, roughened or russeted and greyish green. On cotton, the first symptoms occur on the lower leaf surfaces, and the leaves become rigid and roll under at the edges. Mature leaves may split or crack open, with various shapes (Hambleton, 1938).

Cucumber plants (cultivars ‘M450’ and ‘Kfir’) infested by *P. latus* produce more ethylene than uninfested plants. The broad mite feeds on epidermal cells, inducing their disappearance or collapse. The leaves of infested plants are thicker, smaller and harder, and have additional layers of more compact cells without mesophyll differentiation (Grinberg *et al.*, 2004). The plants also show growth inhibition, have fewer leaves and a decreased leaf area. These aberrations involve the entire leaf tissue, and severe infestation induces a complete loss of the epidermis and an increase in mesophyll cell size and number. The epidermal tissue appears to have collapsed, and the mesophyll cell walls are thick and distorted. The morphological, structural and ultrastructural changes that are induced by *P. latus* are associated with an induction of the genes involved in plant defence pathways (Grinberg *et al.*, 2005). Mite feeding induces the expression of the defence pathway genes *BGL2*, *LOX1*, *LOX2* and *PRX*, and the transcript levels increase between 24 and 72 h post infestation. In contrast, mechanical wounding does not induce these transcripts, with exception of a slight induction of *LOX1*. The gene *ACO1* shows a uniform expression pattern. Feeding by the broad mite causes an induction of both the salicylic acid (SA) and the jasmonic acid (JA) pathways (Grinberg *et al.*, 2004), and infested leaves exhibit the induction of genes related to the JA/ethylene and SA pathways, such as lipoxygenase (*LOX*) and β-1,3 glucanase (*BGL2*), and also an induction of oxidative stress-responsive transcripts, such as those of peroxidase (*PRX*). The transcript levels of ACC oxidase (*ACO*), which is involved in ethylene biosynthesis, remained relatively constant (Grinberg *et al.*, 2005).

The fern mite, *Hemitarsonemus tepidariorum* (Warburton), feeds on various species of ferns in greenhouses in the USA and the UK (Beer, 1954). Mite feeding causes little depressions on the frond surface, which successively become brown speckles. Attacked fronds also show distortions and swellings (Cameron, 1925; Pritchard, 1951a).

Tarsonemus myceliophagus Hussey is a serious pest in mushroom culture (Hussey and Gurney, 1967).

Damage

A close relationship between symptomatology and economic damage usually occurs on flowers and ornamental plants infested by tarsonemid mites (and other pests), because the first symptoms are sufficient to cause damage. On fruit plants, although symptoms and damage also occur on the foliage, the damage is mainly (but not exclusively) related to yield losses, e.g. *Polyphagotarsonemus latus* infestations on lemon fruits are similar to those caused by the eriophyoid *Phyllocoptruta oleivora*, and may result in a reduction of commercial value of up to 100%. In South Africa, lemon losses of between 30 and

70% have been reported from *P. lata* (Meyer Smith and Schwartz, 1998e). In the same country, *Steneotarsonemus ananas* causes the development of leathery pocket disease on pineapples causing up to 16% of the fruit damage (Petty, 1977).

The damage caused by *Steneotarsonemus spinki* on rice can be direct, due to toxin injection during feeding, or indirect, through the spreading of phytopathogens (Návia *et al*., 2010b). When population levels of the mite are low, *S. spinki* is typically found feeding on the internal surfaces of leaf sheaths, but at high density the mite populations spread on to all plant parts, including the kernel (Chow *et al*., 1980; Ramos and Rodríguez, 2001). In China, the Philippines and Taiwan, the mite has caused substantial crop losses, ranging from 30 to 90% (USDA, 2007). In addition to reducing the value of the rice by scarring the kernel, the mite affects yield by transmitting the fungus, *Acrocylindrium oryzae* Sawada, and the mycoplasma-like organism, *Spiroplasma citri* Saglio *et al*., both of which cause rice sterility (Chow *et al*., 1980). Ramos and Rodríguez (2001) estimated that the combined activities of feeding and disease transmission by *S. spinki* lowered rice yield in Cuba by 30–60%.

Infestations of *Hemitarsonemus tepidarum* on ferns can stop plant growth and cause the plant to die (Cameron, 1925; Pritchard, 1951a).

Other Pest Mites

In addition to the mites discussed above that are equipped with typical mouthparts which relate them closely to phytophagy, other mites in different families (Acaridae, Erythraeidae, Histiostomatidae, Penthaleidae and others), although characterized by different mouth structures, may also severely damage economic plants.

Feeding mechanism

The mouthparts of mites lacking stylet-like chelicerae (present in some Penthaleidae) can sometimes lacerate the tender tissues of young leaves, bulbs, etc. and suck up the internal contents. Various morphological structures have been reported that enable this to occur. The Acaridae have the dorsal surface of the gnathosoma not extended and forming a small lobe between the cheliceral bases. The chelicerae are chelate, or pincer like, dorsally free and laterally compressed and with a large basal region stretching forward and forming the digitus fixus articulated with the digitus mobilis. Both chelicerae move in a vertical plane and are often toothed distally. The chelicerae are located under the epistome and over the labrum, and are partially involved in the mouth structure (Griffiths, 1970; Hughes, 1976) (Figs 2.4, 2.5A and B, 2.6A). The chelicerae of the Erythraeidae are retractable into the idiosoma, and the palp is equipped with a thumb-claw process bearing a long straight chela (pincer) (Walter *et al*., 2009); *Balaustium medicagoense* Meyer *et* Ryke feeds on plants using its adapted mouthparts to probe the leaf tissue and in this way obtain food (Arthur and Umina, 2010). The chelicerae of the Histiostomatidae are laterally compressed, not chelate, but with fixed comb-like digits and bearing many fine teeth. The movable digit is short, fused to the base of the fixed digit, and with few short distal teeth (Hughes, 1976; O'Connor, 2009) (Fig. 12.1C). The Penthaleidae have chelate chelicerae, separate at the base and each bearing a seta; the fixed digit is regressed, commonly slender and sometimes finger like at the tip, and the movable digit is sickle like to prong like, and smooth and sometimes strongly stylet like (Baker, 1990, 1995) (Fig. 15.2A). The penthaleid *Penthaleus major* (Dugès) penetrates the epidermal cells of the host plant with chelicerae and removes the cellular contents, making a hole larger than 3 μm (Qin and Halliday 1996a,b). The movable digits of *Penthaleus* spp. can be moved separately or together, but do not form a channel for transporting fluid. The subcapitulum is applied to the plant surface and the cell contents are sucked out using a pharyngeal pump (Nuzzaci and de Lillo, 1991a).

Symptoms of feeding

The feeding symptoms of the erythraeid *Balaustium medicagoense* on canola are distorted and cupped cotyledons, which may have a leathery appearance. Common damage on cereals, grasses and pulses is 'silvering' or 'whitening' of the infested leaves, similar to that caused by red-legged earth mites or blue oat mites (Arthur and Umina, 2010).

The feeding symptomatology of the blue oat mite, *Penthaleus major*, is similar to that of tetranychid mites. The removal of the plant cell contents typically results in silvery to grey patches on the leaf surface. In the paddock, this is often mistaken for frost damage. The leaves appear greyish or silvery and at high levels of attack for several days the tips of the leaves show a scorched aspect, turn brown and the plant may die. Many of the infested plants do not die, but become stunted and produce little forage or grain (Jeppson *et al*., 1975).

On *Gerbera*, the symptoms of the feeding activity of the acarid *Tyrophagus neiswanderi* Johnston *et* Bruce involve the young leaves and consist of more or less extensive curling of the internal parts of the leaf surface, especially in the vicinity of the central veins, accompanied by distortion of the margins of the leaf, and morphological alterations of the flowers. On expanded leaves, the attack can also involve irregular and jagged tears of the surfaces, with the leaf margins more or less curved and regular. On cucumber, melon and pumpkin, the young leaves show similar alterations, while on expanded leaves alterations of the tissues are more frequent in the areas adjacent to the peduncle (Vacante, 1988, 1997b; Vacante and Benuzzi, 2007). Other examples of symptom occur in other families.

Damage

A few examples of the damage that may be caused by miscellaneous groups of pest mites are given here to illustrate the diversity of the topic, which will be extensively treated in the chapters on each single family. The damage caused by *Penthaleus major* on young plants is more severe than that on large, healthy ones. Small grains suffer two types of damage, which give either a reduced amount of forage throughout the winter or reduced yields of grain in the spring and summer. The reduction in forage probably has a greater importance in those countries where winter grazing is used by farmers who rely on the small grains for fall and winter pasturing of livestock (Jeppson *et al.*, 1975). Mite damage reduces the available feed for livestock and severely damages young seedlings; most damage occurs at the establishment phase and this may lead to entire crops needing resowing (Ridsdill-Smith and Pavri, 1998).

Infestations of *T. neiswanderi* on young plants in nurseries and/or post transplanting can cause serious economic damage. The economic impacts of mite infestation of ornamental plants may be similarly severe. For example, infested *Gerbera* flowers are not marketable (Vacante, 1988, 1997b; Vacante and Benuzzi, 2007).

The histiostomatid *Histiostoma feroniarum* (Dufour) has been collected on decaying food material such as wet grain or flour (Hughes, 1976) and on edible fungi (Hussey *et al.*, 1969), and is responsible for serious crop losses to *Agaricus bisporus* (Lange) Pilát, *A. bitorquis* (Quél.) Sacc. and *Lentinula edodes* (Greenslade and Clift, 2004).

Transmission of Plant Diseases

According to Jeppson *et al.* (1975), 'The term plant disease in its broadest meaning includes all injuries or abnormalities generated from sources outside the plant regardless of the cause'. This definition of plant diseases therefore includes mite species that inject toxins or growth regulators into the host plant and also species that transmit virus diseases or spread fungal diseases to the host plant. The relationship between mites and plant disease can be divided into four distinct mechanisms: the causation of local injuries, the injection of systemic or persistent toxins, virus transmission and the transmission of other diseases. The first two of these have already been covered in this chapter. This section examines the other two: virus diseases and diseases caused by fungi or other organisms that are carried by mites or facilitated by their feeding activities.

Species belonging to the Eriophyoidea, Tetranychidae and Tenuipalpidae are known to vector one or more plant viruses (Robertson and Carroll, 1988; Skaf and Carroll, 1995; Oldfield and Proeseler, 1996; Smidansky, 1996; Rodrigues *et al.*, 2000, 2003; Kitajima *et al.*, 2010; Childers and Rodrigues, 2011). However, only the Tenuipalpidae and the Eriophyoidea include important vectors of plant pathogens. There is a high degree of host specificity between these mites and the viruses that they transmit (Oldfield and Proeseler, 1996). No virus is transmitted by more than one eriophyoid or occurs in more than one host plant, and eriophyoid-borne viruses are not transmitted by any other group of mites or insects. This suggests that both mite and virus find a mutual benefit in the transmission and that their association derives from a process of selection, which through a mutualistic virus–mite association has led to a form of co-evolution (Sabelis and Bruin, 1996). Here, a brief treatment is given of the general features of the common diseases that are transmitted. The mite vectors themselves are discussed in the later chapters on separate mite families.

Viruses and virus diseases transmitted by Tenuipalpidae

Brevipalpus spp. transmit the disease of leprosis, which is also known as lepra explosiva, and also passion fruit green spot virus (PFGSV), coffee ringspot virus (CoRSV), and orchid fleck virus (OFV), all of which belong to the Rhabdoviridae family (Childers and Rodrigues, 2011). In addition, tenuipalpids may transmit diseases of ornamental plants (*Annona*, *Brunfelsia*, *Clerodendron*, *Hedera*, *Hibiscus*, *Ligustrum*, *Malvaviscus*, *Pelargonium*, *Pittosporum*, *Salvia*, *Schefflera* and *Thunbergia*) (Kitajima *et al.*, 2003b).

Leprosis/lepra explosiva

Leprosis, or lepra explosiva, is a severe virus disease of citrus reported from the American Continent (Argentina, Bolivia, Brazil, Central America, Colombia, Costa Rica, Honduras, Mexico, Panama, Paraguay, Venezuela) (Kitajima *et al.*, 1972; Rodrigues *et al.*, 1997; Childers *et al.*, 2003a; Bastianel *et al.*, 2010; Childers and Rodrigues, 2011). Currently, the known vector of citrus leprosis in Brazil is the red and black flat mite, *Brevipalpus phoenicis* (Rodrigues *et al.*, 2003). However, in the past, both *B. californicus* in Florida and *B. obovatus* Donnadieu in Argentina have been reported as vectors of citrus leprosis (Frezzi, 1940; Vergani, 1945; Knorr, 1968), but morphological studies of the specimens collected from these earlier reports highlighted the presence of both *B. californicus* and *B. phoenicis* spp. in the Florida samples and of *B. obovatus* and *B. phoenicis* in the Argentinian samples (report from Ochoa, R., US Department of Agriculture, Agricultural Research Service, Systematic Entomology Laboratory, Baltimore, Maryland, 2002, in Childers and Rodrigues, 2011). These earlier reports did not define the vector status of the tenuipalpids involved either. Recently, *B. californicus* and *B. phoenicis* were reported as vectors of citrus leprosis in Guatemala (Palmieri *et al.*, 2007), but no direct transmission tests have been carried out to confirm that *B. californicus* is a vector, and neither are there any available specimens for either *B. phoenicis* or *B. californicus* from citrus samples collected in that country. At present, the only confirmed vector of citrus leprosis in the western hemisphere is *B. phoenicis* (Childers and Rodrigues, 2011).

In Florida, citrus leprosis has been known since the late 1800s, but there have been no reports of it since 1960 (Morishita, 1954; Childers *et al.*, 2001), and later research has not found the virus to be present in Florida and Texas (Childers *et al.*, 2003c). There is then some confusion on the presence and distribution of the virus, and there are few clear differences between damage resulting from feeding and infection with the leprosis virus (Childers *et al.*, 2003a). Until a few years ago, the agent responsible for the disease was identified as citrus leprosis rhabdovirus (CiLV), which occurred in two forms, the more common CiLV-C, which infects the cytoplasm of infected plant cells, and CiLV-N, which occurs in the cell nucleus; the two forms produce the same symptoms (Rodrigues *et al.*, 2003). Recently, the virus associated with the cytoplasm was identified as the type member of the new virus genus, *Cilevirus*, and the virus associated with the nucleus was included in the new genus '*Dichorhabdovirus*', both belonging to the family Rhabdoviridae

(Bastianel *et al.*, 2010). The cytoplasmic type is referred to as *Citrus leprosis virus C* (CiLV-C) and is vectored by *B. phoenicis* (Rodrigues *et al.*, 2003). If the mite vector is not controlled, CiLV-C can kill a tree within 3 years. This *Brevipalpus*-borne virus is one of the most serious emerging exotic diseases threatening sweet orange production within the USA, the Caribbean and potentially other citrus-producing countries in Africa, Asia, Australasia and Europe. Citrus species, especially oranges (*Citrus sinensis* (L.) Osbeck), can be infected by citrus leprosis viruses. Mandarins and hybrids such as 'Murcott' are considerably less susceptible. Annual costs of prevention of the disease in Brazil alone are about US$100 million (Rodrigues *et al.*, 2003). The damage from the disease negatively affects yield and more than US$60 million per season are spent on chemical sprays to control the mite vector (Rodrigues, 2006). Bastianel *et al.* (2010) report that in Brazil the annual costs of the disease to growers are around US$80 million dollars. The virus mainly attacks sweet orange, but also citrange, citron, 'Cleopatra' mandarin, grapefruit, lemon, mandarin, sour orange and tangor (Lovisolo, 2001). The main symptoms are lesions to the fruits, leaves, twigs and small branches, with early fruit drop, leaf drop and death of the twigs and branches until the vitality of the trees declines (Rodrigues *et al.*, 2003).

Passion fruit green spot virus

The passion fruit green spot virus causes a cytoplasmic viral disease vectored by *Brevipalpus phoenicis* that is reported only from Brazil. The symptoms include green spots and patches of green tissue on mature leaves, and the flowers show necrotic lesions that encircle the stems. High population densities of *B. phoenicis* cause leaf and fruit drop. Mature yellow fruits show green spotting along with patches of green spotting on the leaves. The most serious damage results from the necrotic lesions that girdle the stems and kill the plants (Kitajima *et al.*, 2003a,b; Moraes *et al.*, 2006; Childers and Rodrigues, 2011).

Coffee ringspot virus

The coffee ringspot virus causes a nuclear type of viral disease of coffee in Brazil and Costa Rica, and is vectored by *Brevipalpus phoenicis* (Chagas *et al.*, 2003). Symptoms include localized ring spot lesions on both leaves and berries. The disease may cause severe leaf and fruit drop with accompanying reduced coffee berry yields. According to Chagas *et al.* (2003), a similar disease occurs in the Philippines.

Orchid fleck virus

The orchid fleck virus is a nuclear type of virus reported from Australia, Brazil, Denmark, Germany, Japan, Korea and the USA (Kondo *et al.*, 2006), which is transmitted by the false spider mite, *Brevipalpus californicus*, to several orchid genera (Kondo *et al.*, 2003). The virus has been classified in the new genus '*Dichorhabdovirus*' in the family Rhabdoviridae. The virus particles accumulate in the nucleus of infected orchid plants (Kondo *et al.*, 2006; Bastianel *et al.*, 2010), and give rise to the symptoms of chlorotic or necrotic spots and rings on the leaf fronds of several orchid genera (Kondo *et al.*, 2006). The vector is infective for a long time, and the actual distribution of the virus is likely to be much greater than indicated above (Childers and Rodrigues, 2011).

Virus diseases transmitted by Tetranychidae

Few tetranychids are vectors of diseases, and among the viruses that they transmit only the transmission of *Potato virus Y* (PVY) is well known (see below) – that of other viruses is either uncommon or has not been sufficiently investigated. These latter include the mosaic symptoms associated with the feeding of *Tetranychus sinhai* Baker on wheat, maize and rye, which consist of darkening, followed by yellowing and withering in patches along the midrib. However, no data have confirmed the role of a virus, and the symptoms could be due to the injection of toxin by the mites (Slykhuis, 1963, 1965). The brown wheat mite, *Petrobia latens* (Müller), has been reported to transmit a virus-like particle on barley in Montana (Robertson and Carroll, 1988).

Potato virus Y

This widespread virus is transmitted by *Tetranychus* sp. to different Solanaceae (potato, tomato, tobacco and other plants) and displays different severity and symptoms in the various growing areas in which it is found. The first symptoms are observed 19 days after infection as a blotchy mottling on the top leaves, which spreads outward from the veins. On the lower leaf surface, a fine necrosis appears along the veins, followed by necrosis of the upper leaf surface. The necrosis extends from the petioles to the stems, which show brown lesions. The leaves may become necrotic and withered. In the years that follow, the plants show little necrosis, but exhibit leaf drop, have brittle leaves and stems, short internodes and mottled, twisted and bunched leaves. However, despite the plant appearing dwarfed and rosetted, it produces normal tubers (Thomas, 1969; Oldfield, 1970).

Virus diseases transmitted by Eriophyoidea

Virus transmission by the Eriophyoidea has been known since the 1930s (Amos *et al.*, 1927), but has been difficult to investigate because of confusion in several cases between the effects of mite feeding and the symptomatology of virus infection. The situation is further complicated by the small size of these mites and because it is not possible to verify whether the symptoms that develop depend on the injection of mite toxins or a virus (Jeppson *et al.*, 1975). The assumption that an eriophyoid mite is a vector of plant viruses must be completed by verifying the following: that there is a correlation between the presence of the mites and the disease in nature; that the disease symptoms do not depend on the presence of the mites; and that the transmission of the disease symptoms to healthy plants requires that the mites have fed on diseased plants (Jeppson *et al.*, 1975). About 20 years later, Oldfield and Proeseler (1996) reported that about a dozen plant diseases were transmitted by eriophyoid mites, but that the nature of the pathogens transmitted was largely unknown. Further studies showed that the pathogens were viruses in the genera *Rymovirus*, *Tritimovirus* (Potyviridae) or *Allexivirus* (Comoviridae) (Jones, 2000; Kumar *et al*., 2003a, 2005; Kang *et al*., 2007). It is now known that 12 pathogens are transmitted by nine eriophyoid vectors, but research on these has only just begun and many aspects await elucidation, such as an understanding of the mechanisms of virus transmission (Young *et al*., 2007) and virus detection within the mite body (Latha and Doraiswamy, 2008). Among the disease agents transmitted by eriophyoids, those infecting dicotyledonous plants are less well known, while those that usually develop on monocotyledons are better known as viruses. The relationship between eriophyoid vectors and disease agents is usually highly specific (Oldfield and Proeseler, 1996).

A summary is given below of the main features of the major diseases caused by viruses transmitted by eriophyoids, and following Oldfield and Proeseler (1996), these are categorized as 'cereal pathogens' and 'pathogens of woody dicotyledonous plants'.

Cereal pathogens

The most important viruses transmitted by eriophyoids on cereals are *Wheat streak mosaic virus*, *Wheat spot mosaic virus*, *Ryegrass mosaic virus* and *Agropyron mosaic virus* (Oldfield and Proeseler, 1996).

WHEAT STREAK MOSAIC VIRUS. The wheat curl mite, *Aceria tosichella* Keifer, is the only known vector of the *Wheat streak mosaic virus* (WSMV) (Slykhuis, 1955). Immature and adult instars transmit the virus to wheat and other wild and cultivated graminaceous (poaceous) species, and the adults can acquire the pathogen as immatures or adults. The virus persists in the wheat curl mite for several days (Slykhuis, 1955; Orlob, 1966). The disease caused is widespread and probably occurs in all areas of wheat cultivation in the Palaearctic and Nearctic regions. The symptoms are light green to yellow streaks and dashes, followed by general chlorosis, stunting and, depending upon the degree of severity, poorly filled seed heads and shrivelled kernels. At temperatures ranging from 20 to 25°C, the symptoms on wheat appear 6–8 days after inoculation (Styer and Nault, 1996).

WHEAT SPOT MOSAIC VIRUS. The *Wheat spot mosaic virus* (WSpMV) is transmitted by *Aceria tosichella*. Symptoms consist of an initial chlorotic spotting or ring spot, followed by general chlorosis, stunting and, sometimes, plant death. This symptomatology has been observed in several Poaceae, including maize, barley and wheat (Slykhuis, 1956; Nault *at al*., 1970; Styer and Nault, 1996). Studies carried out on the persistence of the virus in the vector showed a lack of transovarial passage and retention after moulting of both WSpMV and WSMV (Nault and Styer, 1970). WSpMV is not sap transmissible (Styer and Nault, 1996).

RYEGRASS MOSAIC VIRUS. *Ryegrass mosaic virus* (RgMV) is transmitted by the cereal rust mite, *Abacarus hystrix*. It is a rod-shaped virus that is sap transmissible but not seed borne and causes mild chlorosis, chlorotic mottle, chlorotic streaks or leaf necrosis (Oldfield and Proeseler, 1996). Elevated amounts of feeding are necessary to cause damage on Italian ryegrass (Gibson, 1974) as a result of the probable absence of phytotoxins from the mite saliva. High densities of attack cause growth retardation and cuticular damage produces wilting (Frost and Ridland, 1996).

AGROPYRON MOSAIC VIRUS. *Abacarus hystrix* is an inefficient vector of *Agropyron mosaic virus* (AgMV) to *Agropyron repens* L. (= *Elymus repens* L. (Gould)), or couchgrass, a weed or forage grass (Slykhuis, 1969), but it causes a secondary disease of wheat and *A. repens* in the USA, Canada, the UK, Finland and Germany (Slykhuis, 1980).

OTHER VIRUSES. *Aceria tosichella* is a vector of three other plant disease viruses apart from WSMV and WSpMV: *Brome streak mosaic virus* (BrSMV) (Stephan *et al*., 2008), *Triticum mosaic virus* (TriMV) (Seifers *et al*., 2009), and High Plains disease (HPD), which affects wheat and maize (Mahmood *et al*., 1998; Seifers *et al*., 2002; Skare *et al*., 2003, 2006). It also transmits kernel red streak of maize (Nault *et al*., 1967; Styer and Nault, 1996; CABI, 2002). The dry bulb mite, *Aceria tulipae*, transmits the important onion mite-borne latent virus (OMbLV) and the shallot mite-borne latent virus (ShMbLV) (van Dijk *et al*., 1991; Perring, 1996; Oldfield and Proeseler, 1996). Infection by both of these viruses can be asymptomatic (Ostojá-Starzewski and Matthews, 2009). In addition, it has recently been found that *A. tulipae* transmits an *Allexivirus* (GarV-B1) in garlic plants (Kang *et al*., 2007).

Pathogens and diseases of woody dicotyledonous plants

The most important viruses transmitted by eriophyoids on woody dicotyledonous plants include *Blackcurrant reversion virus*, *Fig mosaic virus*, *Peach mosaic virus* (PMV), *Cherry mottle leaf virus*, *Rose virus 1* and *Pigeon pea sterility mosaic virus* (PPSMV).

BLACKCURRANT REVERSION VIRUS. The *Blackcurrant reversion virus* (BRV) is transmitted by the blackcurrant big bud mite, *Cecidophyopsis ribis* (Jones, 2000; Susi, 2004). Not much was known about the disease up to 1980 (Slykhuis, 1980), although the evidence for its transmission by the mite was clear (Thresh, 1963). Different *Cecidophyopsis* spp. are probably involved in transmission of the disease (Lemmetty *et al*., 2004). All active instars of *C. ribis* transmit the virus after 3 h of feeding on infected bushes, but the optimum acquisition needs about 50 h. The virus is transmitted after 48 h feeding on healthy blackcurrant bushes (Jacob, 1976). Reversion has been reported for different host *Ribes* species, including *R. nigrum* L., *R. alpinum* L. and *R. spicatum* Robson (Bremer and Heikinheimo, 1979). Medium-to-high levels of infestation cause young buds to become galled, fail to flower and frequently to turn into 'big buds' that fail to differentiate into flowers or true leaves. Buds that are less attacked may develop secondary buds that give rise to grossly deformed or asymmetrical foliage, abnormal flowers and fruits. Higher levels of attack induce reduction of plant vigour and the leader growth is replaced by many short twiggy side shoots (Thresh, 1964a).

FIG MOSAIC VIRUS. *Fig mosaic virus* (FMV) is transmitted by the fig bud mite, *Aceria ficus* (Cotte), only to *Ficus carica* L. (Oldfield and Proeseler, 1996). One single immature instar or adult could acquire the virus after as little as 5 min of feeding activity on infected plants, and transmit it within 5 min of feeding activity on healthy plants. At 20–30°C, virus acquisition was almost twice as great as at 5–10°C. Acquisition was best from the terminal buds, followed by the lower surface of leaves showing symptoms. Moulting did not impede the ability of the mite to transmit the virus and the adult could inoculate the virus for 6–10 days. Virus transmission does not occur transovarially (Proeseler, 1969, 1972a). The first symptoms of infection on fig seedlings are observed 5–7 days after feeding by inoculated mites and chlorotic spots develop first on the leaves and show cleared veins, chlorotic and mosaic areas. The chlorotic spots are often bordered by a rust band. The fruits bear mosaic symptoms and the trees become stunted and with leaves of reduced size. The virus is graft transmissible but not sap transmissible. The disease is widespread in commercial fig orchards, because of the horticultural practice of propagating from rooted cuttings (Bradfute *et al.*, 1970; Plavsic and Milic, 1980; Appiano, 1982).

PEACH MOSAIC VIRUS. The peach mosaic vector mite, *Eriophyes insidiosus* (Keifer *et* Wilson), is the vector of the *Peach mosaic virus* (PMV) (Gispert *et al.*, 1998), the agent of peach mosaic disease (Wilson *et al.*, 1955). On peach, the symptoms of this disease consist of vein clearing and irregular chlorosis, stunted growth of the leaves, colour breaking on the blossoms and rosetting of branches. In south-western USA and Mexico, these symptoms also occur on certain other *Prunus* fruit trees (Oldfield and Proeseler, 1996). The pathogen is not transmitted transovarially (Wilson *et al.*, 1955). The adults can inoculate the virus for at least 2 days after removal from infected plants, and transmit the virus when they feed for 0.5–1 h on peach seedlings, but not when they feed for only 15 min (Oldfield and Proeseler, 1996). In southern California, the disease spreads during the growing season (Jones and Wilson, 1952) as a result of the dispersal of some of the vector mites during those months. In the USA, peach mosaic disease is also known on plum, apricot and almond, but the vector mite has not been collected on these plants (Oldfield and Proeseler, 1996).

CHERRY MOTTLE LEAF VIRUS. *Eriophyes inaequalis* (Wilson *et* Oldfield) transmits a flexuous virus of the Closterovirus group, the *Cherry mottle leaf virus* (CMLV), which causes cherry mottle leaf (CML) disease (James and Mukerji, 1993), a graft-transmissible disease occurring in sweet cherry-growing districts of western North America from northern California to south-western Canada. The symptoms of the disease are irregular chlorotic mottling, edge tattering and small leaves. The fruits seem to be normal but lack flavour and often ripen late (Oldfield and Proeseler, 1996). The disease is commonly found in orchards with natural stands of *Prunus emarginata* (Douglas) (McLarty *et al.*, 1951), but can sometimes spread through sweet cherry orchards in countries where *P. emarginata* is absent. *E. inaequalis* collected on infected *P. emarginata* can transmit the disease to peach (a symptomless host) or to sweet cherry (Oldfield, 1970). Mites collected on *P. emarginata* in California transmitted the disease to sweet cherry in the laboratory. In British Columbia (Canada), the disease occurs in apricots (Hansen, 1978), but the mite does not reproduce on either sweet cherry or apricot (Oldfield and Proeseler, 1996). This suggests the existence of other mite vectors of the disease.

ROSE ROSETTE VIRUS. The wild rose bud and fruit mite, *Phyllocoptes fructiphilus* Keifer, is vector of a virus that was formerly designated *Rose virus 1* (RSV-1), an *Ilarvirus* (Jesse *et al.*, 2006; Tzanetakis *et al.*, 2006), which causes rose rosette disease (RRD) on the wild multiflora rose, *Rosa multiflora* Thunb. ex J. Murray, a weedy scrambling shrub, and on ornamental roses (see also Chapter 8). Recently, however, the virus has been formally identified as *Rose rosette virus* (RRV), an *Emaravirus* (Laney *et al.*, 2011; Hong and Hansen, 2012). The disease occurs mainly in the western and middle states of the USA and in some Canadian provinces, where many *Rosa* varieties are resistant (Amrine, 1996). The symptoms are a red or purplish vein mosaic on the underside of leaflets, reduction in shoot growth, early breaking and stunting of the auxiliary buds, shortened internodes and the development of bright red lateral shoots and foliage, characterized by small, wrinkled and deformed leaflets (Doudrick, 1983; Amrine and Hindal, 1988). The symptoms commonly occur first on auxiliary buds of new shoots, and gradually move towards the shoot apex. Young plants become dwarfed. Symptoms on ornamental roses consist of yellow mosaic on the leaves, thorniness of the stems, the development of lateral shoots larger than the parent stem, misshapen leaves and the early development of lateral buds, with witches' brooms (Amrine and Hindal, 1988). The disease can be transmitted both by grafts and by the feeding activity of *P. fructiphilus* to *R. eglanteris* L., *R. suffulta* Greene, *R. woodsii* Lindley, *R. multiflora* Thunb. and *R. rubrifolia* Villars (Allington *et al.*, 1968). Single mites can transmit the rosette pathogen, which can be transferred to healthy roses from symptomatic roses. The symptoms persist after mite control (Amrine *et al.*, 1988).

PIGEON PEA STERILITY MOSAIC VIRUS. In several countries of the Indian subcontinent, *Aceria cajani* ChannaBasavanna transmits *pigeon pea sterility mosaic virus* (PPSMV), the agent of sterility mosaic disease (SMD) to pigeon peas (*Cajanus cajan* (L.) Huth); the viral nature of SMD has only recently has been documented (Kumar *et al.*, 2001, 2003a; Latha *et al.*, 2007). The disease exhibits three types of symptoms: complete sterility, partial sterility and ring spot. In complete sterility, there is severe mosaic on the leaflets and the plants lack flowers and pods; this manifestation of the disease occurs if the infection begins early (usually before 45 days old). In partial sterility, there is mild mosaic on the leaflets of a few branches and only these branches do not produce flowers and pods; this occurs if the infection takes place at the later stages of plant development (usually beyond 45 days). Ring spot is characterized by green spots surrounded by a chlorotic halo, which appear on leaves, and occurs only in certain genotypes and disappear with plant maturity. Some SMD-tolerant cultivars show this symptomatology without any effect on flowering (Reddy and Nene, 1979; Ghanekar *et al.*, 1992; Reddy *et al.*, 1990a, 1998).

OTHER (NON-VIRUS) PATHOGENS. As well as spreading viruses, mites can spread fungal spores and other non-viral organisms causing plant diseases. Usually, mite behaviour limits the possibility of disease spread, but herbivory does assist in fungal infection by carrying pathogen spores or by creating wound sites for fungal penetration (Agrios, 1980; Hatcher and Paul, 2001), and mite species from different families (Siteroptidae, Acaridae, Tenuipalpidae, Tarsonemidae and Eriophyidae) can increase the rate of some diseases or be closely associated with some pathogens. Some examples are reported below.

Stewart's bud rot – or central bud rot of carnations – is caused by the fungus *Fusarium poae* (Peck) Wollenweber, which is carried as spores attached externally to the body surface of the siteroptid mite *Siteroptes cerealium* Kirchner (Cooper, 1940). *S. cerealium* may also be involved in 'silver top' disease of grasses in North America, Europe and Asia (Hardison, 1959; Suski, 1973, 1984). The symptoms of central bud rot of carnations are a moist, brownish, decayed mass of the inner organs, with rotted stamens, stylets and petals. Externally, the fungus appears as a heavy or sparse white cottony growth (Cooper, 1940). In South Africa, *F. poae* has been found in association with the siteroptid mite *Siteroptes avenae* (Muller). The presence of sporothecae containing microsporidia of the fungus suggests that the mite is involved in *Fusarium* glume spot on wheat (Kemp *et al.*, 1996).

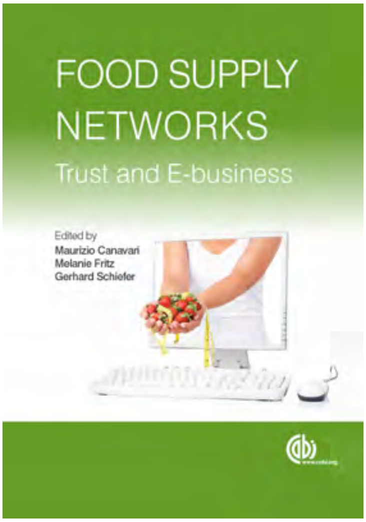
The robine bulb mite, *Rhizoglyphus robini* (Claparède), is closely associated with the spread of fungal diseases caused by *Fusarium*, *Stromatinia* and *Pseudomonas*. The mite feeds on the fungus responsible for *Stromatinia* rot of gladioli and can also be a vector of *Pseudomonas* (Forsberg, 1965; Meyer Smith, 1981a). *R. robini*, together with the mould mite *Tyrophagus putrescentiae* (Schrank), can transfer fungal pathogens that have become attached to the outsides of their bodies to bulbs; the pathogens include *Aspergillus niger* van Tieghem, *Haematonectria haematococca* (Berk. *et* Broome) Samuels *et* Rossman, *Rhyzopus stolonifer* (Ehrenb.) Vuill. and *Penicillium chrysogenum* Thom. In contrast, the pathogens *Aspergillus flavus* J.H. Friedrich Link and *Aspergillus ochraceus* Wilh. are transferred from the mites via their digestive tracts along with their food (Abdel-Sater and Eraky, 2001). The bulb mite, *Rhizoglyphus echinopus* (Fumoze *et* Robin), is often associated with *Fusarium* spp. in gladioli corms and *Freesia*, and with bacterial or fungal rots of dahlia tubers. Attacked freesia and gladiolus corms are usually soft and mushy and may be unsuitable for planting. If only a few bulbs are attacked, any that are soft should be rejected (Hussey *et al.*, 1969).

In Venezuela, *Brevipalpus phoenicis* moves to the scabs caused by the fungus *Elsinoë fawcettii* Bitanic *et* Jenkins (Elsinoaceae) on fruit of sour orange. This pathogen produces a disorder known as 'halo scab', with symptoms ranging from spotting of the leaves to death of the plants; the leaves attacked by the scab fungus alone do not drop, but leaves attacked by both the fungus and the mite drop, resulting in defoliation and death of the plant (Knorr and Malaguti, 1960; Chiavegato and Kharfan, 1993). In Honduras, *B. phoenicis* is associated with *E. fawcettii* on citrus (Evans *et al.*, 1993). A similar interaction between two mite species and the fungus *Sphaceloma fawcetti* Jenkins (= *Elsinoë fawcettii* Bitanic *et* Jenkins) has been reported in Costa Rica (Ochoa *et al.*, 1994). In Brazil, the mite prefers citrus fruits already infected by sweet orange scab, a fungal disease caused by the fungus *Elsinoë australis* Bitancourt *et* Jenkins (Chiavegato and Kharfan, 1993).

The tarsonemid *Steneotarsonemus spinki* causes grain discoloration of rice and facilitates the entry of the fungi *Helminthosporium* and *Sarocladium oryzae* (Sawada) (= *Acrocylindrium oryzae* Sawada), and has also been found to carry the mycoplasma-like organism (MLO), *Spiroplasma citri* Saglio *et al.* It seems likely that the mite, *A. oryzae* and the MLO are all involved in rice sterility (Chow *et al.*, 1980; Cardenas *et al.*, 2003). Ramos and Rodríguez (2001) reported that in Cuba the combined activities of mite feeding and disease transmission lowered rice yield by 30–60%.

The feeding of the pineapple leathery pocket mite, *Steneotarsonemus ananas*, on trichome cells of the pineapple epidermis helps the development of the fungus *Penicillium funiculosum* Thom, the causal agent of inter-fruitlet corking, leathery pocket, and fruitlet core rot/black spot (Petty *et al.*, 2002). The dry bulb mite, *Aceria tulipae*, is implicated in the spread of fungus-causing rot of garlic bulbs in the field (Jeppson *et al.*, 1975).

Research carried out on the association between *Aceria mangiferae* and *Fusarium mangiferae* Britz, Wingfield *et* Marasas in mango, and the cereal rust mite, *Abacarus hystrix*, and rusts of *Puccinia* spp., shows that both mites bear the spores of the two pathogens on their body integument. *A. mangiferae* carries the pathogen's spores into the mango bud (the sole port of entry for the fungus) and the frequency and severity of fungal infection increase in the presence of the mite. However, further research is needed to enhance our understanding of the direct and indirect (plant-mediated) interactions between plant pathogens and eriophyoid mites in different plant–pathogen systems (Gamliel-Atinsky *et al.*, 2010).



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The crucial barrier to adoption is that trust between companies is not mediated appropriately by existing e-commerce technology. Consumers demand trustworthy high-quality food that is safe to eat. Consumers' trust in food demands trust between companies along the food chain because it is not possible to check and control all food quality characteristics. Currently, the barriers to B2B e-commerce for food sector SMEs come from:

- The difficulty of examining the quality and safety of food products. This refers to all kinds of transactions in the food sector, whether supported by e-commerce or not. However, when it comes to e-commerce, the difficulty of physical product examination plays a much larger role because physical product inspection is not possible.
- The (perceived) risk of performing a transaction via e-commerce. This includes concerns regarding secure transfer of data, or the possibly unknown transaction partner.

Existing e-commerce offers apparently do not generate sufficient trust between food companies. The fundamental core challenge for European food chains to competitively deliver affordable high-quality food to European consumers is how to develop trust for e-commerce between companies in the food chain. In order to prevent a growing gap in competitiveness between SMEs in the European food sector and large companies, SMEs urgently need to take up and integrate B2B e-commerce.

Elements for generating trust between companies in the food chain and so trustworthy B2B e-commerce environments for the food sector include: guarantees regarding food quality, multimedia food product presentations to signal their quality, secure e-commerce technology infrastructures and third-party quality signs. Because trust is highly subjective and depends on culture, food chains in different European countries with different cultural backgrounds require different combinations of trust-generating elements regarding the quality and safety of food.

If trustworthy B2B e-commerce environments for food sector SMEs are not included in the food sector, SMEs will not be able to exploit the opportunities and potentials, including cost reductions, created by B2B e-commerce (see above). This would have substantial negative consequences for the provision of affordable, safe, high-quality food to European consumers and the competitiveness of European food sector SMEs, in particular.

Lost competitiveness of SMEs in the food sector would force them to leave the sector, which would result in fewer jobs in Europe. Only highly efficient processes for the exchange of food products along the European food chains will support the supply of European consumers with high-quality food products at affordable prices. This is only possible if the efficiency potential of B2B e-commerce is exploited.

Relevance to the Food Quality and Safety Priority

In general, the Food Quality and Safety Priority has the objective of improving the health and well-being of European citizens through higher quality food

2

The Main Cross-border Food Trade Streams within and to Europe

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Executive Summary

By identifying the most relevant agri-food trade streams we show trading volumes in selected countries and establish a foundation for later research in the e-Trust project, with particular consideration of the specific role of trust in these transactions and how it can then be transferred to e-commerce.

For the elaboration of the collected data, mainly the international statistical database of the United Nations Food and Agriculture Organization (FAOSTAT) is used as a common basis for comparison. This procedure is applied to six European traders in agricultural products (Germany, Austria, Italy, Slovenia, Greece and Spain) and three non-European countries (the USA, Brazil and Turkey). In line with the statistical sources mentioned above, primary commodities are grouped into four categories: cereals, meat, fruit and vegetables, and olive oil.

The trade streams will be identified for each of the above-mentioned countries and for the agri-food chains of the four product groups with regard to the following criteria:

- the two most relevant products for export at every level of the agri-food chain with the two most relevant destination countries; and
- the two most relevant products for import at every level of the agri-food chain with the two most relevant countries of origin.

The findings of the trade streams analysis show that the trade structures in the selected countries are diverse, and present a complex picture. Wheat and maize are major primary cereal commodities that are imported as well as exported. Most meat imports and exports are of cattle, pigs or chickens.

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Overlapping trade streams could be identified between some countries, such as Germany, Austria, Italy and Spain.

The outcome of the trade streams analysis provides industry with measures to enhance the sustainable introduction of e-commerce. Using the findings of the statistical databases, enterprises can obtain an assessment of the level of traded volume and products. These give a clear picture of where the various countries stand with regard to most traded agri-food products compared to cross-border exchanges and where potential for the introduction of e-commerce might exist.

2.1 Introduction

By identifying the most relevant agri-food trade streams, we show trading volumes in selected countries and establish a foundation for the later research of the e-Trust project, with particular consideration of the specific role of trust in these transactions and how it can then be transferred to e-commerce. In this chapter, the focus is on the size of trade streams regarding agri-food products in selected countries, on a yearly basis, and shows the potential for the introduction of e-commerce.

The outline of this chapter is as follows. First, a methodological approach to the classification of international trade streams is discussed in Section 2.2. The following section presents the estimated results of the trade streams with particular focus on import and export data in the selected countries. Finally, Section 2.4 proposes future opportunities and suggestions for business.

2.2 Description of Data Collection and Criteria for Trade Stream Analysis

On the one hand, exports are an important source of income for most countries. On the other, imports are necessary to compensate for a lack of national resources, to benefit from other countries' comparative advantages, to satisfy consumer demand for foreign products, and so on. Hence, analysis of international trade streams is necessary in order to show and understand whether a given country is dependent on resource imports from other countries and to what extent domestic consumption depends on resources found domestically or imported from abroad.

The objective of this chapter is to identify food chains with trans-European cross-border exchange of food products (e.g. fresh vegetables, fresh fruit, meat and grain) and international food chains from Brazil and the USA to Europe with the support of a statistical database, and to classify potential opportunities for enhancing market development and the introduction of e-commerce.

For the elaboration of the collected data, mainly the international statistical database of the United Nations Food and Agriculture Organization (FAOSTAT) is used as a common basis for comparison. Trade data from

2005/06, which is the last year for which information is available, is grouped by country as follows:

- within the EU: Germany, Austria, Slovenia, Italy, Greece and Spain; and
- trans-European cross-border: the USA, Brazil and Turkey.

According to the statistical sources mentioned above, primary commodities are grouped into four categories: cereals, meat, fruit and vegetables, and olive oil.

The trade streams will be identified for each of the countries in question, and for the agri-food chains of the four product groups, respecting the following criteria:

- the two most relevant products for export at every level of the agri-food chain with the two most relevant destination countries; and
- the two most relevant products for import at every level of the agri-food chain with the two most relevant countries of origin.

It is important to analyse trading volume with respect to imported or exported agri-food products not just at one but at all chain levels. This enables us to form a complete picture of agri-food supply networks and potential sources for the introduction of e-commerce.

Figure 2.1 presents an example of the international trade stream analysis. This chart shows the procedure that will be followed for each selected

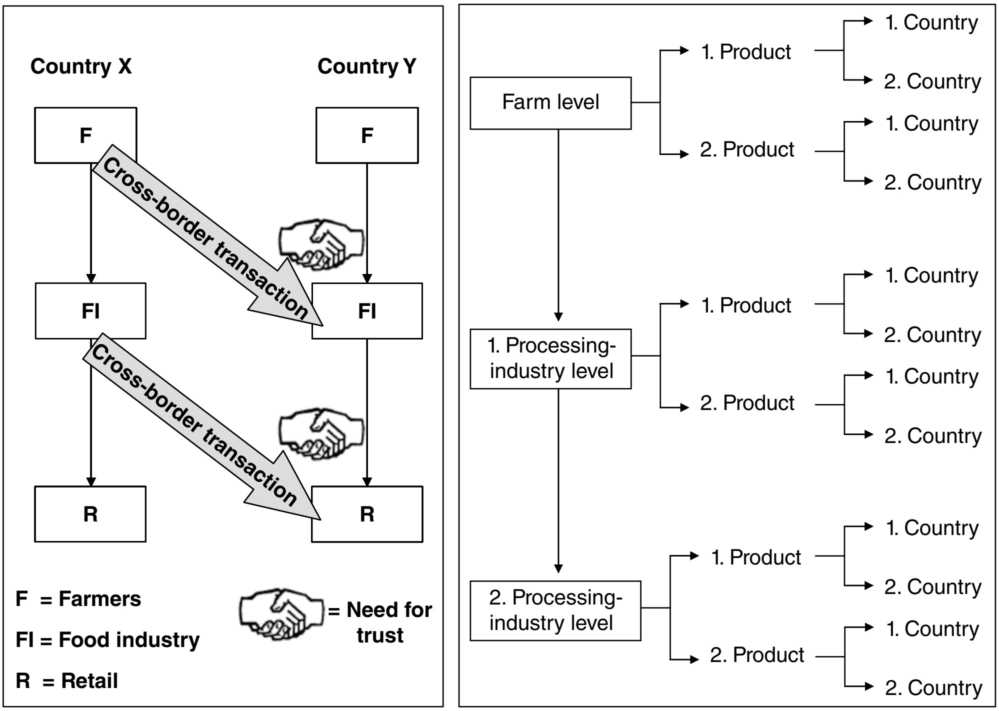

Fig. 2.1. Methodological schema of international trade stream analysis.

country according to the selected agri-food sectors. However, international trade is determined by import and export volume. Thus, the example given shows on the one hand the *import* side and on the other the *export* side of the respective country (the right side of the figure). The left side of Fig. 2.1 shows how information asymmetry and lack of trust can occur between traders, especially on the part of the buyer. Hence, trust in the seller is a crucial element, particularly in international trade where cultural differences dominate.

An in-depth analysis of international trade streams is provided in the following section. In order to go deeper into the food trade stream analysis, the focus is on the selected countries, highlighting the main streams for each level in each chain (cereals, meat, fruit and vegetables, olive oil).

2.3 Identification of the Selected Trade Streams

2.3.1 Trade streams to and from Germany

Trade streams in the cereal sector in Germany

The most relevant commodities in the cereal sector and trading-partner countries for Germany are listed below and shown in Table A2.1.

RAW CEREALS *Imports*: maize and wheat. While maize comes mostly from France and Hungary, wheat is mostly imported from the Czech Republic and France.

*Export*s: wheat and barley. The main destinations for wheat are the Netherlands and Belgium. The Netherlands and Saudi Arabia are the most important trade partners for barley.

PROCESSED CEREALS *Imports/exports at first processing-industry level*: flour and malt. All EU countries are important for imports, except for the Netherlands. The main export trading partners are third countries, e.g. Russia, Japan and Libya.

Imports/exports at the second processing-industry level: beer/pastries. Denmark, Belgium/Luxembourg, the Netherlands and Italy are shown to be essential importing countries for these commodities. France, the UK and Italy can be found on the export site.

Trade streams in the meat sector in Germany

The meat sector is the second largest sector in Germany's agri-food imports and exports. The meat sector analysis consists of three subsectors: beef, pork and poultry. As in the cereal sector, trade relationships within the meat sector are established on a long-term basis. The most important commodities in the meat sector and trading-partner countries for Germany are listed below.

LIVESTOCK *Imports*: cattle, pigs and chickens. Main countries of origin are: the Netherlands, Denmark and Belgium.

Exports: cattle, pigs and chickens. Most exports go to the Netherlands, Italy, Austria and Poland.

PROCESSED MEAT *Imports at the first processing-industry level*: fresh and frozen beef, pork and poultry. The Netherlands, France, Belgium, Denmark and Poland are in this category.

Exports at the first processing-industry level: fresh and frozen beef, pork and poultry. The main destinations for exported processed meat are: Italy, France, the Netherlands and Russia.

Imports at the second processing-industry level: processed beef, pork and poultry. The main countries of origin are: Brazil, the Netherlands, Austria and Italy.

Exports at the second processing-industry level: processed beef, pork and poultry. Exports of processed meat go mainly to France, the Netherlands and Great Britain.

The products with their countries of origin and destination are accompanied by the relevant percentage and shown in Table A2.2.

Trade streams in the fruit sector in Germany

With regard to foreign trade within the fruit sector, Germany is an importing country. The expert interviews with fruit and vegetable enterprises revealed that transactions are carried out mostly with well-known cross-border partners. In addition, they stipulate contracts that vary from short to long term. The most relevant commodities in the fruit/vegetable sectors and trade-partner countries for Germany are listed below (see Table A2.3).

FRESH FRUIT *Imports*: bananas and apples. Bananas come from Ecuador and Colombia and apples from Italy and the Netherlands.

Exports: bananas and apples. Bananas are identified as the most exported fresh fruit and in this case concern primarily re-exports. The exported apples go to the Netherlands and Denmark.

PROCESSED FRUIT/VEGETABLES *Imports*: orange and apple concentrate. Mainly from Brazil, Switzerland, Poland and China.

Exports: orange and apple juice. The Netherlands, France and the UK are the main destinations for these commodities.

Trade streams in the vegetable sector in Germany

In the vegetable sector, Germany is an importing country. The expert interviews with fruit and vegetable enterprises revealed that transactions are mostly with well-known cross-border partners. In addition, they use contracts that vary from short to long term. The principal commodities in the fruit/vegetable sectors and trading-partner countries for Germany are listed below (see Table A2.4).

FRESH VEGETABLES *Imports*: tomatoes and cucumbers. Spain and the Netherlands export tomatoes and cucumbers to Germany.

Exports: onions and white and red cabbage. Sweden and the Czech Republic import white and red cabbage as well as onions from Germany and the Netherlands and Austria.

PROCESSED VEGETABLES *Imports*: tomato purée and tomatoes (not pickled). Italy is the most important trading partner to Germany for processed vegetables, accounting for more than 70%. The second most important country for imported processed vegetables is Spain.

Exports: pasteurized cucumbers and dried peas. Both commodities go to the Netherlands. Denmark is in second place for dried peas and France for pasteurized cucumbers.

2.3.2 Trade streams to and from Austria

Trade streams in the cereal sector in Austria

Cereal production is of great importance in Austria. The export and import trade streams for raw materials are influenced by geographical distances and historical roots. This is why Hungary, Germany and Italy are the most important trading partners in the cereal supply chain. At farm level and in the raw-products trade sector, Austria imports maize and wheat mainly from Hungary. It is noticeable that Austria imports these products more cheaply than it exports them. The main export partner at farm level is Italy. First-level processing of commodity imports and exports is of only marginal importance for the processing industry, with only small quantities being traded. One reason for this may be that the majority of bakeries in Austria are small companies and these bakeries still purchase on a regional basis. Furthermore, products at the first processing level are low-priced. Greater transporting distances are therefore avoided. In addition, purchase decisions are influenced by a trend towards regionalization, a trend primarily initiated by the market-dominating retail chains. Wheat flour and malt flour are mainly imported from Germany; the two most important exported products are malt flour and wheat flour, which are exported to Italy and Bulgaria, and also to Hungary and Germany (see Table A2.5).

Trade streams in the meat sector in Austria

Meat is Austria's most important agricultural product, and cattle meat especially is exported mainly to Germany and Italy. Trade with new EU member states is developing very positively. Because there are still many slaughterhouses in Austria, companies import a considerable quantity of livestock. A large number of pigs are imported and slaughtered in Austria, and then exported again. As for poultry meat, Austria imports these products at the second processing level. Italy and Germany are the main trading partners regarding both import and export. Statistical data details are provided in Table A2.6.

Trade streams in the fruit sector in Austria

Compared to the meat and cereals sectors, fruit and vegetables are of lesser importance in Austria as far as production is concerned. Within the fruit sector, imports from Germany, China, Italy and Belgium are important. The most essential export partner in the fruit sector apart from Germany (for apples and grapes) is Italy (orange juice). Table A2.7 shows the percentage spread of the trade streams and the relevant trading partners.

Trade streams in the vegetable sector in Austria

Table A2.8 highlights the Austrian results regarding the most important imported and exported vegetable products. On the import side, the main countries of origin are Italy, Spain, the Netherlands and Germany. On the export side, Germany, Hungary and the Czech Republic are of great importance.

2.3.3 Trade streams to and from Italy

Trade streams in the cereal sector in Italy

Regarding the cereal supply chain, Italy depends mainly on European countries (France and Hungary) for its supplies of raw materials, but also on partners outside the EU (Canada is Italy's most important source for imports of durum wheat). As for first-level processed products in the cereal supply chain, wheat flour and maize flour are the most imported raw goods from, respectively, Spain and France, and Austria and France. Germany plays an important role for second-level processed products with their imports of pastry and beer to Italy. On the export side, rice, wheat, wheat flour and maize, pasta and pastry are the chief products at all chain levels. Important destinations are France and Germany. More details are provided in Table A2.9.

Trade streams in the meat sector in Italy

Table A2.10 shows that import and export streams in the meat sector in Italy occur between European partners at each link in the chain. If France and Spain are the most important partners at the production level, Germany is the most relevant business partner at the processing level for both import and export.

Trade streams in the fruit sector in Italy

Regarding the Italian fruit supply chain, the analysis shows that exchanges take place with extra-EU partners in the case of fresh produce (e.g. bananas and peaches). Processed-fruit products come mainly from EU countries like Germany, Austria, Spain and Greece. Italy exports mainly apples, grapes and processed fruit to EU countries like Spain, the UK, Germany and France. The relevant percentages are illustrated in Table A2.11.

Trade streams in the vegetable sector in Italy

The Italian vegetable supply chain reveals a similar scenario, with a few EU countries as main trading partners: France, Spain and the Netherlands are the countries of origin of most imported products (potatoes, tomatoes and processed vegetables), and the UK and Germany are the destinations for the most exported products at each level of the supply chain (lettuce, tomatoes and processed vegetables). Further Italian export trading partners are extra-EU countries like China and Australia (see Table A2.12).

Trade streams in the olive oil sector in Italy

The trade streams concerning the olive oil supply chain show that Italy is a net importer of olive oil. Olives and high-quality olive oil are imported mainly from Mediterranean countries (Spain, Greece), while export (both at production and at processing level) involves not only EU countries like Germany and France, but also extra-EU partners (the USA is an important destination for Italian olive oil supply chain products). The percentages and quantities of the Italian exports and imports are shown in Table A2.13.

2.3.4 Trade streams to and from Slovenia

Trade streams in the cereal sector in Slovenia

The main imports to Slovenia are maize from Hungary and Macedonia and wheat from Hungary and Austria. Geographical considerations are of critical importance in the importing of processed products, which is why most are from Italy and Austria. Italy is an important trading partner for Slovenia on the export side as well, and most maize and barley goes there. First and second processing level export products are not quantitatively important; therefore, they are not considered in this analysis. Detailed statistical data are shown in Table A2.14.

Trade streams in the meat sector in Slovenia

Meat production is the most important branch of Slovenian agriculture. Imports are mainly from Austria, Italy and Hungary. Exports are mainly driven by big companies themselves or by agents. These countries are essential as trading partners on the export side as well. In-depth analysis of the statistical data regarding the most important products and their origins and destinations is given in Table A2.15.

Trade streams in the fruit sector in Slovenia

Fruit is imported to Slovenia mainly from Ecuador and Colombia (bananas) and from Italy and Egypt (oranges). Apples are one of the most important fruits in Slovenian production and trade. The most important trading partners are Croatia and Austria. Regarding the exports of bananas, these are mainly re-exported and go to Italy. The quantity of exported processed fruit is not of great consequence and therefore is not considered (see Table A2.16).

Trade streams in the vegetable sector in Slovenia

In the vegetable sector the most important trading partners on the import side are Italy, Turkey, Austria and the Netherlands. Most vegetables exported from Slovenia are to Germany. A detailed analysis of the quantity and the countries is given in Table A2.17.

Trade streams in the olive oil sector in Slovenia

Slovenia is a net importer of olive oil. More than half of all olive oil is imported, mainly from the EU (Italy, Greece and Spain). Slovenia exports mainly to Croatia and Bosnia-Herzegovina (see Table A2.18).

2.3.5 Trade streams to and from Greece

Trade streams in the cereal sector in Greece

Regarding the cereal sector, Greece is import-dependent. Specifically, Greece imports cereal mainly from Russia, France, Hungary, Italy and Germany. On the export side, Italy remains a very important trading partner. For more details see Table A2.19.

Trade streams in the meat sector in Greece

In the meat sector, Greece is import-dependent. Table A2.20 shows that pork and beef and also pigs and cattle are primarily imported from the Netherlands, France, Germany, Hungary and Italy. A significant amount is distributed through a central meat market, while meat-processing companies import directly from suppliers abroad.

Trade streams in the fruit sector in Greece

Greece is export-oriented regarding fruit products. In particular, major Greek exports include grapes and oranges to destinations such as Germany, the UK and Romania. Imports are mainly bananas and lemons from Ecuador, Argentina, Turkey and Italy. The statistical database results are presented in Table A2.21.

Trade streams in the vegetable sector in Greece

Regarding vegetables, Greece, overall, exports more than it imports. In particular, major Greek exports include asparagus and cucumbers to destinations such as Germany, Austria and the USA (see Table A2.22).

Trade streams in the olive oil sector in Greece

In the olive oil sector Greece is clearly an exporting country. Most exports to EU countries are to Italy, but also to Germany and Spain, and, outside the EU, to the USA (see Table A2.23).

2.3.6 Trade streams to and from Spain

Trade streams in the cereal sector in Spain

Regarding cereals, Spain is dependent on imports of wheat and maize. Most imports come from the Ukraine and France. The statistical data show Spain's dependency, regarding imports, on France and Portugal for products at the first and second processing levels. On the export side, France and Portugal are also identified as being very important destinations. An overview of other imported and exported products and their origins and destinations is presented in Table A2.24.

Trade streams in the meat sector in Spain

The pig meat sector in Spain is a significant subsector within the meat sector. The Netherlands is the most active partner in livestock trade, with 73% of the pork livestock sector. More pigs are exported than imported and Portugal receives about 71%. Further statistical data regarding Spanish trade streams are presented in Table A2.25.

Trade streams in the fruit sector in Spain

Fruit is a major sector in Spain. The main fresh-fruit exports are oranges and apples, which go to Germany, France and Portugal. The processed-fruit sector shows that orange juice is mostly exported to France and Germany, and grape juice to Italy and France. Spain's results for the trade streams in the fruit sector are shown in Table A2.26.

Trade streams in the vegetable sector in Spain

Spain, like Greece, is an export-oriented country as far as vegetable products are concerned. Most Spanish fresh vegetables are exported to Germany and the UK (tomatoes and lettuce). In addition to the export side, the quantities of vegetables imported to Spain are shown in Table A2.27.

Trade streams in the olive oil sector in Spain

Olive trees and the olive oil sector are an integral part of Spanish culture. Spain's principal import partners are also olive oil producers (Portugal and Italy), and canned or bottled olive oil goes to France and Portugal. Table A2.28 highlights the results regarding quantities and percentages in the Spanish olive oil sector.

2.3.7 Trade streams to and from the USA

Trade streams in the cereal sector in the USA

Evaluation of US agricultural exports shows that the EU is no longer the number-one trading partner, but remains a primary market for several products produced in the USA (Fritz *et al.*, 2008).

Cereal exports to the EU represent 13% of total US exports to the EU. Note that cereal exports to the EU are not as important as those to the world market, but there is still a relevant export market for US cereals. The main cereals exported are wheat and grain sorghum, and Spain is shown to be the main destination (see Table A2.29).

Trade streams in the meat sector in the USA

US exports of meat to the EU are almost non-existent. This is a direct result of the trade restrictions mentioned above, resulting from outbreaks of disease and production practices. This is confirmed by the statistical data given in Table A2.29.

Trade streams in the fruit sector in the USA

The top two fresh-fruit products exported into the EU are grapefruit and apples. Within the processed-fruit sector, the top products are prunes and raisins. The quantities of these fruit products exported are shown in Table A2.29.

Trade streams in the vegetable sector in the USA

Potatoes are the vegetable most exported to Europe. In particular, the UK and the Netherlands are identified as the chief destinations and the respective quantities are presented in Table A2.29.

2.3.8 Trade streams to and from Brazil

Trade streams in the cereal sector in Brazil

The area dedicated to grain crops in Brazil is estimated to be about 47 million hectares. In the statistical database, exports to EU countries are important only for maize and wheat, and Portugal and Spain are identified as destinations (see Table A2.30).

Trade streams in the meat sector in Brazil

The meat sector is the second largest complex in Brazilian agri-business exports, having gained more importance over the last few years. Brazil has the world's largest commercial cattle herds, which are mainly raised in pastures. The main destinations for cattle exports to Europe are the UK and Italy. While cattle and chickens are significant as fresh-meat exports, pig meat and chicken are the most important products in the form of processed meat and these go to the Netherlands and the UK, and to France and Germany, respectively (see Table A2.30).

Trade streams in the fruit sector in Brazil

Although Brazil is the third largest fruit producer in the world, its export volume is not as important to the Brazilian export balance as the grain or meat sector, with the exception of orange juice. Fresh-fruit exports represent only 1% of the total (Fritz *et al.*, 2008). Bananas and mangoes are the most exported fruits, to the UK and Italy, respectively, and also to the Netherlands and the USA. The exports of orange juice in concentrated and non-concentrated form are defined as processed-fruit products. The largest amounts go to Belgium and the Netherlands (see Table A2.30).

2.3.9 Trade streams to and from Turkey

Trade streams in the cereal sector in Turkey

Cereals are the most important part of Turkish plant production in terms of land sown and production volume. Wheat is the main, and the most exported, product. The wheat flour, macaroni and pastry industries are well developed in line with this wheat production advantage. Germany and Italy are very important destinations for Turkish cereal products. The relative destinations and quantity are shown in Table A2.31.

Trade streams in the meat sector in Turkey

The red-meat sector is not as well developed in terms of foreign trade. In spite of its large numbers of livestock and quantities of animals slaughtered, high domestic consumption and an import–export ban restrain the development of foreign trade. Unlike the red-meat sector, poultry is well developed in all stages of production. Exports are generally limited to poultry. While chickens are exported to Romania and Bulgaria, chicken meat is exported to Bulgaria and Cyprus (see Table A2.31).

Trade streams in the fruit sector in Turkey

Fruit and vegetables are one of Turkey's most valuable agricultural subsectors in terms of production and foreign trade. Lemons and fruit juice are the most exported products. The main importers of lemons are Greece and Romania, and fruit juice Germany and Cyprus. The reported quantities are provided in Table A2.31.

Trade streams in the vegetable sector in Turkey

As mentioned in the section on the fruit sector, Turkey has an important role in the production and foreign trade of fruit and vegetables. The most exported vegetables are tomatoes (fresh as well as peeled) and frozen vegetables (see Table A2.31). Tomatoes are the most exported fresh vegetable and are mainly imported by Romania and Germany. Frozen vegetables and peeled tomatoes figure as processed vegetables in the statistical database. Frozen vegetables are mainly exported to Germany and Belgium and peeled tomatoes are mainly exported to Germany and Ireland.

Trade streams in the olive oil sector in Turkey

Turkey is one of the most important olive-oil-producing countries in the world. However, export is generally limited to Italy and Spain in bulk, mainly due to high import tax rates in European countries (see Table A2.31).

2.4 Future Opportunities and Suggestions

In this chapter, the international trade streams in different agri-food sectors are identified. These agri-food trade streams, in terms of the volume of exchanged goods, are recognized as having great potential, and attention and study should be given to the introduction of e-commerce.

In this identification process the focus was mainly on four agri-food supply chains: cereals, meat, fruit and vegetables, and olive oil. Additionally, an investigation of all tiers of the supply chain – production, consumption and import/export – was carried out.

The procedure was applied to six European traders in agricultural products (Germany, Austria, Italy, Slovenia, Greece and Spain) and three non-European countries (the USA, Brazil and Turkey).

The trade structures among the selected countries are diverse, and the picture is a complex one. Wheat and maize are major primary cereal commodities that are imported as well as exported. Most imports and exports of meat are of cattle, pigs or chickens. Overlapping trade streams could be identified between some countries, such as Germany, Austria, Italy and Spain. An example of overlapping between two countries is shown in Fig. 2.2 regarding the cereal products traded between Italy and Germany.

The results of the trade streams analysis provides the food industry with measures to enhance the sustainable introduction of e-commerce. Using the findings of the statistical databases, enterprises can obtain an assessment of the level of traded volume and products. Table 2.1 shows the results that a business can expect to obtain when searching for new potential ways to introduce e-commerce. They give a clear idea of where different countries stand with regard to the most traded agri-food products involved in cross-border exchanges.

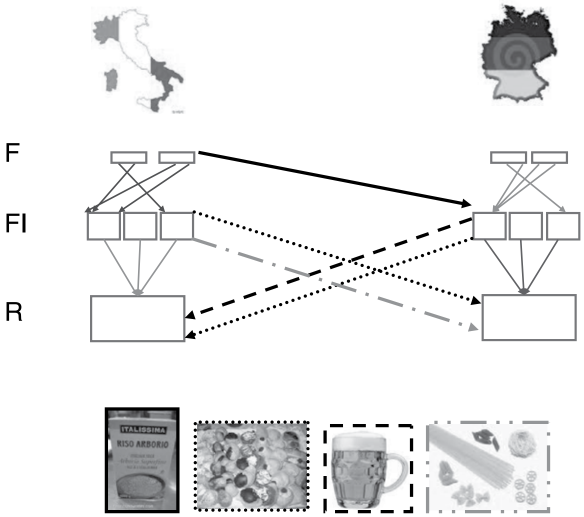

Fig. 2.2. Overlapping of the trade streams between Italy and Germany in the cereal sector.

Table 2.1. Most imported and exported agri-food products to and from the selected countries.

Country	Most imported agri-food product	Most exported agri-food product
Germany	Maize (from FR)	Soft wheat (to NL)
	Fresh pork (from (BE)	Fresh pork (to IT)
	Bananas (from EC)	Orange juice (to FR)
	Tomatoes (from NL)	Dried peas (to NL)
Austria	Soft wheat (from HU)	Soft wheat (to IT)
	Pigs (from DE)	Cattle (to IT)
	Bananas (from DE)	Apples (to DE)
	Tomatoes (from IT)	Not relevant
Italy	Wheat (from FR)	Pasta (to DE)
	Cattle (from FR)	Pigs (to HU)
	Bananas (from EC)	Grapes (to DE)
	Potatoes (from FR)	Tomato preserves (to UK)
	Virgin olive oil (from ES)	Virgin olive oil (to USA)
Slovenia	Maize (from HU)	Maize (to IT)
	Pigs (from AT)	Pigs (to HR)
	Bananas (from EC)	Bananas (to IT)
	Potatoes (from IL)	Potatoes (to DE)
	Olive oil (from ES)	Olive oil (to RS + ME)

Continued

Table 2.1. Continued.

Country	Most imported agri-food product	Most exported agri-food product
Greece	Maize (from HU) Cattle (from HU) Bananas (from EC) Potatoes (from EG) Olive oil (from IT)	Maize (to ES) Chicken (to IT) Oranges (to RO) Pickled vegetables (to USA) Olive oil (to IT)
Spain	Maize (from FR) Pigs (from NL) Apples (from FR) Potatoes (from FR) Olive oil (from IT)	Wheat flour (to LY) Pigs (to PT) Oranges (to DE) Tomatoes (to DE) Olive oil (to FR)
USA	Not relevant	Wheat (to ES) Chicken (to RO) Apples (to UK)
Brazil	Not relevant	Maize (to ES) Cattle (to UK) Mangoes (to NL)
Turkey	Not relevant	Wheat (to IT) Chickens (to RO) Olive oil (to IT) Lemon (to GR) Tomatoes (to RO)

AT, Austria; BE, Belgium; DE, Germany; EC, Ecuador; EG, Egypt; ES, Spain; FR, France; GR, Greece; HR, Croatia; HU, Hungary; IL, Israel; IT, Italy; LY, Libya; ME, Montenegro; NL, The Netherlands; PT, Portugal; RO, Romania; RS, Serbia; UK, United Kingdom; USA, United States of America.

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Appendix

Table A2.1. Trade streams in the cereal sector to and from Germany, 2005. (Sources: SBA, 2008; ZMP, 2007a; FAOSTAT, 2008a,b,c; DBB, 2007; BMELV, 2007.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Maize	1. FR	755,607	48	1. Soft wheat	1. NL	1,465,718	25
		2. HU	380,552	24		2. BE	620,753	11
	2. Soft wheat	1. CZ	455,454	38	2. Barley	1. SA	687,967	26
		2. FR	247,038	21		2. NL	429,970	16
1. Processing-industry level	1. Flour	1. FR	23,989	41	1. Flour	1. NL	122,772	25
		2. BE	21,115	36		2. LY	120,225	24
	2. Malt	1. FR	137,939	67	2. Malt	1. RU	46,410	12
		2. NL	38,336	19		2. CH	41,186	11
2. Processing-industry level	1. Pastries	1. NL	66,815	18	1. Pastries	1. FR	113,138	18
		2. IT	59,546	16		2. UK	75,307	12
	2. Beer (in 100 l)	2. DK	2,410	44	2. Beer (in 100 l)	1. IT	3,205	24
		3. BE/LU	1,105	20		2. FR	1,842	13

BE, Belgium; CH, Switzerland; CZ, Czech Republic; DK, Denmark; FR, France; HU, Hungary; IT, Italy; LU, Luxembourg; LY, Libya; NL, The Netherlands; RU, Russian Federation; SA, Saudi Arabia; UK, United Kingdom.

Table A2.2. Trade streams in the meat sector to and from Germany, 2005. (Sources: BMELV, 2006; ZMP, 2006.)

	Import			Export		
	Two most relevant origins	Tonnes	% of total	Two most relevant destinations	Tonnes	% of total
Livestock (beef and veal)	1. NL	3,269	23	1. NL	6,658	44
	2. BE	2,614	19	2. IT	3,045	20
Livestock (pork)	1. NL	231,852	75	1. AT	36,697	77
	2. DK	50,213	16	2. IT	2,707	6
Livestock (poultry)	1. NL	40,138	68	1. NL	181,593	97
	2. DK	10,450	18	2. PL	3,742	2
Fresh (beef and veal)	1. NL	55,194	31	1. IT	95,176	29
	2. FR	27,718	16	2. NL	62,193	19
Frozen (beef and veal)	1. NL	12,200	30	1. RU	17,436	32
	2. BR	4,013	10	2. NL	13,254	24
Fresh (pork)	1. BE	309,022	35	1. IT	259,776	37
	2. DK	269,363	31	2. NL	101,527	14
Frozen (pork)	1. ES	13,362	20	1. RU	47,227	24
	2. DK	12,927	19	2. RO	25,213	13
Fresh and frozen (poultry)	1. NL	134,283	34	1. NL	63,887	22
	2. PL	68,297	17	2. RU	59,066	20
Processed (canned goods from beef)	1. BR	5,262	27	1. FR	10,719	28
	2. NL	2,590	13	2. NL	6,026	16
Processed (sausage products from pork)	1. AT	13,735	28	1. FR	16,082	14
	2. IT	11,482	24	2. UK	15,936	14
Processed (offal, cans from poultry)	1. BR	93,914	48	1. NL	28,924	23
	2. NL	25,279	13	2. FR	16,477	13

AT, Austria; BE, Belgium; BR, Brazil; DK, Denmark; ES, Spain; FR, France; IT, Italy; NL, The Netherlands; PL, Poland; RO, Romania; RU, Russian Federation; UK, United Kingdom.

Table A2.3. Trade streams in the fruit sector to and from Germany, 2005. (Sources: Janorschke, 2007; ZMP, 2005; BLE, 2006; FAOSTAT, 2007; VdF, 2007.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh fruit	1. Bananas	1. EC	447,230	38	1. Bananas (re-exports)	1. AT	50,895	19
		2. CO	302,369	25		2. SE	44,097	17
	2. Apples	1. IT	327,878	39	2. Apples	1. NL	14,954	16
		2. NL	117,761	14		2. DK	11,285	12
Processed fruit	1. Orange concentrate	1. BR	305,539	65	1. Orange juice	1. FR	140,873	34
		2. CH	63,226	13		2. NL	82,216	20
	2. Apple concentrate	1. PL	113,443	38	2. Apple juice	1. UK	50,392	19
		2. CN	70,054	24		2. NL	42,094	17

AT, Austria; BR, Brazil; CH, Switzerland; CN, People's Republic of China; CO, Colombia; DK, Denmark; EC, Ecuador; FR, France; IT, Italy; NL, The Netherlands; PL, Poland; SE, Sweden; UK, United Kingdom.

Table A2.4. Trade streams in the vegetable sector to and from Germany, 2005. (Sources: ZMP, 2005, 2007b; BLE, 2006; FAOSTAT, 2007; Freitag, 2006.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh vegetables	1. Tomatoes	1. NL	319,341	47	1. White and red cabbage	1. SE	17,408	30
		2. ES	198,784	29		2. CZ	7,348	13
	2. Cucumbers	1. NL	248,644	56	2. Onions	1. NL	10,669	22
		2. ES	145,104	33		2. AT	6,917	14
Processed vegetables	1. Tomato purée	1. IT	150,960	70	1. Pasteurized cucumbers	1. NL	12,869	19
		2. ES	45,763	21		2. FR	6,759	10
	2. Processed tomatoes	1. IT	177,144	92	2. Dried peas	1. NL	61,458	80
		2. ES	3,275	2		2. DK	3,890	5

AT, Austria; CZ, Czech Republic; DK, Denmark; ES, Spain; FR, France; IT, Italy; NL, The Netherlands; SE, Sweden.

Table A2.5. Trade streams in the cereal sector to and from Austria, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Soft wheat	1. HU	133,624	53	1. Soft wheat	1. IT	413,817	83
		2. DE	51,060	20		2. DE	37,229	7
	2. Maize	1. HU	329,940	84	2. Maize	1. IT	348,808	90
		2. DE	19,197	5		2. DE	27,840	7
1. Processing-industry level	1. Wheat flour	1. DE	39,878	80	1. Malt flour	1. IT	13,414	23
		2. HU	6,468	13		2. BG	9,657	16
	2. Malt flour	1. DE	21,378	43	2. Wheat flour	1. HU	9,691	18
		2. SK	19,530	39		2. DE	7,438	15
2. Processing-industry level	1. Beer	1. DE	38,998	65	1. Beer	1. DE	12,111	15
		2. IT	626	18		2. IT	10,215	12
	2. Bakery products	1. DE	41,841	79	2. Pasta	1. DE	19,897	58
		2. IT	2,875	5		2. IT	5,406	16

BG, Bulgaria; DE, Germany; HU, Hungary; IT, Italy; SK, Slovakia.

Table A2.6. Trade streams in the meat sector to and from Austria, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Pigs	1. DE	710,025	99	1. Cattle	1. IT	81,261	63
		2. HU	4,160	0.5		2. DE	24,235	19
	2. Cattle	1. CZ	21516	38	2. Pigs	1. DE	52,210	51
		2. DE	19613	35		2. SK	22,457	22
1. Processing-industry level	1. Pigs (complete or half)	1. DE	36,367	92	1. Cattle parts	1. IT	23,825	43
		2. PL	1,160	3		2. DE	9,490	17
	2. Ham (unprocessed)	1. DE	11,489	81	2. Ham (unprocessed)	1. IT	17,083	67
		2. IT	1,684	11		2. CZ	3,895	15
2. Processing-industry level	1. Chicken meat products	1. DE	4,140	34	1. Chicken meat products	1. DE	9,271	81
		2. SI	1,827	15		2. IT	174	1
	2. Raw sausages	1. DE	6,003	73	2. Raw sausages	1. DE	20,742	70
		2. IT	1,622	20		2. IT	886	3

CZ, Czech Republic; DE, Germany; HU, Hungary; IT, Italy; PL, Poland; SK, Slovakia.

Table A2.7. Trade streams in the fruit sector to and from Austria, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh fruit	1. Bananas	1. DE	68,492	67	1. Apples	1. DE	37,222	52
		2. BE	19,541	19		2. HR	5,699	8
	2. Apples	1. IT	40,616	40	2. Grapes	1. DE	22,068	75
		2. HU	28,559	28		2. NL	5,163	16
Processed fruit	1. Apple juice, single strength	1. CH	26,477	21	1. Orange juice, single strength	1. IT	12,388	25
		2. DE	25,896	20		2. DE	11,498	23
	2. Orange juice, single strength	1. CH	25,738	36	2. Apple juice, single strength	1. DE	22,276	50
		2. DE	20,548	29		2. JP	6,768	15

BE, Belgium; CH, Switzerland; DE, Germany; HR, Croatia; HU, Hungary; IT, Italy; JP, Japan; NL, The Netherlands.

Table A2.8. Trade streams in the vegetable sector to and from Austria, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh vegetables	1. Tomatoes	1. IT	20,097	42	1. Onions	1. DE	6,352	16
		2. ES	16,850	36		2. HU	4,701	12
	2. Cucumbers	1. ES	8,669	42	2. Carrots	1. DE	9,235	48
		2. NL	2,862	14		2. CZ	1,972	10
Processed vegetables	1. Pickled vegetables	1. DE	10,163	60	Not relevant			
		2. TR	1,260	7				
	2.Tomato paste	1. IT	7,405	55				
		2. CN	2,159	16				

CN, People's Republic of China; CZ, Czech Republic; DE, Germany; ES, Spain; HU, Hungary; IT, Italy; NL, The Netherlands; TR, Turkey.

Table A2.9. Trade streams in the cereal sector to and from Italy, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Maize	1. FR	430,800	34	1. Rice milled	1. FR	119,604	19
		2. HU	242,841	19		2. DE	84,985	13
	2. Durum wheat	1. FR	1,730,844	26	2. Wheat	1. DZ	46,714	33
		2. CA	815,185	12		2. TN	19,834	14
1. Processing levels	1. Wheat flour	1. ES	5,157	31	1. Wheat flour	1. LY	241,207	46
		2. FR	4,226	26		2. CU	147,977	28
	2. Maize flour	1. AT	909	46	2. Maize flour	1. IL	25,840	15
		2. FR	707	36		2. EG	23,543	14
2. Processing levels	1. Pastry	1. DE	51,264	40	1. Pasta	1. DE	330,255	22
		2. FR	21,275	17		2. FR	202,844	14
	2. Barley beer	1. DE	295,493	56	2. Pastry	1. DE	57,090	20
		2. DK	49,631	9		2. FR	54,129	19

AT, Austria; CA, Canada; CU, Cuba; DE, Germany; DK, Denmark; DZ, Algeria; EG, Egypt; ES, Spain; FR, France; HU, Hungary; IL, Israel; LY, Libya; TN, Tunisia.

Table A2.10. Trade streams in the meat sector to and from Italy, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Cattle	1. FR	880,123	65	1. Pigs	1. HU	48,985	32
		2. PL	188,608	14		2. DE	13,989	25
	2. Pigs	1. NL	235,453	41	2. Cattle	1. ES	23,708	53
		2. ES	141,662	25		2. NL	18,068	40
1. Processing level	1. Beef meat (fresh and frozen)	1. NL	60,771	22	1. Chicken meat (fresh and frozen)	1. GR	11,926	19
		2. DE	58,022	21		2. DE	6,629	11
	2. Pork meat (fresh and frozen)	1. DE	61,446	29	2. Pork meat	1. DE	8,722	23
		2. FR	60,528	29		2. RO	6,829	18
2. Processing level	1. Pork sausages	1. DE	9,818	78	1. Pork. sausages	1. DE	9,392	27
		2. ES	1,520	12		2. ES	3,067	9

DE, Germany; ES, Spain; FR, France; GR, Greece; HU, Hungary; NL, The Netherlands; PL, Poland; RO, Romania.

Table A2.11. Trade streams in the fruit sector to and from Italy, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh fruit	1. Bananas	1. EC	276,002	49	1. Apples	1. ES	52,406	7
		2. CO	74,855	13		2. UK	43,098	6
	2. Peaches	1. ES	47,639	80	2. Grapes	1. DE	154,978	31
		2. FR	8,050	14		2. FR	80,807	16
Processed fruit	1. Fruit juice	1. AT	13,880	27	1. Fruit juice	1. DE	22,459	27
		2. DE	12,296	24		2. FR	12,315	15
	2. Dried fruit	1. ES	851	35	2. Prepared fruit	1. DE	4,353	26
		2. GR	415	17		2. FR	3,904	24

AT, Austria; CO, Colombia; DE, Germany; EC, Ecuador; ES, Spain; FR, France; GR, Greece; UK, United Kingdom.

Table A2.12. Trade streams in the vegetable sector to and from Italy, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh vegetables	1. Potatoes	1. FR	266,281	47	1. Lettuces, chicories	1. DE	43,897	45
		2. NL	80,066	14		2. CH	8,200	8
	2. Tomatoes	1. NL	34,714	35	2. Tomatoes	1. DE	43,871	48
		2. ES	34,213	34		2. AT	11,306	12
Processed vegetables	1. Vegetables frozen	1. BE	53,164	34	1. Tomatoes preserves and peeled	1. UK	193,659	23
		2. FR	22,837	15		2. DE	135,643	16
	2. Vegetables preserved	1. FR	33,607	49	2. Vegetables and legumes prepared or conserved	1. DE	34,049	38
		2. ES	10,206	15		2. AU	9,144	10

AT, Austria; AU, Australia; BE, Belgium; CH, Switzerland; DE, Germany; ES, Spain; FR, France; NL, The Netherlands; UK, United Kingdom.

Table A2.13. Trade streams in olive oil sector to and from Italy, 2005. (Source: FAOSTAT, 2005.)

	Import			Export		
	Two most relevant origins	Tonnes	% of total	Two most relevant destinations	Tonnes	% of total
Olives	1. GR	2,412	60	1. FR	228	29
	2. ES	1,238	31	2. DE	152	20
Virgin olive oil	1. ES	216,795	38	1. USA	190,795	44
	2. GR	92,013	16	2. DE	47,008	11

DE, Germany; ES, Spain; FR, France; GR, Greece; USA, United States of America.

Table A2.14. Trade streams in the cereal sector to and from Slovenia, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Maize	1. HU	122,122	88	1. Maize	1. IT	26,712	99
		2. MK	8,053	6		2. HR	443	2
	2. Wheat	1. HU	97,340	82	2. Barley	1. IT	1,710	99
		2. AT	8,898	7		2. RS	13	0.75
1. Processing-industry level	1. Maize flour	1. RS	5,106	58	Non-relevant export			
		2. IT	3,603	41				
	2. Wheat flour	1. IT	8,268	40				
		2. AT	8,220	40				
2. Processing-industry level	1. Pastry	1. IT	2,966	18				
		2. HR	2,848	17				
	2. Barley beer	1. DE	8,635	45				
		2. AT	4,565	24				

AT, Austria; DE, Germany; HR, Croatia; HU, Hungary; IT, Italy; MK, Macedonia; RS, Serbia.

Table A2.15. Trade streams in the meat sector to and from Slovenia, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Cattle	1. HU	11,102	43	1. Cattle	1. AT	4,275	54
		2. CZ	7,920	31		2. IT	2,895	37
	2. Pigs	1. AT	17,357	74	2. Pigs	1. HR	5,780	8
		2. HU	2,977	13		2. HU	1,278	18
1. Processing-industry level	1. Pig meat	1. AT	5,356	26	1. Chicken meat	1. AT	2,288	31
		2. NL	4,359	21		2. HR	851	12
	2. Chicken meat	1. IT	3,123	73	2. Beef meat	1. IT	1,981	83
		2. AT	602	14		2. NL	381	16
2. Processing-industry level	1. Chicken meat canned	1. HU	336	8	1. Pork sausages	1. BA	2,143	25
		2. AT	215	28		2. MK	2,036	24
	2. Pork sausages	1. IT	337	43	2. Chicken meat canned	1. BA	1,802	22
		2. AT	142	23		2. AT	1,625	2

AT, Austria; BA, Bosnia and Herzegovina; CZ, Czech Republic; HR, Croatia; HU, Hungary; IT, Italy; MK, Macedonia; NL, The Netherlands.

Table A2.16. Trade streams in the fruit sector to and from Slovenia, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh fruit	1. Bananas	1. EC	22,894	45	1. Apples	1. HR	8,277	32
		2. CO	19,296	38		2. AT	7,078	27
	2. Oranges	1. IT	4,651	23	2. Bananas	1. IT	15,243	83
		2. EG	3,004	15		2. HU	1,415	8
Processed fruit	1. Fruit Prp Nes	1. ES	1,891	16	Not relevant export			
		2. IT	1,745	15				
	2. Orange juice, single strength	1. BE	1,568	34				
		2. DE	1,004	22				

AT, Austria; BE, Belgium; CO, Colombia; DE, Germany; EC, Ecuador; EG, Egypt; ES, Spain; HR, Croatia; HU, Hungary; IT, Italy; Nes, not elsewhere specified; Prp, prepared.

Table A2.17. Trade streams in the vegetable sector to and from Slovenia, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh vegetables	1. Potatoes	1. IL	5,406	22	1. Potatoes	1. DE	11,787	84
		2. NL	4,126	17		2. HR	858	6
	2. Tomatoes	1. IT	5,302	37	2. Tomatoes	1. DE	241	35
		2. TR	4,931	35		2. IT	141	20
Processed vegetables	1. Onions, dry	1. AT	4,205	35	1. Onions, dry	1. ES	1,171	68
		2. NL	3,378	28		2. HU	206	12
	2. Vegetables preserved Nes	1. IT	5,011	61	2. Vegetables preserved Nes	1. RS	432	31
		2. AT	619	7		2. DE	318	23

AT, Austria; DE, Germany; ES, Spain; HR, Croatia; HU, Hungary; IL, Israel; IT, Italy; Nes, not elsewhere specified; NL, The Netherlands; RS, Serbia; TR, Turkey.

Table A2.18. Trade streams in the olive oil sector to and from Slovenia, 2005. (Source: FAOSTAT, 2005.)

	Import			Export		
	Two most relevant origins	Tonnes	% of total	Two most relevant destinations	Tonnes	% of total
Olives preserved	1. IT	289	44	1. RS + ME	26	30
	2. GR	136	21	2. HR	24	28
Olive oil	1. ES	556	54	1. BA	4	33
	2. IT	354	34	2. HR	3	25

BA, Bosnia and Herzegovina; ES, Spain; GR, Greece; HR, Croatia; IT, Italy; ME, Montenegro; RS, Serbia.

Table A2.19. Trade streams in the cereal sector to and from Greece, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Soft wheat	1. RU	295,861	33	1. Hard wheat	1. IT	122,844	62
		2. FR	136,600	15		2. DZ	18,241	1
	2. Maize	1. HU	524,002	82	2. Maize	1. ES	211,094	50
		2. FR	31,715	0.05		2. CY	110,328	26
1. Processing-industry level	1. Wheat flour	1. IT	7,112	44	1. Wheat flour	1. LY	10,000	40
		2. DE	4,464	27		2. BG	6,112	25
	2. Maize flour	1. IT	215	42	2. Maize flour	1. MK	1,017	45
		2. USA	87	17		2. RO	924	40
2. Processing-industry level	1. Beer	1. DE	21,846	45	1. Macaroni	1. IT	18,873	40
		2. NL	14,119	29		2. AL	8,260	17
	2. Pastry	1. IT	9,442	29	2. Pastry	1. IT	3,990	20
		2. DE	7,598	23		2. UK	2,903	14

AL, Albania; BG, Bulgaria; CY, Cyprus; DE, Germany; DZ, Algeria; ES, Spain; FR, France; HU, Hungary; IT, Italy; LY, Libya; MK, Macedonia; NL, The Netherlands; RO, Romania; RU, Russian Federation; UK, United Kingdom; USA, United States of America.

Table A2.20. Trade streams in the meat sector to and from Greece, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Cattle	1. HU	100,900	41	Despite the high production of goat meat in Greece, exports are not relevant due to very high local consumption.			
		2. FR	62,456	25				
	2. Pigs	1. NL	71,047	84				
		2. FR	4,191	0.04				
1. Processing-industry level	1. Pork	1. NL	67,265	43	1. Chicken	1. IT	2,571	35
		2. FR	48,669	32		2. MK	1,453	20
	2. Beef meat	1. FR	56,140	72	2. Pork	1. FR	1,134	58
		2. DE	7,765	1		2. BG	312	16
2. Processing-industry level	1. Pork sausages	1. DE	4,839	64	1. Pork sausages	1. CY	575	59
		2. IT	1,075	14		2. AL	195	20
	2. Chicken meat canned	1. DE	1,888	36	2. Chicken meat canned	1. AL	302	33
		2. IT	1,785	34		2. MK	257	28

AL, Albania; BG, Bulgaria; CY, Cyprus; DE, Germany; FR, France; HU, Hungary; IT, Italy; MK, Macedonia; NL, The Netherlands.

Table A2.21. Trade streams in the fruit sector to and from Greece, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh fruit	1. Bananas	1. EC	40,747	49	1. Grapes	1. DE	33,522	37
		2. IT	37,598	45		2. UK	21,854	24
	2. Lemons and limes	1. AR	27,351	44	2. Oranges	1. RO	38,146	18
		2. TR	25,807	41		2. DE	31,521	15
Processed fruit	1. Orange juice (single strength)	1. DE	6,008	30	1. Grape juice	1. IT	12,027	98
		2. BE	4,621	23		2. TR	208	2
	2. Apple juice (concentrated)	1. DE	7,467	93	2. Orange juice (single strength)	1. UK	665	15
		2. IT	556	7		2. MK	590	14

AR, Argentina; BE, Belgium; DE, Germany; EC, Ecuador; IT, Italy; MK, Macedonia; RO, Romania; TR, Turkey; UK, United Kingdom.

Table A2.22. Trade streams in the vegetable sector to and from Greece, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh vegetables	1. Potatoes	1. EG	49,527	43	1. Cucumbers and gherkins	1. DE	9,235	64
		2. FR	20,949	18		2. AT	1,663	11
	2. Tomatoes	1. TR	5,267	33	2. Asparagus	1. DE	7,914	81
		2. MK	4,473	28		2. AT	976	10
Processed vegetables	1. Vegetables frozen	1. BE	7,615	31	1. Pickled vegetables	1. USA	10,611	73
		2. BG	3,384	14		2. DE	1,201	8
	2. Vegetables preserved Nes	1. TR	3,554	25	2. Vegetables preserved Nes	1. DE	4,294	36
		2. CY	2,127	15		2. SE	1,012	8

AT, Austria; BE, Belgium; BG, Bulgaria; CY, Cyprus; DE, Germany; EG, Egypt; FR, France; MK, Macedonia; Nes, not elsewhere specified; SE, Sweden; TR, Turkey; USA, United States of America.

Table A2.23. Trade streams in the olive oil sector to and from Greece, 2005. (Source: FAOSTAT, 2005.)

	Import			Export		
	Two most relevant origins	Tonnes	% of total	Two most relevant destinations	Tonnes	% of total
Olives	1. IT	446	89	1. IT	3,683	59
	2. BE	29	6	2. DE	618	10
Olives (preserved)	1. EG	1,092	27	1. USA	17,277	24
	2. DE	857	22	2. IT	13,143	18
Olive oil	1. IT	2,213	59	1. IT	79,012	80
	2. ES	1,061	28	2. ES	3,999	4

BE, Belgium; DE, Germany; EG, Egypt; ES, Spain; IT, Italy; USA, United States of America.

Table A2.24. Trade streams in the cereal sector to and from Spain, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Wheat	1. FR	1,997,240	27	1. Wheat	1. DZ	59,660	26
		2. UA	1,433,975	19		2. PT	56,590	25
	2. Maize	1. FR	2,144,470	50	2. Rice milled	1. UK	18,692	15
		2. UA	322,489	8		2. UA	15,726	13
1. Processing-industry level	1. Maize flour	1. FR	90,113	92	1. Wheat flour	1. LY	91,654	37
		2. PT	3,489	4		2. FR	43,233	18
	2. Wheat flour	1. FR	19,596	45	2. Forage products	1. PT	64,279	39
		2. PT	16,113	37		2. FR	49,940	31
2. Processing-industry level	1. Pastry	1. FR	37,273	25	1. Pastry	1. PT	48,278	29
		2. IT	35,852	24		2. FR	31,778	19
	2. Macaroni	1. IT	13,360	64	2. Macaroni	1. FR	20,627	59
		2. PT	3,279	16		2. PT	6,165	18

DZ, Algeria; FR, France; IT, Italy; LY, Libya; PT, Portugal; UA, Ukraine; UK, United Kingdom.

Table A2.25. Trade streams in the meat sector to and from Spain, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Farm-level products	1. Pigs	1. NL	689,698	73	1. Pigs	1. PT	1,036,350	71
		2. DE	129,094	14		2. FR	135,749	9
	2. Cattle	1. FR	259,009	30	2. Cattle	1. IT	59,884	46
		2. PT	229,767	27		2. FR	56,407	43
1. Processing-industry level	1. Chicken meat	1. BR	34,920	43	1. Pig meat	1. FR	63,815	12
		2. UK	11,658	14		2. PT	55,589	19
	2. Pig meat	1. FR	10,215	45	2. Cattle meat	1. FR	35,206	32
		2. DE	2,247	10		2. PT	31,393	32
2. Processing-industry level	1. Chicken meat, canned	1. FR	5,565	31	1. Pork sausages	1. FR	7,985	29
		2. BR	5,174	29		2. PT	4,380	16
	2. Pork sausages	1. DE	6,043	46	2. Chicken meat, canned	1. PT	3,725	55
		2. DK	1,919	15		2. FR	1,255	19

BR, Brazil; DE, Germany; DK, Denmark; FR, France; IT, Italy; NL, The Netherlands; PT, Portugal; UK, United Kingdom.

Table A2.26. Trade streams in the fruit sector to and from Spain, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh fruit	1. Apples	1. FR	73,817	33	1. Oranges	1. DE	308,333	28
		2. IT	37,395	17		2. FR	290,419	26
	2. Pears	1. BE	18,256	34	2. Apples	1. FR	26,185	29
		2. NL	8,644	16		2. PT	24,650	27
Processed fruit	1. Orange juice, single strength	1. BE	22,247	21	1. Orange juice, single strength	1. FR	106,656	72
		2. NL	15,118	21		2. DE	22,825	15
	2. Orange juice, concentrated	1. NL	4,088	39	2. Grape juice	1. IT	31,623	27
		2. FR	2,543	24		2. FR	13,440	12

BE, Belgium; DE, Germany; FR, France; IT, Italy; NL, The Netherlands; PT, Portugal.

Table A2.27. Trade streams in the vegetable sector to and from Spain, 2005. (Source: FAOSTAT, 2005.)

	Import				Export			
	Two most relevant products	Two most relevant origins	Tonnes	% of total	Two most relevant products	Two most relevant destinations	Tonnes	% of total
Fresh vegetables	1. Potatoes	1. FR	507,851	68	1. Tomatoes	1. DE	198,893	22
		2. UK	79,373	11		2. UK	183,845	20
	2. Tomatoes	1. PT	41,287	57	2. Lettuce and chicory	1. DE	155,531	29
		2. MA	13,840	19		2. UK	131,074	24
Processed vegetables	1. Vegetables preserved	1. CN	45,201	23	1. Vegetables frozen	1. FR	51,744	27
		2. PE	39,741	18		2. DE	33,599	18
	2. Vegetables frozen	1. BE	31,208	37	2. Vegetables preserved	1. FR	40,420	30
		2. FR	24,643	29		2. USA	38,503	29

BE, Belgium; CN, People's Republic of China; DE, Germany; FR, France; MA, Morocco; PE, Peru; PT, Portugal; UK, United Kingdom.

Table A2.28. Trade streams in the olive oil sector to and from Spain, 2005. (Source: FAOSTAT, 2005.)

	Import			Export		
	Two most relevant origins	Tonnes	% of total	Two most relevant destinations	Tonnes	% of total
Olives	1. PT	583	76	1. DE	3,386	60
	2. FR	92	12	2. IT	582	10
Olive oil	1. IT	17,526	26	1. FR	53,712	17
	2. MA	11,727	17	2. PT	34,599	11

DE, Germany; FR, France; IT, Italy; MA, Morocco; PT, Portugal.

Table A2.29. Trade streams in the cereal, meat, fruit and vegetable sector from the USA, 2005. (Source: Fritz *et al.*, 2008.)

Two most significant products	Two most significant destinations	Tonnes	% of total
Cereal export			
Wheat (not durum)	1. ES	257,779	1.07
	2. BE	106,337	0.44
Grain sorghum	1. ES	152,524	3.36
	2. FR	696	0.02
Meat export			
Chicken	1. RO	90,193	3.87
	2. LT	78,495	3.37
Pork	1. RO	25,294	3.1
	2. UK	2,872	0.35
Fruit export			
Apples	1. UK	34,274	5.08
	2. FI	1,968	0.29
Grapefruit	1. NL	15,399	7.02
	2. FR	20,266	9.24
Plums, dried	1. DE	5,376	11.78
	2. IT	3,473	7.61
Fruits, dried	1. UK	1,743	7.52
	2. DE	540	2.33
Vegetable export			
Potatoes	1. UK	7,446	2.58
	2. NL	5	0

BE, Belgium; DE, Germany; ES, Spain; FI, Finland; FR, France; IT, Italy; LT, Lithuania; NL, The Netherlands; RO, Romania; UK, United Kingdom.

Table A2.30. Trade streams in the cereal, meat and fruit sector from Brazil, 2005. (Source: Fritz *et al.*, 2008.)

Two most significant products	Two most significant destinations	Tonnes	% of total
Cereal export			
Maize	1. ES	66,460	6.21
	2. PT	32,554	3.04
Wheat	1. ES	56,950	37.21
	2. IT	146	0.1
Meat export			
Cattle	1. UK		4
	2. IT		3
Chickens	1. NL		4
	2. DE		2
Chicken meat	1. NL		0.3
	2. UK		0.3
Pork	1. FR		1.5
	2. DE		1.4

Continued

Table A2.30. Continued.

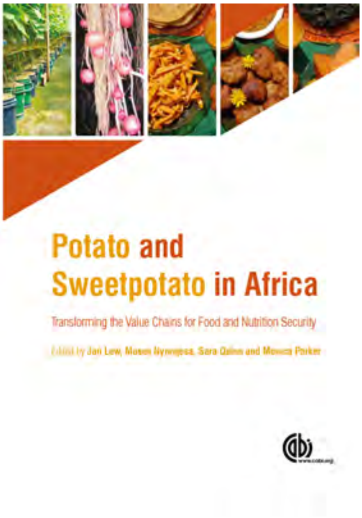
Two most significant products	Two most significant destinations	Tonnes	% of total
Fruit export			
Banana	1. UK		28
	2. IT		9
Mango	1. NL		50
	2. USA		23
Orange juice (concentrated)	1. BE		50
	2. NL		4
Orange juice (non-concentrated)	1. NL		44
	2. BE		31

BE, Belgium; DE, Germany; ES, Spain; FR, France; IT, Italy; NL, The Netherlands; PT, Portugal; UK, United Kingdom; USA, United States of America.

Table A2.31. Trade streams in the cereal, meat, fruit, vegetable and olive oil sector from Turkey, 2005. (Source: Fritz *et al.*, 2008.)

Two most significant products	Two most significant destinations	Tonnes	% of total
Cereal export			
Wheat	1. IT	58,380	22.99
	2. PT	25,750	10.14
Maize	1. CY	5,680	2.24
	2. IT	1,735	0.68
Wheat flour	1. CY	6,814	2.68
	2. DE	794	0.31
Pastry	1. DE	9,495	3.74
	2. BG	4,476	1.76
Macaroni	1. DE	3,980	1.57
	2. NL	1,044	0.41
Meat export			
Chickens	1. RO	3,378	65.3
	2. BG	568	10.98
Chicken meat	1. BG	1,473	28.47
	2. CY	630	12.18
Fruit export			
Lemon	1. GR	25,503	8.64
	2. RO	22,688	7.69
Fruit juice	1. DE	5,463	1.85
	2. CY	1,736	0.59
Vegetable export			
Tomatoes	1. RO	28,070	11.59
	2. DE	7,002	2.89
Frozen vegetables	1. DE	12,431	5.13
	2. BE	10,676	4.41
Tomatoes peeled	1. DE	1,036	0.43
	2. IE	830	0.34
Olive oil export			
Olive oil	1. IT	40,609	73.6
	2. ES	20,039	36.31

BE, Belgium; BG, Bulgaria; CY, Cyprus; DE, Germany; ES, Spain; GR, Greece; IE, Ireland; IT, Italy; NL, The Netherlands; PT, Portugal; RO, Romania.



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Acronyms

ABS, accelerated breeding scheme
ADC, Agricultural Development Cooperation
AEZ, agroecological zones
AFLP, amplified fragment length polymorphism
AGRA, Alliance for a Green Revolution in Africa
AgR4D, agricultural research for development
AI, activity index
AIDs, acquired immune deficiency syndrome
AIS, Agricultural Innovation Systems
AMMI, Additive main effects and multiplicative interaction
ANOVA, analysis of variance
AOAC, Association of Official Analytical Chemists
AP, after planting
APA, African Potato Association
APF, AgriProFocus
APLV, *Andean potato latent virus*
ARC, Agricultural Research Council
ARC-VOPI, Agricultural Research Council-Roodeplaat Vegetable and Ornamental Plant Institute
ARI, Agricultural Research Institute
ASARECA, Association for Strengthening Agricultural Research in Eastern and Central Africa
AUDPC, area under the disease progress curve
AVRDC, Asian Vegetable Research and Development Center
BMGF, Bill & Melinda Gates Foundation
BoA, Bureau of Agriculture
BSPM, boiled sweetpotato meal
Bt, toxin derived from *Bacillus thuringiensis*
CAADP, Comprehensive African Agriculture Development Programme
CARE, Carry American Relief Everywhere
CARE EEEGL, Carry American Relief Everywhere (CARE) Enterprise, Environment and Equity in the Great Lakes (a CARE project)
CBO, community-based organization
CBSPM, composite boiled sweetpotato meal

CCAFS, Climate Change, Agriculture and Food Security
CCD, composted cow dung
C-D, Cobb-Douglas (model)
CEC, cation exchange capacity
CES, constant elasticity of substitution
CFC, Common Fund for Commodities
CIDA, Canadian International Development Agency
CIE, Commission Internationale de l'Eclairage
CIP, International Potato Center
CMV, cucumber mosaic virus
COII, cytochrome oxidase II
COoA, Chencha Office of Agriculture
CP, coat protein
CP, crude protein
CPRI, Central Potato Research Institute
CRS, Catholic Relief Services
CSIR-CRI, Council for Scientific and Industrial Research, Crops Research Institute
CSRW, commercial storage root weight
CSSPM, composite sun-dried sweetpotato meal
CV, coefficient of variation
CVP, crystal violet pectate (medium)
DAP, diammonium phosphate
DARS, Department for Agricultural Research Services
DAS-ELISA, double antibody sandwich ELISA
DFID, Department for International Development (UK)
DIIVA, Diffusion and Impacts of Improved Varieties in Africa
DLS, diffused light storage/store
DM, dry matter
DMC, dry matter content
DONATA, Dissemination of New Agricultural Technologies in Africa
DRC, Democratic Republic of the Congo
DSPs, Decentralized Seed Producers
DTI, drought tolerance index
dwb, dry weight basis
EAC, East African Community
EC, electrical conductivity
ECA, East/Eastern and Central Africa
EFSA, European Food Safety Authority
EI, establishment risk index
EIAR, Ethiopian Institute of Agricultural Research
ELISA, enzyme-linked immunosorbent assay
ESA, East and Southern Africa
EST, expressed sequence tag
ETDF, equivalent thermal driving force
ETP, evapotranspiration
EU, European Union
FAO, Food and Agriculture Organization of the United Nations
FARA, Forum for Agricultural Research in Africa
FCR, feed conversion ratio
FFS, farmer field school
FP, farmers' practice (seed)
FPU, food production unit

FRG, farmers' research group
FS, farmer selection (seed)
FSE, farmer seed enterprise
FUNAAB, Federal University of Agriculture, Abeokuta
fwb, fresh weight basis
GAIN, Global Alliance for Improved Nutrition
GAP, gender action plan
GAPs, Good Agricultural Practices
GBS, genotyping by sequencing
GCA, general combining ability
GCM, general circulation model
GDP, gross domestic product
G × E, genotype by environment interaction
GEBVS, genomic estimated breeding values
GI, generation index
GIL, Groupement Interprofessionnel des Légumes
GIS, geographic information system
GLM, general linear model
GMO, genetically modified organism
GMP, good manufacturing practices
GPB, Golden Power Biscuit
GPS, global positioning system
GS, genomic selection
GTSPI, Genomic Tools for Sweetpotato Improvement
HARC, Holetta Agricultural Research Centre
HEBS, heterosis-exploiting breeding scheme
HI, harvest index
HIV, human immunodeficiency virus
HMNEH, Horticulture Mission for North East and Himalayan States
HPLC, high performance liquid chromatography
IA, investment area
IAA, indole-3-acetic acid
IARC, International Agricultural Research Centres
ICP-OES, inductively coupled plasma argon optical emission spectrometry
ICT, information and communication technology/technologies
IGS, intergenic spacer
IIAM, Mozambique Institute of Agricultural Research
ILCYM, Insect Life Cycle Modelling software
IMPACT, International Model for Policy Analysis of Agricultural Commodities and Trade
INERA, Institut de l'Environnement et de Recherches Agricoles
INES, Institut d'Enseignement Supérieur de Ruhengeri
INGO, international non-governmental organization
INRAT, Institut National de la Recherche Agronomique de Tunisie
IPGRI, International Plant Genetic Resources Institute
IPM, integrated pest management
IPPC, International Plant Protection Convention
IRR, internal rate of return
ISAR, Rwandan Institute for Agricultural Sciences
ISO, International Organization for Standardization
ISPMs, International Standards for Phytosanitary Measures
ISTA, International Seed Testing Association
ISTRC, International Society for Tropical Root Crops

IVOMD, *in vitro* organic matter digestibility
KALRO, Kenya Agricultural and Livestock Research Organization
KAPAP, Kenya Agricultural and Agribusiness Project
KARI, Kenya Agricultural Research Institute
KENAPOFA, Kenya National Potato Farmers’ Association
KEPHIS, Kenya Plant Health Inspectorate Service
KIST, Kigali Institute of Food Science
LB, late blight
LBHT, late blight resistant heat tolerant
LED, light-emitting diode
LER, land equivalent ratio
LGA, local government area
LR, likelihood ratio
LSD, least significance difference
lsmean, least-squares mean
LSU, Louisiana State University
masl, metres above sea level
MI, Micronutrient Initiative
MLE, maximum likelihood estimate
MoA, Ministry of Agriculture
mos, microorganisms
MOU, memorandum of understanding
MP, microplant
MRDR, modified relative-dose–response test
MS, Murashige and Skoog (medium)
MT, microtuber
mtDNA, mitochondrial DNA
MTP, microtuber raised plant
NAADS, National Agricultural Advisory Services
NaCRRI, National Crops Resources Research Institute
NARC, Njala Agricultural Research Centre
NARI, National Agricultural Research Institute
NARO, National Agricultural Research Organisation
NARS, National Agricultural Research System
NASPOT, Namulonge Sweetpotato
NCM-ELISA, nitrocellulose membrane ELISA
NCSR, number of commercial storage roots
NCSU, North Carolina State University
NFL, normal fluorescent light
NGO, non-governmental organization
NIRS, near-infrared reflectance spectroscopy
NPCK, National Potato Council of Kenya
NPT, National Performance Trial
NPV, net present value
NRCRI, National Root Crops Research Institute
OECD, Organization for Economic Cooperation and Development
OFSP, orange-fleshed sweetpotato
OLS, ordinary least squares
PAR, photosynthetically active radiation
PBRSV, *Potato black ring-spot virus*
Pcb, *Pectobacterium carotovorum brasiliense*
PCR, polymerase chain reaction

PDR	pathogen-derived resistance
PEG	polyethylene glycol
PLRV	potato leaf roll virus
PMCA	Participatory Market Chain Approach
PNAP	Programme National pour l'Amélioration de la Pomme de terre
PPP	public–private partnership
PQBS	Plant Quarantine and Biosecurity Station
PRA	participatory rural appraisal
PRA	pest risk analysis
PRAPACE	Programme Régional d'Amélioration de la Pomme de Terre et de la Patate Douce en Afrique Centrale et de l'Est
PS	positive-selection (seed)
PT	preliminary trials
PTNRD	potato tuber necrotic ringspot disease
PVA	potato virus A
PVM	potato virus M
PVS	potato virus S
PVX	potato virus X
PVY	potato virus Y
PYT	preliminary yield trial
QDPM	Quality Declared Planting Material
QDS	Quality Declared Seed
qRT-PCR	quantitative real-time reverse transcriptase polymerase chain reaction
QTL	quantitative trait loci
RAA	reduced ascorbic acid
RAB	Rwanda Agriculture Board
R&D	research and development
RAE	retinol activity equivalents
RAPD	random amplified polymorphic DNA
RBDO	refined, bleached and deodorized oil
RBP	retinol-binding protein
RBS	Rwanda Bureau of Standards
RCBD	randomized complete block design
RDA	recommended daily allowance
REU	Reaching End Users (project)
RKN	root knot nematodes
RMT	rapid multiplication techniques
RSA	response surface analysis
R/V	ratio of total dry matter yield of roots to vines
SARI	South Agricultural Research Institute
SASA	Science and Advice for Scottish Agriculture
SASHA	Sweetpotato Action for Security and Health in Africa
SBCC	social and behaviour change communication
SCCI	Seed Control and Certification Institute
SE	standard error of the mean
SED	standard error of the difference of means
SFLCs	sweetpotato flour from limed chips
SFNLCs	sweetpotato flour from non-limed chips
siRNA	small interfering RNA
SNHP	State National Harmonization Program
SNNPR	Southern Nations Nationalities and Peoples' Region
SNPs	single nucleotide polymorphisms

SPCSV, sweet potato chlorotic stunt virus
SPFMV, sweet potato feathery mottle virus
SPHD, State Plant Health Director
SPHI, Sweet potato for Profit and Health Initiative
SPLCV, Sweet potato leaf curl virus
SPMMV, sweet potato mild mottle virus
SPPV, Sweet potato pakakuy virus
SPRO, State Plant Regulatory Official
SPS, sanitary and phytosanitary (measures)
SPSMV, sweet potato symptomless virus 1
SPSS, Statistical Program for Social Scientists
SPVC, Sweet potato virus C
SPVD, sweet potato virus disease
SPVG, Sweet potato virus G
SPVZ, sweet potato virus Z
SPV2, Sweet potato virus 2
SRE, soft rot *Enterobacteriaceae*
sRSA, small RNA sequencing and assembly of viral genomes
SSA, sub-Saharan Africa
SSPM, sun-dried sweetpotato meal
SSR, simple sequence repeat
SUN, Scaling Up Nutrition (initiative)
3G (a seed production model), ‘3 seed potato generation revolution’
TAS-ELISA, triple antibody sandwich
TATI, Tinarha Agri Tourism Initiative
TIPs, Trials for Improved Practices
T_{max}, daily maximum temperature
T_{min}, daily minimum temperature
TOT, Training of Trainers
TSNI, Towards Sustainable Nutrition Improvement (project)
UNICEF, United Nations Children’s Fund
UNSPPA, Uganda National Seed Potato Producers’ Association
UPOV, Union for Protection of Plant Varieties
USAID, United States Agency for International Development
USDA-APHIS, United States Department of Agriculture Animal Plant Health Inspection Service
VAD, vitamin A deficiency
VAS, vitamin A supplementation
VFAs, volatile fatty acids
VITAA, Vitamin A for Africa
VPCs, vegetatively propagated crops
WACCI, West Africa Centre for Crop Improvement
WATSAN, water and sanitation sector
WHO, World Health Organization
WTO, World Trade Organization
XSPRC, Xuzhou Sweetpotato Research Center
YWCA, Young Women’s Christian Association
YWT, yellow water trap
ZARI, Zambia Agriculture Research Institute

12 Public–Private Partnership Supporting Women-driven Seed Potato Multiplication in the Lumwana Catchment Area of North-Western Province of Zambia

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Abstract

The opening of mines and associated population boom is contributing to the increase in potato (*Solanum tuberosum* L.) consumption, which calls for increased production of the crop in North-Western Province of Zambia. However, the major constraint hampering expansion of potato production in the region is lack of seed for improved potato varieties. As no seed company is engaged in potato seed production in Zambia, all improved seed is imported from South Africa and Europe in the form of 'seed potatoes'. Even so, the quantity imported is not adequate to guarantee year-round production of the crop by small-scale farmers in the province. In response to the national government's strategic plan of fostering development of the agricultural sector through the establishment of public–private partnerships in Zambia, Barrick Lumwana Mining Company, Zambia Agriculture Research Institute (ZARI) and the Department of Extension of the Ministry of Agriculture and Livestock are working in partnership to support women-driven seed multiplication to promote year-round market-oriented production of potatoes in the Lumwana catchment area. In this arrangement, the mining company provides funds for the projects, while ZARI and extension agents are responsible for training and provision of technical backstopping to farmers in the project. ZARI serves as the primary multiplication site. Six women's groups were trained and attained a 1:10 multiplication ratio of seed from rain-fed upland and wetland nurseries. Gross margin analysis indicates that women in Silenda and Muyashi camps were able to obtain high revenue returns on labour either by working as a group or individually. This chapter highlights the experiences, successes and challenges encountered in the implementation of this women-driven seed multiplication and distribution project. The project provides a unique example of the social corporate responsibility in which a private company ploughs back part of the proceeds to benefit communities among which it does business.

Keywords: Barrick Lumwana, multiplication, potato, public–private partnerships, women-driven, ZARI

12.1 Introduction

Potato is the fourth most important crop in the world, but its significance varies widely from country to country (Namasiku, 1995). In Zambia potato production and consumption is increasingly becoming important as a source of income. In particular, the opening of new

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Potato and Sweetpotato in Africa: Transforming the Value Chains for Food and Nutrition Security (eds J. Low *et al.*)

mines in North-Western Province and associated population increase is contributing to the increase in potato consumption in the region. Local restaurants, supermarkets, hospitals, colleges (which include Solwezi College of Education, Solwezi School of Nursing and Solwezi Trades), as well as boarding schools and mine kitchens are potential buyers of potato in Solwezi.

However, efforts to promote year-round production of potato among local farmers are hindered by lack of availability of adequate seed stocks at the required times. As such, initiatives are required to establish local seed-production centres for improved varieties which can easily be accessed by local farmers in order to increase production of the crop. Small-scale farmers in North-Western Province have been supplying potatoes to the mining communities who provide a ready market for the commodity. Despite the presence of a ready market, the quality of the available potatoes is poor. The tubers are normally small, have a short shelf life and are not good for chips.

With this background, Barrick Lumwana Mining Company and the Zambia Agriculture Research Institute (ZARI) are working together to introduce to farmers highly marketed improved varieties of potato, and provide them with the necessary skills in production, processing and marketing of the product. The project targets women since much of the production and marketing of potato in Solwezi is done by women. This chapter outlines some of the successes and challenges encountered so far in the implementation of a women-driven seed multiplication and distribution project.

12.2 Materials and Methods

Public–private partnership (PPP)

In 2010, a PPP was established with the goal of raising the living standards of small-scale potato farmers in the Lumwana catchment area through the use of improved potato seed. The PPP involved three major players, namely: (i) Barrick Lumwana copper mining company; (ii) ZARI; and (iii) the Department of Extension of the Ministry of Agriculture and Livestock. Funding for the project was provided by Barrick Lumwana, while ZARI and the Department of Extension provided training and technical backstopping on agronomic aspects of seed production to farmers. All partners contributed to continuous monitoring and provision of an advisory service.

Identifying target women's groups

Although the opening of mines in the area has opened employment opportunities for the male members of the communities, women, youths and old men still farm in the catchment area. The project aimed to empower women by offering them an alternative economic opportunity. The identification of the target group for this project was done through participatory rural appraisal (PRA) via focus group discussions and individual interviews with small-scale producers and traders within the catchment area. Two agricultural camps were identified in each of three chiefdoms and one women's group was selected from each agricultural camp (Fig. 12.1).

Training of target women's groups

Mobile training sessions were undertaken with the members of each of the identified women's groups. The women were given practical training which focused on various aspects of seed potato production (Fig. 12.2).

Sourcing seed of improved varieties and other agro-inputs

Improved varieties were sourced from South Africa through Buya Bamba Ltd in Lusaka. The project sourced a variety known as 'Red eye' which is normally found in the major supermarkets in Zambia and is highly desired for making French fries. Third generation pre-sprouted large-sized tubers were procured and distributed. The women's groups were also supported with other agro-inputs such as fertilizers, fungicides, insecticides and sprayers.

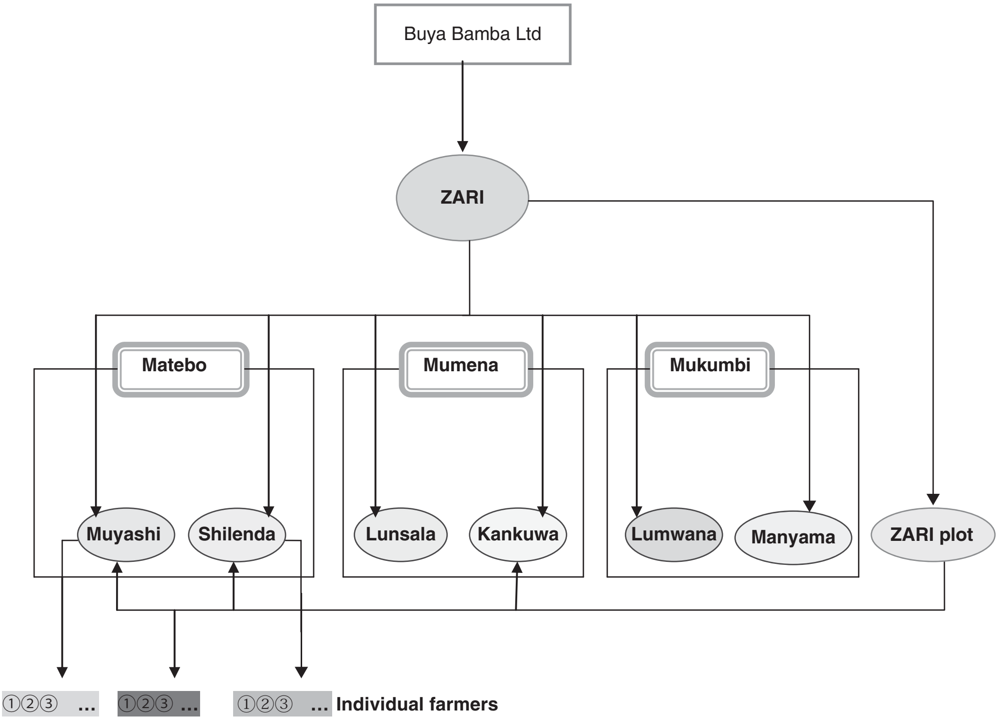

Fig. 12.1. Seed potato multiplication and distribution scheme for Lumwana potato project. Improved varieties were sourced from South Africa through Buya Bamba Ltd and were distributed to the chiefdoms (Matebo, Mumena and Mukumbi) by Zambia Agriculture Research Institute (ZARI). From each chiefdom, two agricultural camps (e.g. Muyashi and Shilenda for Matebo) were identified and from each camp a women's group was selected.

Fig. 12.2. Farmers being trained in the field.

Planting and maintenance of nurseries

Each of the six women's groups was given 75 kg of the seed to multiply during the 2011/12 rainy season. Each group planted a 22 m × 15 m plot on ridges with spacing of 80 cm between ridges and 25 cm within the ridge. Weeding was done by hand using hoes, and inorganic fertilizers were applied as recommended by Namasiku (1995).

Women's group-managed nurseries

The group members were responsible for preparing the land, planting and general maintenance of nurseries. The groups practised positive and negative selection (Gildemacher *et al.*, 2007). Routine inspections of the nurseries for diseases and pests were conducted by seed inspectors from the Seed Control and Certification Institute (SCCI) (Fig. 12.3), with a view to enable the women to produce Quality Declared Seed (QDS). After 4 months, all the seed produced by women in the group nurseries was reserved

Fig. 12.3. Plant health inspectors and farmers inspecting potato field for pests and diseases.

for distribution to individual members of the same group to plant in their own individual fields in the 2012/13 rainy season.

ZARI-managed nursery

The ZARI at Mutanda Research Station also multiplied seed in a similar way. The multiplication field was better isolated from other *Solonaceae* crops such as tomatoes and tobacco. The seed produced from ZARI nurseries was distributed to the group nurseries in order to enable the women to establish new group nurseries for the 2012/13 rainy season.

Monitoring and evaluation

Field activities were monitored by a team which included all the partners. Monitoring visits were undertaken to the multiplication fields on a monthly basis. During monitoring, discussions were held with the women's group members regarding the performances of the multiplication plots, to learn about the challenges that farmers were encountering and what improvements could be made.

Gross margin analysis

Gross margin analysis was made to determine the net returns on farmers' labour during the 4 month production period. This was done by subtracting the cost of all purchased inputs (seed, fertilizers and pesticides) from the gross income. To obtain the net monthly returns, the returns for the 4 month period were divided by four (Demo *et al.*, 2009).

Gross margin analysis was only done for two sites, namely Shilenda and Muyashi. Marketed potato yields per hectare were computed for the actual quantities of marketable-size potatoes (≥ 40 mm diameter) harvested (Demo *et al.*, 2009). From yield per hectare, the gross income per hectare was computed using the price of ZK6.00 (Zambian kwacha) per kilogram.

12.3 Results and Discussion

Effectiveness of training approach

All the farmers who had attended a Training of Trainers (TOT) course demonstrated the ability to apply the knowledge in their own individual fields correctly. Follow ups indicated that use of the TOT approach was 75% effective in transferring knowledge to the rest of the members of the women's groups. The group-managed nurseries served as field schools and information was transferred effectively through practical training of farmer to farmer. The training method proved to be cheaper and more effective than theory-based training. The farmer-field-school approach enabled women to develop the confidence and expertise through learning cycles which enabled them to make evidence-based crop management decisions with the aim of growing a healthy crop (van den Berge and Jiggins, 2006).

Effectiveness of positive selection in rain-fed potato seed multiplication

Though there were some reductions in the yield and quality of tubers with progression of seed generations (from third to fifth generation), the magnitude of the reduction was very minimal between ZARI- and group-managed nurseries at Muyashi and Shilenda. Similarly, there was only a very small reduction in the yield and quality of tubers between group-managed and individual-farmer-managed nurseries, which probably resulted from the corresponding increase in bacterial wilt and late blight in individual farmers' fields. The yields varied among individual farmers in both agricultural camps (Tables 12.1 and 12.2). The drop in tuber yield from the primary multiplication site (ZARI) to the tertiary site (farmers') indicated a significant role played by seed inspection and ZARI technical backstopping in advancing positive selection technology. Farmers were anxious to sell the potatoes, so they were harvesting progressively (piecemeal), and this contributed to the lower yields of marketable tubers in individual farmer nurseries at the end of the 4 month period. This, however, was not the case for group-managed nurseries.

Furthermore, because individual farmers were not provided with fertilizer and pesticides by the project and were expected to buy these for themselves, there is a possibility that some farmers may not have applied these inputs in the correct doses or not at all, which could also contribute to the low yields and differences observed in crop yields. Possible heterogeneity in soil fertility status and climatic conditions (data not shown) could also be another source of variation.

Regarding the extension agents, their contribution to the project was stretched and erratic since each camp officer handled many projects supported by the Ministry of Agriculture and Livestock and other non-governmental

Table 12.1. Tuber yield, gross income and returns on individual farmer's labour from the rain-fed pilot potato seed multiplication nurseries at Muyashi camp.

Farmer/group	Total tuber yield (t/ha)	Gross income[a]		Net returns on farmer's labour		Mean monthly return on farmer's labour	
		ZK	US$	ZK	US$	ZK	US$
Farmer 1	12.12	60,300.00	11,596.15	39,870.00	7,667.31	9,967.50	1,916.83
Farmer 2	10.61	48,900.00	9,403.85	28,470.00	5,475.00	7,117.50	1,368.75
Farmer 3	13.64	72,720.00	13,984.62	52,250.00	10,048.08	13,062.50	2,512.02
Farmer 4	11.21	54,900.00	10,557.69	34,470.00	6,628.85	8,617.50	1,657.21
Farmer 5	11.67	52,500.00	10,096.15	32,070.00	6,167.31	8,017.50	1,541.83
Bukwasho	15.00	72,000.00	13,846.15	51,570.00	9,917.31	12,892.50	2,479.33
ZARI	16.67	85,020.00	16,350.00	64,590.00	12,421.15	16,147.50	3,105.29
Mean	12.99	63,762.86	12,262.09	43,327.14	8,332.14	10,831.79	2083.04

[a] US$1 = ZK5.20. Purchased input costs (seed, fertilizer, pesticides) per hectare = ZK20,430.00 (US$3,928.85).

Table 12.2. Tuber yield, gross income and returns on individual farmer's and group labour from the pilot rain-fed pilot potato seed multiplication nursery at Shilenda camp.

Farmer/group	Total tuber yield (t/ha)	Gross income[a]		Net returns on farmer's labour		Mean monthly return on farmer's labour	
		ZK	US$	ZK	US$	ZK	US$
Farmer 1	10.11	48,900.00	9,403.85	28,470.00	5,475.00	7,117.50	1,368.75
Farmer 2	14.39	73,380.00	14,111.54	52,950.00	10,182.69	13,237.50	2,545.67
Farmer 3	7.56	31,260.00	6,011.54	10,830.00	2,082.69	2,707.50	520.67
Farmer 4	18.18	87,900.00	16,903.85	67,470.00	12,975.00	16,867.50	3,243.75
Farmer 5	7.56	31,680.00	6,092.31	11,250.00	2,163.46	2,812.50	540.87
Lukusa nkunde	14.5	69,900.00	13,442.31	49,470.00	9,513.46	12,367.50	2,378.37
ZARI	18.03	86,520.00	16,638.46	66,090.00	12,709.62	16,522.50	3,177.40
Mean	12.90	61,362.86	11,800.55	40,932.86	7,871.70	10,233.22	1,967.93

[a] US$1 = ZK5.20. Purchased input costs (seed, fertilizer, pesticides) per hectare = ZK20,430.00 (US$3,928.85).

organizations (NGOs). There is need to assign a full-time field-based supervisor who should be fully dedicated to the project to ensure that camp officers, who are paid allowances on a monthly basis by Barrick Lumwana Mining Company, are able to visit and provide advisory services to farmers as planned. Generally, the findings suggest that the current seed system is quite efficient but requires strengthening of the extension service to ensure affordable production of quality seed and increased yields.

Incidence of late blight and bacterial wilt

There were differences in the occurrence of the diseases at the six different sites (Fig. 12.4). Manyama and Lunsala had the highest incidence of late blight (65% and 55%, respectively), which could not be controlled by spraying with Dithane M-45. On the other hand, Muyashi and Shilenda recorded the least incidences of late blight (5% and 8%, respectively). Symptoms of bacterial wilt were also observed at all the sites, with Manyama and Luwana East recording the highest incidence of 35% and 30%, respectively, while less than 5% incidence of bacterial wilt was recorded at Shilenda, Muyashi and the ZARI station. Due to high disease incidence at Manyama and Lumwana East, the seed nurseries at these sites failed the inspection tests and were condemned. However, soil and water analyses were not performed to ascertain the source of the bacterial wilt inoculum.

Gross margin analysis shows that Bukwasho, Lukusa nkunde, Kankuwa and Lunsala women's groups had positive returns for their labour (Table 12.3), while Manyama and Lumwana East women's groups had negative returns on their labour (Bukwasho women's group is in the Muyashi camp and Lukusa nkunde women's group is in Shilenda camp). Bukwasho and Lukusa nkunde women's groups had the highest positive mean monthly return of ZK15,352.50 (US$2952.40), and ZK11,932.5 (US$2294.71), respectively.

The women at Muyashi have a longer history of growing potato in the catchment area and are therefore more experienced than their counterparts in the other women's groups. However, like other women's groups, Bukwasho women require skills on how to store seed potato tubers. Considerable losses were incurred in storage which further reduced the quantity of seed at the beginning of the next rainy season. Potato

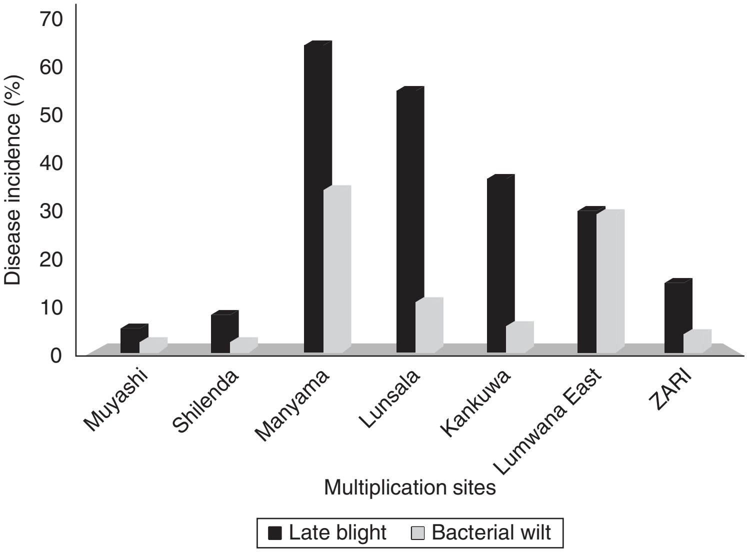

Fig. 12.4. Incidence of bacterial wilt and late blight in potato seed multiplication plots at Solwezi.

Table 12.3. Tuber yield, gross income and returns on labour of farmer groups from the pilot rain-fed potato seed multiplication nurseries managed by women's groups in Solwezi District, Zambia.

Group	Total tuber yield (t/ha)	Gross income[a]		Net returns on farmer's labour		Mean monthly return on farmer's labour	
		ZK	US$	ZK	US$	ZK	US$
Bukwasho	18.18	81,840.00	15,738.46	61,410.00	11,809.62	15,352.5	2,952.40
Lukusa nkunde	15.15	68,160.00	13,107.69	47,730.00	9,178.85	11,932.5	2,294.71
Manyama	1.52	7,320.00	1,407.69	–13,110.00	–2,521.15	–3,277.5	–630.29
Lumwana East	3.03	14,520.00	2,792.31	–5,910.00	–1,136.54	–1,477.5	–284.13
Kankuwa	6.06	27,240.00	5,238.46	6,810.00	1,309.62	1,702.5	327.40
Lunsala	9.09	46,380.00	8,919.23	25,950.00	4,990.38	6,487.5	1,247.60
ZARI	21.21	88,860.00	17,088.46	68,430.00	13,159.62	17,107.5	3,289.90
Mean	10.61	47,760.00	9,184.62	27,330.00	5,255.77	6,832.5	1,313.94

[a] US$1 = ZK5.20. Purchased input costs (seed, fertilizer, pesticides) per hectare = ZK20,430.00 (US$3,928.85).

requires good field management in terms of weeding, frequent field inspection and rouging of infected plants. The high incidence of late blight and bacterial wilt contributed to the lower yields at Manyama, Lumwana East and Kankuwa (Table 12.3) as compared with Muyashi and Shilenda (Fig. 12.4).

Ultimately, the results indicate that small-scale production of potatoes in Lumwana catchment area is a feasible and highly profitable venture which has the potential to reduce poverty among women. The returns on farmers' labour, US$24.60 (ZK127.92) and US$19.12 (ZK99.45)/day obtained from growing 0.25 ha of potatoes by Lukusa nkunde and Bukwasho women's groups, respectively, can enable women to live far above the daily poverty datum line of US$1.00/day (Demo *et al.*, 2009).

The two groups, managed to produce and distribute QDS to their members in the next rainy season. The yields varied among farmers, ranging from 8.15 t/ha to 12.12 t/ha. Some of the individual farmer-managed nurseries yielded more tubers than the group-managed nurseries, and vice versa. The ZARI-managed nursery had the highest yield of all (Table 12.3).

However, all the five farmers of Bukwasho women's group had monthly positive returns on their labour, which ranged between US$1500 and US$2500 expected from 1 ha of seed potato. The best return on farmer's labour was US$2512.02/ha which translates into a daily net return of US$83.73 (ZK435.42). Therefore, by growing 0.25 ha of seed potato, which seems to be currently manageable for women in Zambia, a farmer would expect a daily net return of US$20.93 (ZK108.85) on labour.

The returns on individual farmers' labour were highly positive for members of Lukusa nkunde women's group (Table 12.2).

The best farmer had monthly returns of US$3243.75 on labour, translating into daily returns of US$108.12 (ZK562.25)/ha, implying that by growing 0.25 ha of seed potato such a farmer in Shilenda would expect a return of US$27.03 (ZK140.56) on labour. This suggests that, either by working individually or as a group, women can still improve their livelihood by growing potatoes in the Lumwana catchment area. However, the group-managed nursery served as a field school for group members and should be promoted alongside individual farmer plots.

Challenges

In the absence of improved irrigation facilities, establishment and maintenance of off-season potato nurseries proved to be very challenging. Watering by hand using a watering can is a very burdensome and labour-tasking activity which limits expansion of production fields by small-scale potato farmers. This makes off-season farming more expensive than rain-fed production of potatoes for small-scale farmers. Worse still, the quality of water from streams or rivers can be very difficult to control and especially when it gets contaminated/infected with *Ralstonia solanacearum*.

The high market demand for potato against low production in the catchment area has prompted small-scale traders to import potatoes from Tanzania across the Tunduma/ Nakonde border into the catchment area and many parts of the country. This uncontrolled movement of planting materials is likely to contribute to the spread of plant diseases, such as late blight (*Phytophthora infestans*), bacterial wilt (*R. solanacearum*) and viruses. Poor knowledge of farmers on the control of such diseases constituted a major challenge.

Lack of high yielding varieties suitable for different end uses is another limitation to increased productivity. Availability of a variety of our choice is not guaranteed at Buya Bamba Ltd at the time that small-scale farmers need it. The primary interest of this supplier is to respond to the cooperative members' demands in terms of seed, while supplies to other buyers are only made on request and are given a secondary consideration. Seed is the most expensive input for potato production. Efforts to support establishment of local seed-production schemes in Solwezi would help to reduce the cost of seed. Storage of locally produced seed constituted another serious challenge for small-scale producers and it needs urgent attention.

12.4 Recommendations

First, there is need for ZARI to develop a collection of potato germplasm comprising local and introduced accessions to support potato variety development. This is an essential step towards strengthening the national breeding programme to produce varieties with resistance to late blight, bacterial wilt and viruses and that are adaptable to local farming conditions.

Secondly, interventions through provision of a labour-saving irrigation scheme in Muyashi and Shilenda such as sinking boreholes and providing women's groups or individual potato farmers with solar-operated water pumps could make year-round farming possible, boost potato production and contribute to poverty reduction.

Finally, promising individual farmers should be identified and supported to take up seed potato production as a business in addition to introduction of improved infrastructures such as the low-cost diffused light storage (DLS) of seed potato tubers to reduce postharvest losses and ensure proper sprouting of seed potato. This technology has proved successful in Malawi and Mozambique (Paul Demo, International Potato Center, Citedze Research Station, 2013, personal communication).

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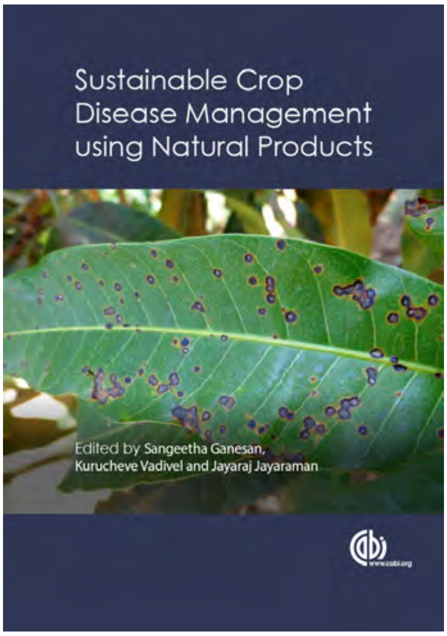

Sustainable Crop Disease Management using Natural Products

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9 Role of Natural Products in Disease Management of Rice

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9.1 Introduction

Rice plays an important role in ensuring the food security of India. It has great importance in Indian culture and from birth to death its existence always prevails. Almost half of the world's population consumes rice as a staple food. India contributes 21.5% of global rice production. Within the country, rice occupies one-quarter of the total cropped area and contributes about 40–43% of total food grain production. The major rice-producing states in India are West Bengal, Andhra Pradesh and Uttar Pradesh (Shobha Rani *et al*., 2010). With the advent of significant progress in the areas of agricultural research, extension, education and other infrastructural facilities, there has been a corresponding increase in rice production in India. At the same time the adoption of improved technologies such as high yielding varieties by the average farmer is very low. Among various biotic stresses, rice diseases cause huge losses and the annual losses vary from 10–15% on average across the world (Prasanna Kumar *et al*., 2013).

Rice diseases caused by various pathogens appear to be proliferating at ever-increasing rates. Owing to apparent changes in climatic conditions and changes in varietal composition and cultivation practices in a particular region, the profile of diseases occurring on rice has changed over time. Many diseases earlier considered as minor have become threatening (Laha *et al*., 2009). More than 70 diseases have been reported to occur on rice. Of these, bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae*), blast (*Magnaporthe grisea*; anamorph: *Pyricularia grisea*), sheath blight (*Rhizoctonia solani* Kuhn; teleomorph: *Thanetophorus cucumeris* (Frank) Donk), rice tungro (rice tungro spherical virus, RTSV; rice tungro bacilliform virus, RTBV) and false smut (*Ustilaginoidea virens*) are the major diseases and cause substantial quantitative and qualitative losses especially in endemic areas. In addition, foot rot or bakanae (*Fusarium moniliforme*; teleomorph: *Gibberella fujikuroi*), sheath rot (*Sarocladium oryzae*), brown spot (*Helminthosporium oryzae*; synonym: *Drechslera oryzae*; teleomorph: *Cochliobolus miyabeanus*), stem rot (*Sclerotium oryzae*) and postharvest diseases have increased in importance in different parts of the country (Sharma and Bambawale, 2008; Singh, 2012). Unexpected diseases such as udbatta (*Ephelis oryzae*), glume discoloration (*Drechslera oryzae*, *Sarocladium oryzae*, *Alternaria padwickii*, *Curvularia* spp., *Epicoccum* sp., *Fusarium moniliforme*), Leaf scald (*Rhynchosporium oryzae*) and kernel smut (*Tilletia barclayana*) are projected to become

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more important as location-specific diseases, and are becoming serious problems where they were previously insignificant.

Despite the progress recently achieved by using chemical pesticides and host plant resistance under pest control strategies, even today pests and diseases are increasingly serious problems in crop production. Owing to lack of proper knowledge about pest control measures, farmers tend to use pesticides indiscriminately to manage pest problems. Due to overuse of chemical pesticides, pesticide-resistant strains have developed in the pest populations, thereby newer pesticide molecules have become less effective and have an adverse effect on the environment. These circumstances necessitate the search for certain alternative approaches, which should be locally produced, easily available, ecofriendly and inexpensive for major portions of the farming community in India. At this stage, such alternatives appear to be prepared from naturally available plant products, which are known to be easily recyclable and to express lower mammalian toxicity than synthetic substances. Therefore, sincere attempts have been made to extract the alkaloids present in some plants that have antifungal properties enabling resistance to pathogens. Many researchers have discovered the antifungal activities of various plant species and have shown the significance of plants as promising sources of natural fungicides. In this review an attempt has been made to bring together the information generated by various workers worldwide on the possibilities of using naturally available plant products as potential fungicides in combatting rice diseases.

9.2 Blast

Blast disease is aptly named bearing in mind the damage it causes. It is caused by *Magnaporthe grisea* (anamorph: *Pyricularia oryzae*), which is distributed worldwide and occurs in more than 85 countries. It is known to appear at three stages of crop growth (on the leaf, node and neck) causing heavy to total loss in yield. The yield loss due to this disease may be as high as 75% or more (Ou, 1985; Srinivas Prasad *et al.*, 2011).

As an alternative to chemicals used for control of paddy blast, which cause health hazards and environmental pollution, several workers have examined the antifungal nature of different plant species (Table 9.1). Rajeswari (1995) observed 57% reduction in percentage of disease incidence compared with a control by leaf extracts of *Adathoda vasica*, which contained maximum tannin (28.3 mg). Kamalakannan *et al.* (2001) revealed that the leaf extract of *Prosophis juliflora* and *Zizyphus jujube*, which contain higher levels of proteins, glycoproteins, total phenol and tannin, had a greater antifungal effect on the blast pathogen and drastically reduced the disease incidence under glasshouse conditions. Similarly, methanol extracts of fresh materials of 57 plants were tested for *in vivo* antifungal properties on *Magnaporthe grisea* (Choi *et al.*, 2004). The methanol extracts of *Chloranthus japonicus* (roots) and *Paulownia coreana* (stems) displayed the highest antifungal activity; stem extracts of *P. coreana* and also root extracts of *C. japonicas* had a therapeutic activity against the blast pathogen. Plant extracts such as garlic juice (Punja, 2005; Slusarenko *et al.*, 2008) contain allicin, a chemical compound obtained from garlic that has successfully reduced blast infection. Fiona *et al.* (2005) also obtained similar results whereby allicin effectively checked the infectivity and development of the pathogen. Water and ethanol leaf extracts and oil extract of neem seed (Amadioha, 2000) reduced the mycelia growth, development and spread of *Magnaporthe oryzae* under *in vitro* and field conditions. Similarly, Rajappan *et al.*, 2001 reported the potential role of neem oil in reducing the grain discoloration of rice. Other successful findings revealed the presence of fungitoxic substances in the neem extracts and their fungitoxic properties against rice pathogens (Annapurna *et al.*, 1983; Qasem and Abu-Blan, 1996). Neem contains nimbicidin or azadirachtin, which has antifungal properties. In other studies, Sireesha and Venkateswarlu (2013) reported that neem seed kernel extract followed by neem oil, *Pongamia*, panchagavya (mixture of fresh cow dung, cow urine, cow milk, cow curd and cow ghee) and Asafoetida (*Ferula asafoetida)* significantly suppressed fungal growth as well as spore germination. Application of silicon sources like burnt rice husk and organic manure (animal dung + chopped paddy straw 1:1) at a concentration of 10 t ha^{-1} before transplanting and foliar spray of sodium metasilicate at a concentration of 1 kg ha^{-1} reduced neck blast incidence

Table 9.1. Fungicidal activity of plant products tested against blast disease of rice.

Common name	Scientific name	Plant part; formulation/ dosage	Activity/action	Reference
Hitori-sizuka (Japanese)	*Chloranthus japonicas*	Roots, stem (crude extract)	Antifungal and curative	Choi *et al.* (2004)
Phoenix tree	*Paulownia coreana*	Roots, stem (crude extract)	Antifungal and curative	Choi *et al.* (2004)
Garlic	*Allium sativum* L.	Garlic (bulb) juice	Reduced fungal infection and mycelial growth	Punja (2005); Fiona *et al.* (2005) Slusarenko *et al.* (2008); Hajano *et al.* (2012); Amadioha (2000)
Neem	*Azadirachta indica* L.	Leaf extract	Inhibited mycelial growth	Hajano *et al.* (2012); Amadioha (2000); Rajappan *et al.* (2001); Annapurna *et al.* (1983)
		Neem seed kernel extract	Suppressed mycelial growth and spore germination	Sireesha and Venkateswarlu (2013); Kamalakannan *et al.* (2001)
		Neem oil	Suppressed mycelial growth and spore germination	Sireesha and Venkateswarlu (2013); Kamalakannan *et al.* (2001)
Calotropis	*Calotropis procera* L.	Leaf extracts	Inhibited mycelial growth	Hajano *et al.* (2012)
Giant Angelica	*Angelica gigas*	Root crude extracts	Inhibited spore germination; Prohibited the spread of the disease	Yoon *et al.* (2011)
Pongam oil tree	*Pongamia pinnata*	Kernel extract	Inhibited mycelial growth	Sireesha and Venkateswarlu (2013)
Asafoetida	*Ferula asafoetida*	Essential oil	Antifungal	Sireesha and Venkateswarlu (2013)
Holy basil/tusli	*Ocimum sanctum* L.	Essential oil	Fungitoxic	Tewari (1995)
		Oscilene-e, a formulated product	Inhibited conidial germination and mycelial growth	Upadhyaya and Tiwari (2013)
Adhatoda, vasa or vasaka	*Adathoda vasica*	Leaf extracts	Reduced disease incidence	Rajeswari (1995)

by 37–57% under low to moderate disease pressure (Dodan *et al*., 2007). Oscilene-e, a formulated product, was developed by combining ethanolic extract (EE) of *Ocimum sanctum* L. with a coded surfactant, A+ (FA) and was bioassayed under *in vitro* conditions against rice blast pathogen (Upadhyaya and Tewari, 2013). This formulated product has not only been found to inhibit conidial germination and mycelial growth, but also produced distortion patterns such as reduced and granulated germ tube and/or granulation of conidial cytoplasm, resulting in reduced mycelial growth.

9.3 Sheath Blight

Sheath blight disease of rice is caused by the fungal pathogen *R. solani* Kuhn (teleomorph: *Thanetophorus cucumeris* (Frank) Donk). The disease is widely prevalent but seldom emerges to the extent of creating epidemics in rice-growing areas of the world. It can lead to huge losses in rice yields (Gautham *et al*., 2003; Prakasam *et al*., 2013).

Recently, the exploitation of plant products to act against the sheath blight organism is gaining in importance. Different plant extracts have been tested by various workers (Table 9.2) and, among them, neem formulations are very effective in managing sheath blight. Kandhari and Devakumar (2003) reported that neem oil and its stabilized formulations were very effective in reducing disease incidence.

Biswas (2006) studied the effectiveness of neem-based botanicals such as Achook and Tricure on sheath blight fungus. Furthermore, Biswas (2007) reported that field application of neem products, 0.03% (300 ppm azadirachtin) and 0.15% EC (1500 ppm azadirachtin) at a concentration of 4.5 ml l^{-1} during the afternoon hours was very successful in minimizing disease incidence and also in increasing grain yields.

Bulb extracts of garlic at 5% concentration (w/v) completely restricted the mycelial growth of the sheath blight pathogen of rice (Meena and Muthusamy, 1998). The antifungal properties of 44 plant extracts and eight plant oils against *R. solani* were studied by Sehajpal *et al*. (2009). Among them *Allium sativum* proved to express strong fungitoxicity even at the lowest concentration, that is, 100 ppm. Similarly, among the oil samples tested, *Syzygium aromaticum* oil exhibited more inhibition at lower concentrations.

Naidu and John (1981) noticed that *Parthenium hysterophorus* leaf extract restricted the growth of *R. solani*. Furthermore, plant extracts such as *Odiyana wodier*, *Lawsonia alba*, *Ocimum sanctum* and *Pongamia glabra* were known to be effective in inhibiting both mycelial development and sporulation of *R. solani* under *in vitro* conditions. Similarly, field studies with *O. wodier* and *O. sanctum* were very effective (26% and 28% sheath blight severity) compared with the control (42%) (Karthikeyan and Chandrasekaran, 2007).

Other useful plant extracts against *R. solani* consist of *A. sativum*, *Prosopis juliflora*, *Gynandropsis pentaphylla*, *Leucos aspera* and *Vitex negundo* (Sundarraj *et al*., 1996). Shylaja and Ranakausar (1997) reported that the leaf extracts of *Clerodendron viscosum*, *Lantana camara*, panchagavya and *V. negundo* were highly inhibitory to both fungal growth and formation of sclerotia of *R. solani*. Similarly, it was noticed that palmarosa oil (at 0.05 and 0.1% concentrations) efficiently restricted the mycelial growth and sclerotial production of *R. solani* (Meena and Muthusamy, 1998). Leaf extract of *Pithecellobium dulce* was highly effective in inhibiting mycelial growth of *R. solani* (2.5 cm compared with 8.9 cm in the control). Meena *et al*. (2002) revealed that leaf extracts of *P. dulce* and *Prosopis juliflora* were uniformly efficient in reducing the number of sclerotia, dry weight and spore germination. Gautham *et al*. (2003) evaluated 24 botanicals belonging to family Compositae (Asteraceae) *in vitro* to assess their fungitoxicity against *R. solani*.

9.4 Sheath Rot

Sheath rot caused by *Sarodadium oryzae* (Sawada) W. Gams & D. Hawksw is reported to be seed borne and present in almost all paddy-growing regions of the world. In India, the disease has become widespread in Andhra Pradesh, Kerala, Orissa, Tamil Nadu, Bihar, West Bengal and North Eastern States, causing significant losses in yield (Singh and Dodan, 1995; Laha and Muthuraman 2009). The degree of grain yield

Table 9.2. Fungicidal activity of plant products tested against sheath blight disease of rice.

Common name	Scientific name	Plant part; formulation/ dosage	Activity/action	Reference
Neem/margosa	*Azadirachta indica*	Leaf – achook formulations (azadirachtina), neem oil	Fungitoxic, reduced fungal infection	Kandhari and Devakumar (2003); Kandhari (2007)
		Achook and tricure (neem-based formulations)	Reduced disease incidence	Biswas (2006, 2007)
Hitori-sizuka (Japanese)	*Chloranthus japonicas*	Roots, stem (crude extract)	Antifungal and curative	Choi *et al.* (2004)
Phoenix tree	*Paulownia coreana*	Roots, stem (crude extracts)	Antifungal and curative	Choi *et al.* (2004)
Garlic	*Allium sativum*	Bulb extracts at 5% concentration (w/v)	Fungitoxic effect, inhibited mycelial growth	Sundarraj *et al.* (1996); Meena *et al.* (1998); Sehajpal *et al.* (2009)
Clove	*Syzygium aromaticum*	Oil extracts	Inhibited mycelial growth	Sehajpal *et al.* (2009)
Congress grass or gajar ghans	*Parthenium hysterophorus*	Leaf extracts	Inhibited fungal growth	Naidu and John (1981)
Holy basil/tusli	*Ocimum sanctum*	Leaf/plant extracts	Reduced mycelial growth and inhibited sporulation	Karthikeyan and Chandrasekaran (2007)
Pongam tree/Indian beech tree	*Pongamia glabra*	Leaf/plant extracts	Reduced mycelial growth and sporulation	Karthikeyan and Chandrasekaran (2007)
Henna	*Lawsonia alba*	Leaf/plant extracts	Reduced disease severity	Karthikeyan and Chandrasekaran (2007)
Chaste tree	*Vitex negundo*	Leaf/plant extracts	Inhibited both fungal growth and production of sclerotia	Sundarraj *et al.* (1996); Shylaja and Ranakausar (1997)
Thumbai	*Leucos aspera*	Leaf/plant extracts	Inhibited both mycelial growth and sclerotial production	Sundarraj *et al.* (1996)
Hill glory bower	*Clerodendrum infortunatum*	Leaf/plant extracts	Inhibited mycelial growth and reduced the number of sclerotia	Shylaja and Ranakausar (1997)
Palmarosa	*Cymbopogon martinii*	Oil at 0.05% and 0.1% concentrations	Inhibited mycelial growth and sclerotial production	Meena and Muthusamy (1998)
Manilla tamarind	*Pithecellobium dulce*	Leaf extracts	Inhibited mycelial growth, sclerotial number	Meena *et al.* (2002)

loss due to sheath rot may be approximately 50% or more. A severe outbreak of sheath rot occurred in Punjab during the wet season of 1978–1979, where there were reports of heavy yield loss (Raina and Singh, 1980). The disease appears during heading to maturity stages and the pathogen generally attacks the uppermost leaf sheath enclosing the young panicles. If the pathogen attacks after the panicle emergence, the grains may be partially or completely filled and there is glume discoloration.

Mariappan *et al.* (1995) reported that sheath rot fungus of rice was successfully controlled by using neem oil and neem seed kernel extracts. Neem and Pungam oil-based EC formulations formulated by Tamil Nadu Agricultural University have successfully controlled sheath rot under field conditions (Narasimhan *et al.*, 1998). The foliar application of neem seed kernel extract (5%) alone and combined with basal application of neem cake (150 kg ha^{-1}) was shown to be as effective as the recommended fungicide carbendazim in managing the disease (Singh and Dodan, 1995). Similarly, crude leaf extracts of *Cuscuta*, neem and bael (*Aegle marmelos*) provided about 40% disease control compared with 75% by propiconazole. A variety of plant extracts, namely, *Eugenia caryophyllata* and *Eucalyptus globules*, was recorded to have effective fungicidal properties in checking the growth of the fungus, biomass production and also spore germination under *in vitro* conditions (Meera and Balabaskar, 2012).

9.5 Brown Spot

Brown spot of rice caused by *Bipolaris oryzae* Breda de Hann (formerly *Helminthosporium oryzae*) (teleomorph: *Cochliobolus miyabeanus*), is documented as a significant limiting factor in rice production in all rice-growing regions of the world, particularly under semi-dry situations (Ou, 1985). The disease was more significant and made history during the 'Great Bengal Famine' in 1942–1943 in India. The range of reported yield losses due to brown spot, often expressed in relative terms, is variable from 26% to 50% (Padmanabhan, 1973; Chakrabarti, 2001). The disease occurs more or less every year in mild to severe form in many upland and rain-fed lowland rice-growing areas. Besides causing brown spot on the leaves, the fungus is also responsible for grain discoloration, which is another important setback in several paddy-growing areas.

The exploitation of natural products for the control of brown spot in rice has attained greater significance over the past 20 years (Table 9.3). Chelven and Sumathi (1994) observed the inhibitory effect of *Solanum nigrum* a steroid, which is inhibitory to the mycelial growth of *B. oryzae*. Later, Vijayakumar (1998) reported that application of neem oil (3%) + neem cake (150 kg ha^{-1}) effectively reduced brown spot of rice both in pot culture and the field. The oleandrin toxin present in *Nerium oleander* is a cardiac glycoside and this might be responsible for the antimicrobial activity. In another experiment, around 50 plant extracts and four oil cakes were tested for their efficacy against brown spot both under *in vitro* and in field conditions. The results indicated that leaf extracts of *N. oleander* and *P. dulce* exhibited more percentage inhibition of fungal growth and reduced spore germination. Among the four oil cake extracts tested, neem cake extract exhibited the maximum inhibition percentage of mycelial growth and spore germination. Glasshouse studies confirmed that postinfectional application of rice plants with neem cake extract, *N. oleander* leaf extract was effective in reducing the incidence of brown spot. Two sprays of neem cake extract and *N. oleander* leaf extract at initial appearance of the disease reduced the incidence of brown spot and increased the yield, respectively (Harish *et al.*, 2008). Devi and Chhetry (2013) noticed the antifungal activity of leaf and rhizome extracts of a locally available plant (*Acorus calamus*) in reducing mycelial growth and disease spread of brown spot.

9.6 False Smut

False smut of rice caused by *Ustilaginoidea virens* (Cooke) Takahashi (teleomorph: *Claviceps oryzae-sativae* Hashioka) is one of the emerging grain diseases and has potential to cause severe losses in rice (Dodan and Singh, 1996; Ladhalakshmi, 2012). The disease causes both

Table 9.3. Fungicidal activity of botanicals tested against brown spot of rice.

Common name	Scientific name	Plant part; formulation/ dosage	Activity/action	Reference
Neem	*Azadirachta indica*	Neem cake and neem oil cake	Inhibited mycelial growth and spore germination	Harish *et al.* (2008)
Gingelly	*Sesamum indicum*	Oil cake	Inhibited mycelial growth and spore germination	Harish *et al.* (2008)
Castor	*Ricinus communis*	Oil cake	Inhibited mycelial growth and spore germination	Harish *et al.* (2008)
Mahua	*Bassia latifolia*	Oil cake	Inhibited mycelial growth and spore germination	Harish *et al.* (2008)
Henna	*Lawsonia inermis*	Leaf extracts		Natarajan and Lalithakumari (1987)
Oleander	*Nerium oleander*	Leaf extracts	Inhibited mycelial growth and spore germination	Harish *et al.* (2008)
Madras thorn	*Pithecolobium dulce*	Leaf extracts	Inhibited mycelial growth and spore germination	Harish *et al.* (2008)
Crimson bottlebrush	*Callistemon citrinus*	Essential oils and solvent extracts	Reduced radial growth of fungus	Nguefack *et al.* (2013)
Calamus or bitter pepper root	*Acorus calamus*	Aqueous extracts of leaves and rhizomes	Inhibited mycelial growth and reduced the spread of the incidence	Devi and Chhetry (2013)

quantitative and qualitative losses. Normally, this disease appears more in upland than in lowland rice areas. It is well understood that whenever a spell of wet weather coincides with the heading time, false smut disease appears. Information on the use of plant extracts or botanical products for controlling the disease is very scanty and most of the research work in this potential area has not been conclusive.

9.7 Bakanae or Foot Rot

In India, bakanae or foot rot disease is caused by the fungus *Fusarium moniliforme* (teleomorph: *Gibberella fujikuroi*), which is known to cause severe damage in the states of Tamil Nadu, Andhra Pradesh, eastern districts of Uttar Pradesh and in Haryana. Neem oil and extracts of onion, garlic and tobacco have been reported to inhibit the conidial production, conidial germination and fungal growth of bakanae (Singh and Sunder, 1997). Out of 55 angiospermic plants examined for their fungitoxic properties against *Fusarium*, about 17 plants exhibited varied levels of inhibitory effects (Yasmin *et al.*, 2008). They reported that *Lawsonia inermis* leaf extracts showed the maximum inhibition followed by roots extracts of *Asparagus racemosus*. For the first time the antifungal properties of leaves of *Andrographis paniculata* and *Lagerstroemia speciosa* were demonstrated against bakanae disease. Manandhar and Yami (2008) reported that out of four fermented products of compost and vermicompost teas tested, the maximum reduction in disease incidence was obtained from aerated vermicompost tea. This was achieved by increasing the percentage germination of the seeds. In fact, very few reports have indicated the inhibitory effect of plant extracts against bakanae. Thus, it is necessary to find out the plant that has antifungal activity against *F. moniliforme.*

9.8 Stem Rot

Stem rot disease of rice is caused by the fungus *Sclerotium oryzae* Catt. (perfect state: *Magnaporthe salvinni* Catt.). The disease is most destructive under favourable environmetal conditions in all rice-growing regions of the world. Kumar (2003) reported that the disease contributes to rice yield losses to the tune of 75%. The disease is prevalent in India in states like Haryana, Bihar, Uttaranchal and Andhra Pradesh. The first symptoms can be seen after the mid-tillering stage in the field and symptoms appear as a small, blackish, irregular lesion on the outer leaf sheath near the water line. When the fungus penetrates into the inner leaf sheaths it causes rotting and infection of the culm, which may result in lodging, unfilled panicles, chalky grains, and tillers may die under severe conditions.

Information on the utilization of botanical products that are known to have antifungal properties in checking stem rot fungal growth is very meagre. Antifungal characteristics of *Ocimum sanctum* L. were studied by Jalal and Ghaffar (1992) and revealed that its leaf extract completely reduced the growth of *Sclerotium rolfsii* and also other fungi. Similarly in another study, 15 medicinal plants were screened for their antifungal and phytochemical properties against *S. oryzae* (Venkateswarlu *et al.*, 2013). The medicinal plants are: *Andrographis paniculata, Calotropis procera, Pongamia glabra, Azadirachta indica, Terminalia alata, Cassia montana, Cissampelos pareira, Leucas aspera, Vitex leucoxylon, Caesalpinia pulcherrima, Datura stramonium, Aristolochia indica, Rinchosia beddomi, Phyla arvencis* and *Eukaliptas globules.* The screening results revealed the presence of saponins, steroids, tannins, glycosides, alkaloids and flavonoids in these 15 plants and the compounds also have antimicrobial properties.

9.9 Bacterial Leaf Blight

Bacterial leaf blight (BLB), caused by *Xanthomonas campestris* pv. *oryzae*, shot into prominence after the introduction of nitrogen responsive, high yielding variety TN1 rice, in the mid-1960s. The disease may incur severe crop losses of up to 50% depending on the stage of the crop, degree of cultivar susceptibility and, to a great extent, the conduciveness of the environment in which it occurs (Gnanamanickam *et al.*, 1999; Laha *et al.*, 2009). Severe epidemics were recorded in 1979 and 1980 in north-western India, reducing the grain yields drastically.

Attempts have been made by several researchers to manage bacterial blight using plant extracts, botanical formulations, antibiotics, fungicides and resistance-inducing chemicals (Table 9.4). Seed treatment with *Adathoda vasica* leaf extract significantly reduced the bacteria, by inducing the activation of defence enzyme accumulation, which can be associated with induction of resistance against rice BLB (Govindappa *et al.*, 2011). Six plant extracts from different solvent systems were tested for their antibacterial activity against *Xanthomonas oryzae* pv. *oryzae* both *in vitro* and *in vivo*. Among these extracts, *Cocculus hirsutus* leaf chloroform extract exhibited significant antibacterial activity against BLB (Umesha and Sateesh, 2013). Indigenous medicinal plants possessing antibacterial properties that could be used as substitutes for bactericides in managing BLB were investigated by Jabeen (2011). The *Terminalia chebula* decoction proved to be the best and showed its effectiveness in limiting BLB both under *in vivo* and *in vitro* conditions. Leaf extracts of *Datura metel* considerably reduced the growth of BLB pathogen under *in vitro* conditions (Kagale *et al.*, 2004). Arun Kumar and Rengasamy (2000) demonstrated that the saponified and unsaponified fractions of brown and green seaweed were found to be efficient in combatting the bacterial blight of rice.

9.10 Rice Tungro Virus

Among the viral diseases that affect rice, tungro disease is widely prevalent, particularly in the north-eastern and east coastal region of peninsular India (Muralidharan *et al.*, 2003; Krishnaveni

Table 9.4. Bactericidal activity of plant products tested against bacterial leaf blight of rice.

Common name	Scientific name	Plant part; formulation/ dosage	Reference
Neem	*Azadirachta indica*	Leaf, seed in the form of achook, neemazal	Sunder *et al.* (2005)
Malabar nut tree	*Adathoda vasica*	Leaf extracts	Govindappa *et al.* (2011)
Lantana	*Lantana camera*	Leaf extracts	Govindappa *et al.* (2011)
Onion	*Allium sativum*	Bulb extracts	Govindappa *et al.* (2011)
Broom creeper	*Cocculus hirsutus*	Leaf chloroform extract	Umesha and Sateesh (2013)
Black myrabolan	*Terminalia chebula*	Fruits (methanolic extracts)	Rukhsana (2011)
Datura or devil's weed	*Datura metel*	Leaf extracts	Kagale *et al.* (2004)
Seaweeds	*Sargassum wightii*, *Enteromorpha flexuosa*	Whole plant	Lourdu (1998)

et al., 2009). Rice tungro is a composite disease caused by a bacilliform DNA para retro virus (RTBV) and a spherical RNA plant picorna virus (RTSV). The disease can occur at any stage from nursery onwards. The disease spread depends upon the availability of virus infected plants, the green leafhopper population and the susceptibility of the variety.

The use of natural plant products against tungro virus disease (RTD) and its vector have been tested under glasshouse and field conditions by different workers. In glasshouse conditions, different oil formulations were tested, among which neem oil 60 EC (3%) and a combination of neem oil 60 EC with pungam oil 60 EC (3%) were more efficient in minimizing the disease incidence as well as in boosting the growth of infected plants (Muthamilan and Revathy, 2007). Similarly under field conditions, leaf extracts of *Vitex negundo* L., *Synadenium grantii* Hook. F. and *P. juliflora* (SW) and cake of *A. indica*, A. Juss. were evaluated for their efficacy against green leafhoppers and their transmission of RTV (Rajappan *et al.*, 2000). Though all the products reduced the green leafhopper population significantly, the lowest population was recorded with application of neem cake at a concentration of 5 kg 0.032 ha^{-1} of nursery followed by foliar spray of neem seed kernel extract at 5% in the field. Similar studies have been attempted by many workers and details of the products used are given in Table 9.5.

9.11 Glume Discoloration

Rice grains may be infected by various organisms before or after harvest, causing discoloration. The discoloration may appear externally on the glumes or internally on the kernals, or both. The organisms associated with grain discoloration are *Cochiliobolus miyabeanus*, *Drechslera oryzae* and *Alternaria padwickii*, *Gibberalla fujikuroi*, *Nigrospora* spp., *Epicoccum* spp., *Curvularia* spp. and *Phoma* sp. These microorganisms have various effects on the grains.

Deterioration of stored seeds and grains caused by a variety of fungi is a persistent problem in the Indian storage system because of the prevailing tropical hot and humid climatic situations. Application of synthetic fungicides is not allowed or is restricted because of the residue problem and associated health risks to consumers. The available literature makes a convincing case that there is immense scope for plant-derived fungicidal compounds that act as grain protectants. Reddy *et al.* (2009) revealed that the use of botanicals and biocontrol agents are effective for the reduction of aflatoxin B_1 (AFB1) in stored rice. Among the plant extracts tested, *Syzigium aromaticum* (5 g kg^{-1}) showed complete inhibition of *A. flavus* growth and AFB1 production. *Curcuma longa*, *A. sativum* and *O. sanctum* also successfully reduced the *A. flavus* growth (65–78%) and AFB1 production (72.2–85.7%) at 5 g kg^{-1} concentration. This finding

Table 9.5. Antiviral and insecticidal activity of plant products tested against rice tungro virus and green leafhoppers of rice.

Common name	Scientific name	Plant part; formulation/dosage	Biological activity	Reference
Neem	*Azadirachta indica*	Neem oil spraying	Population reduction of GLH	Marippan and Saxena (1983)
		5% aqueous neem seed kernel extract (NSKE)	Reduced survival of GLH and also acted as antifeedant	Narsimhan and Mariappan (1988)
		Neem-coated urea as soil application	Reduced incidences of both GLH and virus	David (1986)
		5% aqueous neem seed kernel extract (NSKE)	Ovipositional deterrent by seedling root dip for 24 h	Kareem *et al*. (1987)
		Neem leaf bitters (NLB)	Reduced oviposition and development of GLH	Kareem *et al*. (1989)
Neem		Neem seed bitters 0.25%	Reduced egg laying and adult emergence of GLH	Kareem *et al*. (1989)
		NSKE	Young rice seedling when soaked in NSKE reduced the nymphal development and growth-inhibiting activity of GLH	Kareem *et al*. (1988)
		NSKE	Repellant to GLH	Songkittisuntron (1989)
		Neem oil odour	Disturbed feeding and longevity of GLH	Saxena and Khan (1985)
		5% neem oil coated urea	As antifeedant and reduced RTV incidence	Heyde *et al*. (1984); Krishnaiah and Kalode (1984)
Indian laurel	*Calophyllum inophyllum*	1% seed oil	Checked GLH population and RTV transmission	Narsimhan and Mariappan (1988)
Custard apple/ sweet sop/ supper apple	*Annona squamosa*	Leaf and fruit extracts	Reduced the survival activity of GLH	Mariappan *et al*. (1982a, 1982b); Epino and Saxena (1982)
		Seed oil	Reduced survival of GLH	Marippan and Saxena (1983)
		Neem oil + custard apple (1:4) mixture	Reduced population of GLH	Kareem *et al.* (1987)
		Seed oil	Reduced survival of GLH and tungro transmission	Narsimhan and Mariappan (1988); Mariappan *et al.* (1988)
Mahua	*Madhuca indica*	Seed oil	Reduced survival of the insects and RTV disease	Narsimhan and Mariappan (1988); Mariappan *et al.* (1988)
Jamalghota/croton	*Croton sparsiflorum*	Seed oil	Reduced survival and longevity of GLH	Narsimhan and Mariappan (1988)

GLH, green leafhopper.

demonstrated the possibility of using plant extracts of *S. aromaticum* as a grain protectant against *Aspergillus* contamination.

Seed treatment with botanical fungicides is an environmentally friendly measure in managing seed-borne organisms. Treating the seed with garlic extracts at 1:1 dilution significantly enhanced the germination of the seed and also controlled the seed-borne fungi in rice. Similarly Ahmed *et al.* (2013) reported the effectiveness of neem extracts against seed-borne fungi. It is conclusive that proper seed treatment measures can significantly improve the quality of seed and thereby increase the yield.

Table 9.6. Examples of ITKs followed by farmers for control of pests and diseases of rice in India.

Serial no.	ITK method	Pest/disease	Place/state
1	Make a slurry of 20 kg cow dung in 200 l of water and filter. Dilute the filtrate into 50 l of water and allow it to stand, then decant it and spray the rice plants to check BLB	Bacterial leaf blight (BLB)	Uttar Pradesh
2	By spreading neem leaves on the field. Approximate cost–benefit ratio obtained by this practice was 1:6	Banki or rice case worm	Okhargarha village, Kanke Block in Ranchi district of Ranchi
3	Spreading the leaves of markati plant in the field. This practice has been used since time immemorial and 80–85% of farmers rely on this practice	Reduced the disease incidence and leaves acted as repellent for the pests	East Siang district of Arunachal Pradesh
4	Crushing of 2–3 kg bark of kavlusaraka (*Careya arborea*) in water; 500 ml extract of this bark is mixed with 15 l water and sprayed on the affected crop at 12 day intervals.	Rice blast	Andhra Pradesh
5	Soaking paddy seeds in diluted cow urine	Brown leaf spot and rice blast	Tamil Nadu
6	Spreading of 50 kg common salt per acre of paddy field	Brown leaf spot	West Bengal
7	Boil 1 kg of Malabar nut leaves (*Adathoda vasica*) in10 l water for 30 min. Mixing the strained juice with 60–70 l water and spray on the infected field	Rice blast	Kerala
8	Keep 5–10 kg of marigold leaves (*Tagetes* sp.) in a drum filled with water. Stir it regularly and allow it to stand for 5–10 days. Mix 1 l strained water with one teaspoon of soap and spray on the infected field	Rice blast	Kerala
9	Mix 2–3 kg of lime and one bucket full of cow dung in 200 l water; spray the solution on the affected crop. One spray controls 50% of the deficiency	Khaira disease (mineral deficiency)	–
10	Mix cow dung in water; spray the top filtered solution on the BLB-infected field		Koipuram, Ezumattoor of Pathanmathitta district, Kerala

9.12 Indigenous Rice Disease Management

The advent of the concept of sustainable agriculture in the late 1980s in the Indian agricultural scenario has evoked interest in indigenous technical knowledge (ITK), which uses natural products to solve the problems pertaining to agriculture and allied activities. Over the years, Indian farmers have civilized to practise agriculture for the sake of livelihood and food, by intermingling agriculture with the ITKs available to them. Among all the food crops, rice is known to attract greater numbers of pests and diseases and, consequently, farmers have employed their own pest management practices. Muthuraman *et al.* (2009) reviewed and assessed the ITKs that are followed by Indian farmers for pest management in rice and some of them are listed in Table 9.6.

9.13 Conclusions

Heavy yield losses are reported in rice crops due to diseases such as rice blast, bacterial blight, sheath blight, false smut and rice tungro disease. These diseases have been observed in severe form due to the widespread cultivation of highly fertilizer–responsive cultivars and hybrids, heavy application of nitrogenous fertilizer and an apparent change in climate. Chemical control has been successful and widely practised. However, due to concern over the excessive use of chemical pesticides, emphasis is being placed on alternative approaches, namely, host plant resistance, biocontrol and use of botanicals in the control of the diseases. Most of the botanicals have been studied in the laboratory. It would be more useful if extraction methods were standardized and efficacy on target pathogens was tested so that the investigations for new biologically active botanical products could be more systematic. More investigations are needed on the isolation and characterization of antifungal products and evaluation of the products at field level. Use of naturally available antimicrobial compounds extracted from plant species, which hinders the multiplication and growth of fungal pathogens, would be a more realistic and ecologically sound method for integrated disease management in rice. More emphasis may be given to managing emerging and re-emerging rice pathogens such as stem rot, false smut, glume discoloration, leaf scald and bakanae disease using plant-derived products.

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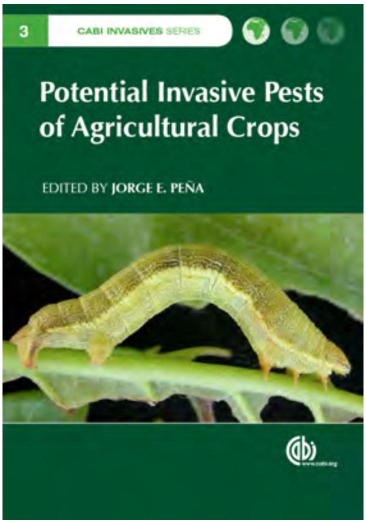
Index



Potential Invasive Pests of Agricultural Crops

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6 Biology, Ecology and Management of the South American Tomato Pinworm, *Tuta absoluta*

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6.1 Introduction

The South American tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is one of the most devastating pests of tomato crops (Estay, 2000; Leite *et al*., 2004; EPPO, 2006; Desneux *et al*., 2010). In the absence of control strategies, damage to tomatoes (*Lycopersicon esculentum*) can reach 100% because this pest attacks leaves, flowers, stems and especially fruits (López, 1991; Apablaza, 1992). *Tuta absoluta* has had several scientific names since its original description in Huancayo (Perú) in 1917 by Meyrick, namely, *Phthorimaea absoluta*, *Gnorimoschema absoluta*, *Scrobipalpula absoluta* or *Scrobipalpuloides absoluta*, but was finally placed under the genus *Tuta* (Barrientos *et al*., 1998). This species is multivoltine, having tomato as its primary host.

Although originally from South America (Miranda *et al*., 1998; Barrientos *et al*., 1998; Estay, 2000), *T. absoluta* was detected in eastern Spain at the end of 2006 (Urbaneja *et al*., 2008). Since then, it has rapidly invaded other European countries and spread throughout Mediterranean Basin countries, including areas in North Africa and the Middle East (Potting, 2009; Desneux *et al*., 2010; Seplyarsky *et al*., 2010; Kýlýc, 2010). Currently, *T. absoluta* is considered a serious threat of tomato in all of these newly infested areas.

Given the importance of the pest to infield- and greenhouse-grown tomatoes throughout the growing season, numerous studies related to its biology, ecology and management have been conducted in South America (Vargas, 1970; Fernández and Montagne, 1990). Accordingly, in newly invaded areas in Europe, several collaborative research projects have provided data, not only about *T. absoluta*'s biology and ecology, but also about the most cost-effective control strategies. In this chapter, we have focused on (i) pest origin, spread and current distribution; (ii) basic

Potential Invasive Pests of Agricultural Crops (ed. J. Peña)

but critical information regarding *T. absoluta* bioecology; (iii) rearing techniques; (iv) known host plants; (v) sampling and monitoring techniques; and (vi) control methods available from both South America and newly infested areas, as well as their potential use for integrated pest management (IPM). Finally (vii), we have provided some hints on present and future management strategies.

6.2 Origin, Spread and Current Distribution

6.2.1 Current distribution and history of spread

Tuta absoluta is thought to be native to Central America, and has spread to the south where, since the early 1980s, it has been recorded as a pest in Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay and Venezuela (Barrientos *et al*., 1998; Estay, 2000; EPPO, 2008). In most cases, dissemination throughout South America was attributed to fruit commercialization (Cáceres, 1992).

Despite quarantine efforts [the pest is included in list A1 (EPPO, 2006)], the pest was detected in the north of Castellón de la Plana (eastern Spain) at the end of 2006 (Urbaneja *et al*., 2008). During 2007, it was detected in several locations throughout the Spanish Mediterranean region, causing very serious damage. In the following growing season, it was found in all of the main coastal areas of tomato cultivation. In these areas, populations of *T. absoluta* immediately reached damaging levels. This has led to a progressive extension of their geographic distribution. In 2008 and 2009, the species spread not only to other Mediterranean countries such as Italy, France, Greece, Portugal, Morocco, Algeria and Tunisia (EPPO, 2008), but also to some European countries with colder climates, (i.e., Switzerland, UK, Germany and the Netherlands (Potting, 2009). In 2010, the establishment of *T. absoluta* in central Europe (Albania, Bulgaria, Romania), Lithuania (Ostrauskas and Ivinskis, 2010), and the Middle East (Bahrain, Kuwait, Israel, Jordan, Syria, Iraq, Saudi Arabia) was reported (Fig. 6.1).

6.2.2 Potential for future spread

The wide distribution of tomato crops along coastal areas of the Mediterranean region correlates with the expansion and movement of *T. absoluta* populations. Moreover, the high concentration of greenhouse cultivation provides longer seasonal availability of their preferred host plant species. The suitability of leguminous plants as a host needs further attention (EPPO,

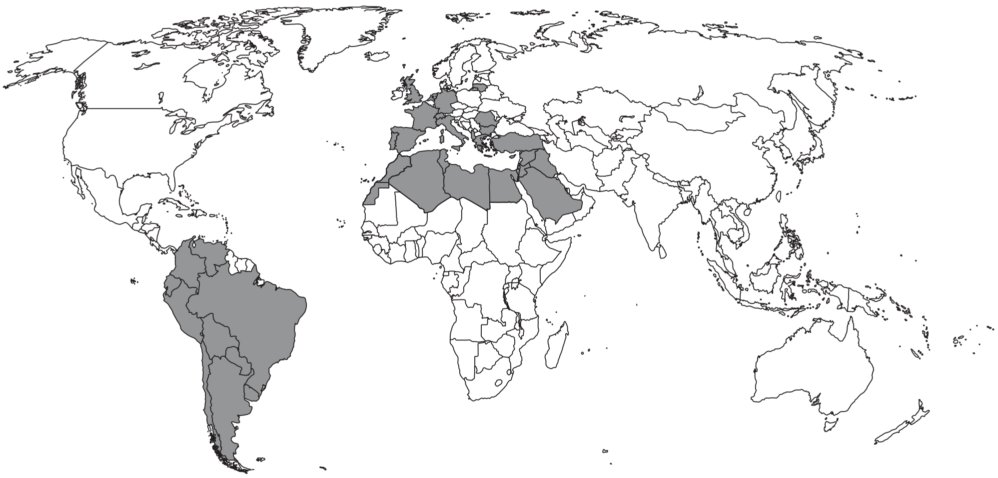

Fig. 6.1. Current distribution map of *Tuta absoluta* (updated from Desneux *et al*., 2010).

2009). If *T. absoluta* expands its host range to several species of this family, it is likely that invasions into new areas of the world will occur in the future. Nevertheless, introductions into new regions appear to be linked to the import and export of tomato fruits. Several reports suggest that international trade is the main route for *T. absoluta* dissemination, for example in the UK, The Netherlands, Russia and Lithuania. Although data from sampling with pheromone traps seem to indicate that this species is characterized by an active dispersal capacity, more reliable information is needed to shed light on the contribution of *T. absoluta* adult dispersion to its spread in the palaeoarctic ecozone.

6.3 Bioecology

6.3.1 Description

The *T. absoluta* life cycle consists of four stages of development: egg, larva, pupa and adult (Fig. 6.2). The eggs measure 0.4 mm in length and 0.2 mm in diameter, and are cylindrical in shape, creamy-white when laid but becoming yellow-orange near hatching. The larval stage includes four instars which are well-defined in size and colour. The first instar is cream coloured and the head is dark; it measures c. 1.6 mm in length. After hatching, young larvae penetrate leaves, tomato fruits or stems to feed and develop, progressively changing to green. Larvae feed only on mesophyll tissues, leaving the epidermis intact. The second instar is c. 2.8 mm in length and the third instar is c. 4.7 mm. Upon reaching the fourth larval instar, a reddish spot appears at the dorsal level, extending longitudinally from the ocellus to the outer margin of the body. In this last instar, larvae can reach 8 mm in length.

The larva stops eating when it is ready to pupate, and usually drops to the ground using a silk thread to complete the pupal stage there; however, pupae can often be found on leaves as well. *T. absoluta* pupae are cylindrical and greenish in their early form, but become darker as they near adult emergence. The pupae measure c. 4.3 mm in length and 1.1 mm in diameter, and are usually covered by a white silky cocoon.

Adults measure 7 mm in length and present filiform antennae. The colour of scales varies

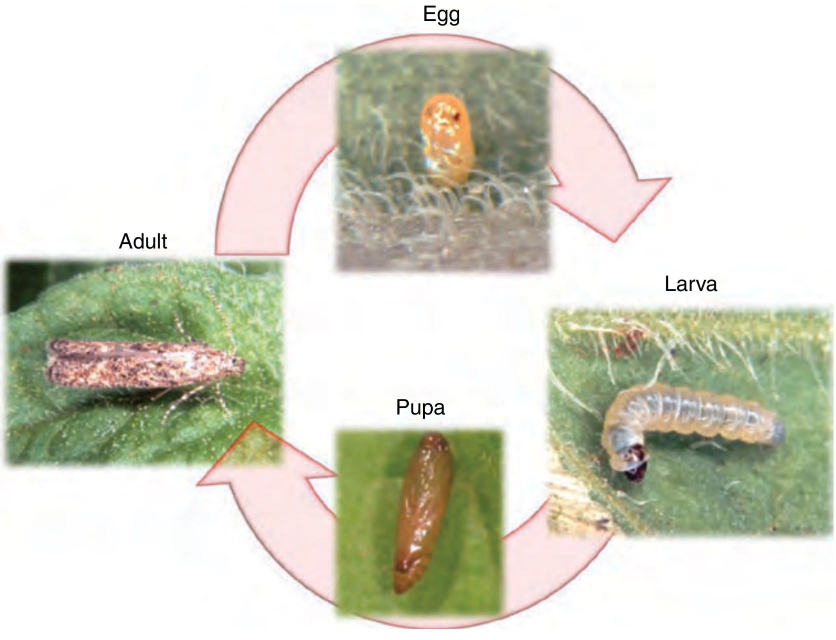

Fig. 6.2. Life cycle of *Tuta absoluta*.

from silver to grey, and black spots are present on anterior wings. Usually adults remain hidden during the day, showing greater morning–crepuscular activity. The abdomen of females is cream coloured, and they are typically wider and heavier than the males (Fig. 6.3). Adult dispersal is by flight.

6.3.2 Biology and life history parameters

T. absoluta has a high reproductive potential. Its life cycle is completed between 22 and 73 days depending on environmental conditions (Barrientos *et al*., 1998). On tomato leaves, for example, the life cycle can be completed in as few as 22 days when temperatures are between 25 and 27°C. Temperature thresholds and thermal constants of the different stages of *T. absoluta* have been already established (Table 6.1) (Bentancourt *et al*., 1996; Barrientos *et al*., 1998; Mihsfeldt, 1998). Larvae do not enter diapause, and there can be 10–12 generations per annum in South America (Barrientos *et al*., 1998). Mihsfeldt (1998) estimated that this species could have 6 to 9 generations per annum in São Paulo, Brazil.

Adult longevity is also influenced by environmental conditions. The mean lifespan is about 10–15 days for females and 6–7 days for males (Estay, 2000). Nevertheless, uncoupled males live significantly longer than coupled males and females, whatever their stage (Fernández and Montagne, 1990).

Females mate only once each day and they are able to mate six times during their life. Mating lasts an average of 4–5 h. The most prolific period is 7 days after the first mating, when females are able to lay 76% of their eggs (Uchoa-Fernandes *et al*., 1995). At 25–27°C, the pre-oviposition period lasts for 2–3 days (Haji *et al*., 1995; Mihsfeldt, 1998) with an egg-to-adult survival of 81.7%. Females oviposit preferentially on leaves (73%), and to a lesser extent on leaf veins and stem margins (21%), sepals (5%) or green fruits (1%) (Estay, 2000). Oviposition was found to be possible on unripened tomatoes only (Monserrat, 2009a). A single female can lay up to 260 eggs throughout its life (Uchoa-Fernandes *et al*., 1995). However, the number of eggs laid by each female depends on the tomato variety, and under the same conditions can vary from 130.1 ± 11.2 on leaves of the Santa Clara variety (Mihsfeldt, 1998) to 158.0 ± 10.9 on Santa Cruz Kada (Giustolin and Vendramim, 1996a). Rearing on artificial diet strongly reduces the number of eggs laid, reaching only 77.8 ± 14.1 (Mihsfeldt and Parra, 1999).

Fig. 6.3. Male and female of *Tuta absoluta*.

6.4 Rearing Techniques

Little research has been reported with artificial diets, and most of these studies have used plants of different tomato varieties (Vargas, 1970; Rázuri and Vargas, 1975; Quiroz, 1976; Muszinski *et al*., 1982; Souza *et al*., 1983; França *et al*., 1984; Salas and Fernández, 1985; Paulo, 1986; Haji *et al*., 1988; Imenes *et al*., 1990; Pratissoli, 1995; Bentancourt *et al*., 1996; Giustolin and Vendramim, 1996a; Ferreira and Anjos, 1997).

Among the various artificial diets tested, that developed by Greene *et al*. (1976) has been shown to be the most suitable (Mihsfeldt and Parra, 1999). Based on the work done by Greene *et al*. (1976), Mihsfeldt and Parra (1999) adapted a new diet for *T. absoluta*; they used dried beans with white husk and leaf extracts from the Santa Clara tomato variety to stimulate the larvae to feed. This diet appeared particularly suitable for *T. absoluta* larval development; however, in comparison with larvae fed on plant leaves, the development of both larval and pupal stages took longer and fewer eggs were laid. The same authors pointed out that further research should be conducted on reducing diet granulation, as

Table 6.1. Thermal requirements of *Tuta absoluta* according to various authors.*

Development stages	Tt (°C) Temperature threshold			K (DD) Thermal constant		
	On leaves[a]	On artificial diet[b]	On leaves[c]	On leaves[a]	On artificial diet[b]	On leaves[c]
Egg	6.9	7.9	9.7	103.8	76.6	72.3
Larva	7.6	11.2	6.0	238.5	366.6	267.2
Pupa	9.2	10.7	9.1	117.3	135.0	130.8
Egg–adult	8.1	10.8	8.0	453.6	574.5	463.0

* [a]Barrientos *et al.* (1998); [b]Mihsfeldt (1998); [c]Bentancourt *et al.* (1996).

large particles can make the ingestion process more difficult for recently hatched larvae. Accordingly, these authors considered that adapting to laboratory conditions may last from four to seven generations in this type of microlepidopteran (P. Singh, DSIR, New Zealand, pers. comm.). Therefore, a simple rearing system with tomato leaves may be the most effective (Pratissoli, 1995). It is worth mentioning that rearing on artificial diet leads to a significant reduction in the number of eggs laid by females, dropping from 130–158 to about 78 (Mihsfeldt and Parra, 1999).

In the laboratory, females lay eggs singly or in masses with up to ten eggs depending on attractive visual and olfactory stimuli (Mihsfeldt, 1998). Using white sulfite paper coated with smooth, green polyethylene and tomato leaf extract obtained in sulfuric ether as visual and olfactory stimuli (1 mL of ether per sulfite paper), Mihsfeldt (1998) reported 144.6 ± 15.6 eggs for each female, which suggested that tomato leaves could be replaced for the purposes of obtaining eggs in the laboratory.

According to Mihsfeldt (1998), the optimum temperature range for rearing is 18–25°C. Fertility life-table studies have demonstrated that a population reared on a natural diet can increase 72.28 times each generation (Ro = 72.28), with a finite rate of increase (λ) of 1220 (Mihsfeldt, 1998).

6.5 Plant Hosts and Damage

Tomato is the preferred host plant for *T. absoluta*. It is able to lay single eggs on almost every part of the tomato plant and can complete its life cycle feeding on leaves, stems, flowers and fruits. *T. absoluta* can also be found in other cultivated Solanaceae, such as aubergine (*Solanum melongena*), potato (*S. tuberosum*), pepper (*S. muricatum*) and tobacco (*Nicotiana tabacum*), as well as on other alternative plant hosts (Solanaceous weeds) such as *S. saponaceum*, *S. guitoense*, *S. nigrum*, *S. elaeagnifolium*, *S. bonariense*, *S. sisymbriifolium*, *Lepidium puberulum*, *Datura stramonium*, *D. ferox* and *Nicotiana glauca* (Vargas, 1970; Povolny, 1975; Campos, 1976; Garcia and Espul, 1982; Larraín, 1987; Desneux *et al.*, 2010). In Italy, *T. absoluta* has been recorded on *Physalis peruviana* (Tropea Garzia, 2009), beans (EPPO, 2009) and *Lycium* and *Malva* spp. (Caponero, 2009). On potato, *T. absoluta* only attacks aerial portions of the plant and does not develop on tubers. Damage is caused when larvae feed on the leaf mesophyll, expanding galleries, which affect the photosynthetic capacity of the plants and subsequently reduces yields (Fig. 6.4). Injuries made directly to the fruits may lead to severe yield losses. Tomato plants can be attacked at any developmental stage, from seedlings to mature plants. After hatching, young larvae penetrate the leaves, stems or tomato fruits creating conspicuous mines and galleries where they feed and develop. Larvae can also attack flowers and stop fecundation. At early stages, larval damage may go undetected due to the small diameter of the entrance hole made under the sepals, but when larval development is completed, a dark yellow halo can be observed surrounding the hole used by the adult to exit the host. Galleries in stems can alter general plant development if they become necrotic. Moreover, a single larva may create multiple galleries attacking several plant tissues, thereby increasing the damage level (Fig. 6.5). Fruits can also be attacked as soon as they are

Fig. 6.4. *Tuta absoluta* galleries.

Fig. 6.5. Damage caused by *Tuta absoluta* in the fruits and leaflets.

Fig. 6.6. Damage caused by *Tuta absoluta* in the fruits and leaflets.

formed. The galleries bored inside fruits are usually invaded by secondary pathogens, leading to fruit rot (Fig. 6.6) (Bahamondes and Mallea, 1969; Vargas, 1970).

Yield losses occur in fruits destined for the fresh market as well as in those used for industrial processing. The amount of these losses depends on the success of controlling the pest, ranging from 80% to 100% if there is no control whatsoever (Nakano and Paulo, 1983; Scardini *et al.*, 1983; López, 1991; Apablaza, 1992).

6.6 Sampling and Monitoring Techniques

There are different sampling methods to determine the risk of damage in a tomato crop. One is monitoring for pest presence and density based on direct observations of the plant to estimate plant damage and how the damage develops. This can be complemented with the use of pheromone traps to estimate the level of male populations.

6.6.1 Pheromone traps

T. absoluta *sex pheromone*

Using capillary GC-MS, Attygalle *et al.* (1995) examined hexane extracts made from excised pheromone-producing glands of calling *T. absoluta* females, and found two significant chromatographic peaks in the region where Lepidopteran pheromones usually appear; each gland contained about 1-5 ng of the pheromone components. The major component was identified as (3E,8Z,11Z)-3,8,11-tetradecatrienyl acetate (Attygalle *et al.*, 1995). Synthetic (3E,8Z,11Z)-3,8,11-tetradecatrienyl acetate was highly attractive to *T. absoluta* males and identical to the natural substance from female gland extracts. The complete female sex pheromone of *T. absoluta* was later found also to contain approximately 10% of (3E, 8Z)-3,8-tetradecadienyl acetate as a secondary component (Attygalle *et al.*, 1996; Griepink *et al.*, 1996; Svatos *et al.*, 1996).

The market prior to the European invasion only required the manufacturing of small quantities of the synthetic pheromone for monitoring lures. As invasive *T. absoluta* populations became established, and then exploded across Europe and North Africa (Desneux *et al.*, 2010), the demand for synthetic pheromone [(3E,8Z,11Z)-3,8,11-tetradecatrienyl acetate] increased significantly. Intense scale-up research and development resulted in increased availability, in tandem with a drastic reduction in the cost of synthetic sex pheromone for *T. absoluta*.

Monitoring

Monitoring for pest presence and density is a critical first step for its management. The primary value of sex pheromones, combined with traps, is to determine the presence and density of pest populations in the field. The sex pheromone of *T. absoluta* is highly species-specific. It attracts males to traps even when field population densities are extremely low. Pheromone-baited traps are, therefore, remarkable tools for detection of this insect, and should help in determining pest distribution at larger geographic scales.

Using pheromone traps as tools for monitoring the density of insect pest populations in the field requires an appropriate calibration, requiring correlation of certain combinations of trap and lure with the actual presence of the pest in the target area. This is usually done by correlating catches in pheromone traps with the population density of immature forms and the level of damage detected in the crop. Preliminary lure efficacy studies were conducted in Brazil to determine appropriate dosing and field longevity. Captures peaked with lures containing between 0.25 and 1.0 mg of pheromone per septum. No moths were captured in any of the non-baited traps. The analysis of these data revealed that captures in pheromone traps correlate with the density of leaf-mine and larvae in the field (Gomide *et al*., 2001; Filho *et al*., 2000, Ferrara *et al*., 2001; Salas, 2004). In South America, pheromone traps are starting to be used for monitoring, with the economic injury level (EIL) established at 45 ± 19.5 adults/trap/day (Benvenga *et al*., 2007). In Chile, the economic injury level (EIL) is established at 100 adults/trap/day (Bajonero *et al*., 2008), or with two females or 26 larvae per plant. Despite previous experience, this correlation is not properly validated in newly infested areas in the Mediterranean region. The number of captures obtained per trap is, however, used to establish the risk level (Monserrat, 2009a, b). Normally, a delta trap baited with pheromone is used as standard (Fig. 6.7). The trap is placed at 0.5 m height at the beginning of the season and can later be raised to 1.5 m depending on the size of the plant. In fields or greenhouses where *T. absoluta* has not yet been established, it is common to find a time lapse of 3–4 weeks between the start of male captures and the detection of plant damage. When there are no male captures, the plant damage risk is very low or null.

Fig. 6.7. Delta trap lured with *Tuta absoluta* pheromone.

Plant sampling

Visually monitoring for the presence and density of *T. absoluta* in the field requires intensive training and specialized manual labour. Finding, counting and annotating the number of eggs on meristematic parts of the plant, as well as the estimation of gallery density and damaged fruit in the crop, are difficult and time-consuming tasks.

Direct plant sampling must be conducted to estimate the actual damage inflicted on the crop by *T. absoluta*. To this end, the percentage of infested plants should be counted. Only plants infested with healthy larvae should be considered in this sampling, ruling out those plants with dead larvae or old-damage symptoms. The periodicity of this sampling is correlated with the risk of damage, 5–7 days for periods of high risk and 14 days during those periods of no risk (Monserrat, 2009a). As with the pheromone trap index, depending on the percentage of infested plants, a particular control method should be adopted. Treatments with chemicals should only be applied when *T. absoluta* larvae can be found in the plants.

A level of 8% defoliation is used as the EIL in Colombia (Desneux *et al*., 2010). In Brazil, sampling twice weekly on 60 plants/ha in staked tomatoes and 10 plants/ha in industrial tomatoes, the EIL used is 25% of the upper portion of the plant with larvae or eggs; or 25% of the leaves with larvae; or 5% of tomatoes (cluster) with eggs (Benvenga *et al*., 2007).

Unfortunately, the injury level threshold (i.e., fruit damage in terms of percentage of plant or fruit infested) has not yet been scientifically established in the Mediterranean region and thus it is currently difficult to correlate the results of plant sampling and percentage of damage to the crop. However, a significant relationship between logarithmic estimation of the abundance of *T. absoluta* galleries in the seven upper leaves of the tomato plant with the percentage of damaged young fruits was observed when ten commercial tomato fields were surveyed periodically (Arnó, Matas and Gabarra, unpublished data). This relationship suggests that evaluation of the abundance of galleries may allow estimation of the level of damage on young fruits (Fig. 6.8).

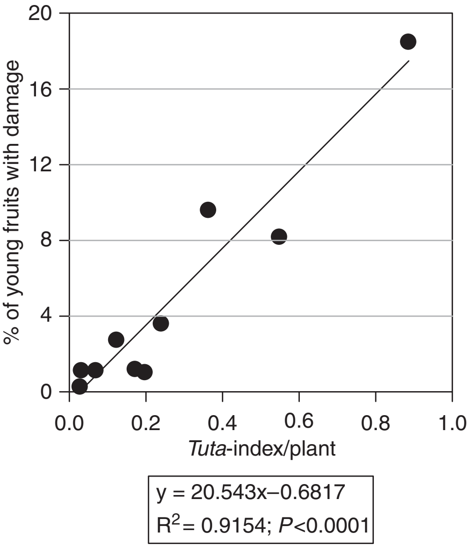

Fig. 6.8. Relationship between the mean percentage of young tomato fruits damaged and the logarithmic estimation of the abundance of *Tuta absoluta* galleries (mean *Tuta*-index). Data from ten open-field tomato crops surveyed periodically (Arnó, Matas and Gabarra, unpublished data).

6.7 Control Methods

The best methods for managing *T. absoluta* involve prevention of pest outbreaks, and long-term and economic control. These methods include biological, biotechnological, cultural and chemical control. The use of pesticides is recommended only when preventive measures are inadequate and careful field monitoring indicates that economic loss is likely.

6.7.1 Biological control

Biological control represents one of the main strategies for the integrated pest management of this insect pest (Haji *et al*., 2002). Many natural enemies have been described for *T. absoluta* in the area of origin of this pest. Furthermore, since *T. absoluta* has been detected in the Mediterranean region, some indigenous natural enemies have been reported on this exotic pest as fortuitous biological control. In newly infested areas, evaluation is currently under way to determine if these natural enemies can be used in biological control programs that target *T. absoluta*.

Parasitoids

A list of c. 50 parasitoids of *T. absoluta* eggs, larvae and pupae in South America was reported by

Desneux *et al*. (2010). Parasitoids of eggs and larvae predominate, with only a few records for pupal and none for adult parasitoids. Before this study, and except for one citation (Polack, 2007), no publications had grouped all of the parasitoids together.

T. absoluta eggs are parasitized by Encyrtidae, Eupelmidae and Trichogrammatidae wasps (*Trichogramma* spp. being predominant). The species associated with *Tuta absoluta* in South America are *Trichogramma exiguum* Pinto and Platner, *T. nerudai* Pintureau and Gerding, and *T. pretiosum* Riley (Zucchi *et al*., 2010).

Successful control of *Tuta absoluta* with *Trichogramma* spp. releases has been reported in Colombia (Garcia Roa, 1989; Salas, 2001) and in Brazil (Haji *et al*., 2002; Parra and Zucchi, 2004), whereas unsuccessful control has been reported in Chile (Jimenez *et al*., 1998; Taco *et al*., 1998).

At the end of 1981, *Tuta absoluta* was recorded in Brazil's sub-medium São Francisco region where all the tomato extract industries were concentrated at that time, with a total area of 15,000 ha of industrial tomatoes. Due to *T. absoluta* resistance to Cartap (thicarbamate), the government developed an integrated pest management program which included cultural, legislative, microbiological and biological measures, the latter involving the import of *Trichogramma pretiosum* from Colombia (Haji *et al*., 2002). The adoption of these measures resulted in excellent control of *Tuta absoluta* with only 1–9% damaged tomatoes and with 30–49% parasitism observed in industrial tomato crops (Haji *et al*., 1995). Around 450,000 parasitoids were released per hectare, twice per week for 10 weeks, with the first release taking place when the first eggs of *T. absoluta* were detected on plants, 20–30 days after planting. Between releases, applications of *Bacillus thuringiensis* (Berliner) (Bt) were also made, totaling ten treatments per crop period, guaranteeing the control of those caterpillars which had emerged from eggs not parasitized by *Trichogramma pretiosum*.

It should be noted that for parasitism to be successful, the selection of the right parasitoid strains is fundamental (Pratissoli and Parra, 2000b, 2001; Pratissoli *et al*., 2005a). The best temperatures for successful parasitism by *T. pretiosum* range between 22°C and 25°C (Pratissoli, 1995) (Fig. 6.9). Developmental time ranges from 26.5 days at 18°C to 7.1 days at 32°C, and thermal requirements are 131.3 degree days for complete development (lowest temperature threshold of 13°C) (Table 6.2 and Fig. 6.10) (Pratissoli and Parra, 2000).

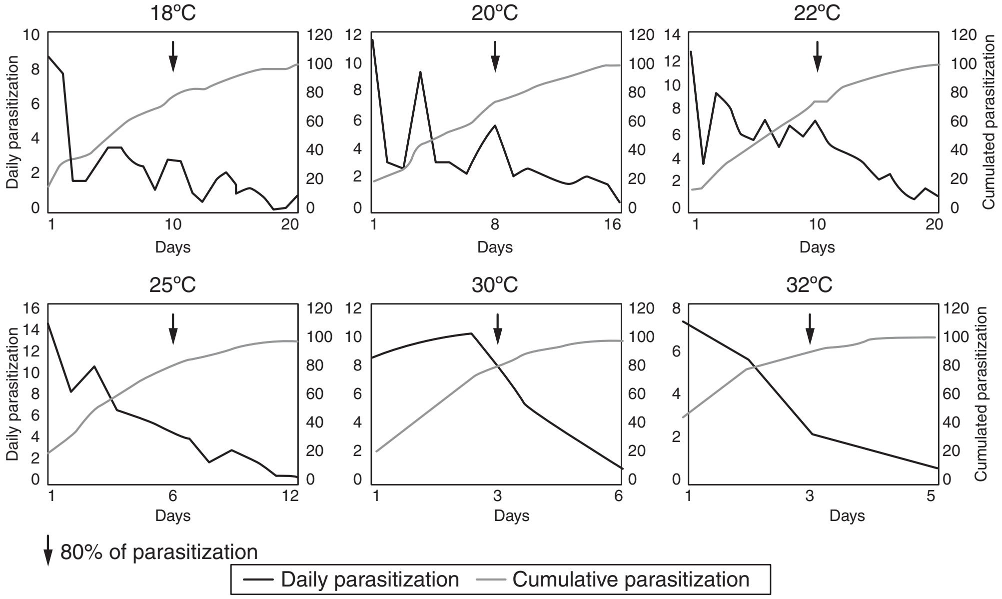

Fig. 6.9. *Trichogramma pretiosum* daily and total parasitization on *Tuta absoluta* at different temperatures (Pratissoli and Parra, 2000a).

Other studies that have focused on *T. pretiosum* have shown that nine inundative releases of the parasitoid at 800,000 individuals/ha once per week, on industrial tomatoes, and ten releases (same rate) on staked tomatoes, resulted in reductions of 82% and 85% in *Tuta absoluta* populations, respectively (Papa, 1998). Egg parasitism varied from 32% to 35%, and the level of control was similar to that obtained from conventional insecticides for *T. absoluta* management. In the case of tomatoes in greenhouse cultivation, the use of *Trichogramma pretiosum* resulted in 87% parasitism in Brazil (Parra and Zucchi, 2004). The dispersal capacity of *T. pretiosum* varies from 7 to 8 m, 24 h after release over an area of 120–140 m^2, indicating that 75 points/ha should be used for parasitoid release (Pratissoli *et al.*, 2005b).

In the Mediterranean region, some egg parasitoids have already been detected (Desneux *et al.*, 2010). *Trichogramma achaeae* Nagaraja and Nagarkatti has been identified as a potential biological control agent of *T. absoluta*. In greenhouse exclusion cages, seven releases of this parasitoid at a rate of 30 adults per plant every 3 or 4 days significantly reduced the number of *T. absoluta* larvae, galleries and damaged fruits, compared to control plots (Cabello *et al.*, 2009b). Based on these findings, *T. achaeae* has become commercially available, with a recommended release dose, depending on the infestation level, of 250,000–500,000 adults/ha per week (Cabello *et al.*, 2010). However, these high rates may not be economically sustainable, and thus parasitoid releases should be combined with other biological control methods.

Larval parasitoids can also be important, and species from the Bethylidae, Braconidae, Eulophidae, Ichneumonidae and Tachinidae have been recorded (Desneux *et al.*, 2010). Several species of larval parasitoids have been recorded from Argentina (Berta and Colomo, 2000; Luna *et al.*, 2007; Sanchez *et al.*, 2009), Chile (Rojas, 1981; Larraín, 1986), Brazil (Uchoa-Fernandes *et al.*, 1995; Miranda *et al.*, 1998; Marchiori *et al.*, 2004; Bacci *et al.*, 2008), Colombia (Oatman and Platner, 1989), Perú and Venezuela (Desneux *et al.*, 2010). *Apanteles gelechiidivoris* Marsh (Hymenoptera: Braconidae) has been reported to be an efficient biocontrol agent and is currently used in Colombia to control *T. absoluta* (Benavides *et al.*, 2010). In laboratory experiments, Bajonero *et al.* (2008)

Table 6.2. Development of *Trichogramma pretiosum* on *Tuta absoluta* at different temperatures (Pratissoli and Parra, 2000b).

Temperature (°C)	Duration (days)	Viability (%)
18	26.47	79.80
20	17.78	86.12
22	16.32	94.34
25	10.30	96.24
30	7.50	88.97
32	7.11	83.37

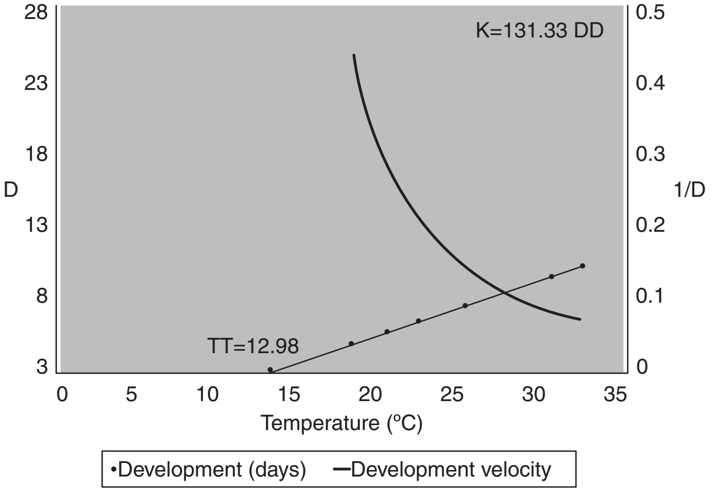

Fig. 6.10. *Trichogramma pretiosum* thermal requirements on *Tuta absoluta* (Pratissoli and Parra, 2000a).

demonstrated that *A. gelechiidivoris*, which lays its eggs singly on third instar *T. absoluta* larvae, can develop in a wide range of temperatures, with lower and higher developmental thresholds at 4°C and 33°C. *A. gelechiidivoris* was introduced into Chile from Colombia in the mid-1980s, and was found in abundance in 1997 in tomato crops in some areas of Chile (Rojas, 1997); however, a subsequent study indicated that *A. gelechiidivoris* resulted in low levels of parasitism and that *Dineulophus phthorimaeae* (De Santis) (Hymenoptera: Eulophidae) was the main natural enemy of *T. absoluta* with 70% parasitism (Larraín, 2001). In Argentina, the most important larval parasitoids are *Pseudoapanteles dignus* (Muesebeck) (Hymenoptera: Braconidae) and *D. phthorimaeae* (Polack, 2007). Data from surveys conducted over a 4-year span in tomato crops in Argentina showed that 53% of the parasitoids collected were *P. dignus* followed by *D. phthorimaeae* (Colomo *et al*., 2002). Luna *et al*. (2007) demonstrated that *P. dignus* was able to synchronize its larval development time with that of the host, and to detect and parasitize the host even at low host densities. In addition, high levels of parasitism by *P. dignus* (up to 46%) were observed in commercial crops (Sanchez *et al*., 2009), suggesting the importance of conservation biological control measures aimed at keeping populations of *P. dignus* in tomato crops. However, when studying field interactions of this parasitoid with *D. phthorimaeae*, Luna *et al*. (2010) determined that both species may coexist even at the leaf scale, but *D. phthorimaeae* is more efficient in situations of competition.

In the Mediterranean region, the parasitoid *Necremnus artynes* (Walker) (Hymenoptera: Eulophidae) (Fig. 6.11) has been sporadically observed in several locations along the coast (Mollá *et al*., 2008; Arnó *et al*., 2009a; Mollá *et al*., 2010; Gabarra and Arnó, 2010). Another species of the same family has also been detected in north-eastern Spain: *Stenomesius* sp. (Hymenoptera: Eulophidae), which was cited as *Hemiptarsenus zilahisebessi* Erdös (Hymenoptera: Eulophidae) in Gabarra and Arnó (2010) due to a misidentification. Both *N. artynes* and *Stenomesius* sp. are idiobiont ectoparasitoids, which parasitize second and third instars of *T. absoluta*. *Neochrysocharis formosa* (Westwood) (Hymenoptera: Eulophidae) has been identified as a potential larval parasitoid of *T. absoluta* in the same area (Lara *et al*., 2010) and *Habrobracon hebetor* (Say) (Hymenoptera: Braconidae) has been observed parasitizing larvae on

Fig. 6.11. The larval parasitoid *Necremnus artynes*.

tomato field samples (Gabarra and Arnó, unpublished data). In addition, recent reports of various undetermined species, mainly Braconidae, attacking *T. absoluta* along the Mediterranean coast (Mollá *et al*., 2008; Arnó *et al*., 2009b; Gabarra and Arnó, 2010) may signal that the local parasitoid complex is progressively adapting to this new pest. Recently, two companies that produce natural enemies have identified *N. artynes*, *N. tidius* (Walker) and *Diadegma ledicola* Horstmann (Hymenoptera: Ichneumonidae) as good biocontrol candidates for *T. absoluta*, and plan to make *N. artynes* commercially available (Koppert, 2010; Bioplanet, 2010).

Although pupal parasitoids of *T. absoluta* have been neglected, Polack (2007) has recorded up to 30% pupal parasitism by *Conura* sp. (Hymenoptera: Chalcididae).

Predators

The biology of predators associated with *T. absoluta* in South America has been studied much less than that of parasitoids (Desneux *et al*., 2010), although several studies have stressed the importance of predators in mortality of *T. absoluta*. Miranda *et al*. (1998) found that the highest natural mortality occurred during the larval stage, and the mortality associated with predation was much higher than that associated with parasitism. In contrast, predation on eggs was slightly lower than parasitism. According to these authors, this mortality was caused by the anthocorid *Xylocoris* sp. (Hemiptera: Anthocoridae), the coccinelid *Cycloneda sanguinea* (Linnaeus) (Coleoptera: Coccinellidae) and some members of the Phlaeothripidae family. Bacci *et al*. (2008) also found that the most important mortality factor for the larvae of *T. absoluta* was predation, particularly by the wasp *Protonectarina sylveirae* (Saussure) (Hymenoptera: Vespidae) and anthocorid and miridae bugs. Alternatively, several authors reported a significant decrease in populations of *T. absoluta* related to an increase in predator populations when conservation biological controls were applied, such as companion plants (Paula *et al*., 2004; Miranda *et al*., 2005; Medeiros *et al*., 2009).

Several predators have been associated with crops infested by *T. absoluta* (Desneux *et al*., 2010), but relatively few groups, genera or species have been demonstrated to prey on *T. absoluta* (Table 6.1), and even fewer are the number of species that have been studied in detail.

The predators that have been directly associated with *T. absoluta* are mainly predators of larvae, although some of them prey on eggs or pupae. As shown in Table 6.1, in the area of origin of this pest, most of the recorded predators belong to the order Hemiptera (mainly anthocorids) and wasps. No laboratory studies on the biology of the particular wasps have been conducted; but based on field observations, *P. sylveirae* may be a very efficient predator of second, third and fourth instar larvae, causing mortality of up to 30% in *T. absoluta* populations (Bacci *et al*., 2008). Other wasps have also been observed to be predators of *T. absoluta* larvae (Medeiros *et al*., 2009).

One of the most studied predators of *T. absoluta* in South America is the pentatomid, *Podisus nigrispinus* (Dallas) (Hemiptera: Pentatomidae). It is able to develop by preying solely on *T. absoluta* (Vivan *et al*., 2002a, b, 2003). However, studies on life-table parameters showed that *T. absoluta* has more generations per annum than *P. nigrispinus*, and therefore the predator would most likely be unable to provide sufficient control. When comparing the effect of two types of prey [larvae of *T. absoluta* and larvae of the beetle, *Tenebrio molitor* (L.)] on the biological parameters of *P. nigrispinus*, these authors demonstrated that developmental time and reproduction were negatively affected when *P. nigrispinus* preyed on *T. absoluta*. Conversely, Torres *et al*. (2002) studied the dispersal potential of *P. nigrispinus* in tomatoes grown in a greenhouse environment, and found that second instar nymphs dispersed better if they were starved for 24 h prior to release, and if they were released either in the morning or in the evening.

Some studies of the biology of *Chrysoperla externa* (Hagen) (Neuroptera: Chrysopidae) report that eggs of *Sitotroga cerealella* (Oliv.) (Lepidoptera: Gelechiidae) were better prey for the development of this lacewing than *T. absoluta* eggs. Larval developmental time was longer and pupal weight was lower on a diet of *T. absoluta* eggs, despite the predator having consumed a higher number of eggs (Carneiro and Medeiros, 1997).

In the Mediterranean region, eight species, predominantly Hemiptera, have been identified as *T. absoluta* predators (Table 6.3). Adults of *Macrolophus pygmaeus* Rambur (Fig. 6.12) and *Nesidiocoris tenuis* Reuter (Fig. 6.13) (Hemiptera: Miridae) are predators of all pre-imaginal stages

Table 6.3. Known *Tuta absoluta* predators, and geographical area where they were recorded.

Taxa	Geographical area	First reference
Acari		
Phytoseidae		
Amblyseius swirskii	Mediterranean	Mollá *et al.*, 2010
Amblyseius cucumeris	Mediterranean	Mollá *et al.*, 2010
Pyemotidae		
Pyemotes sp.*	South America	Oliveira *et al.*, 2007
Araneae		
Araneidae		
Misumenops pallidus	South America	Medeiros, 2007
Coleoptera		
Coccinellidae		
Cycloneda sanguinea	South America	Miranda *et al.*, 1998
Chilocorus sp.	South America	Vasicek, 1983
Hemiptera		
Anthocoridae		
Orius insidiosus	South America	Salas, 1995
O. majusculus	Mediterranean	Gabarra & Arnó, unpublished
O. laevigatus	Mediterranean	Gabarra & Arnó, unpublished
Lasiochilus sp.	South America	Bacci *et al.*, 2008
Xylocoris sp.	South America	Miranda *et al.*, 1998
Miridae		
Hyaliodocoris insignis	South America	Bacci *et al.*, 2008
Annona bimaculata	South America	Bacci *et al.*, 2008
Macrolophus pygmaeus	Mediterranean	Arnó *et al.*, 2009; Urbaneja *et al.*, 2009
Nesidiocoris tenuis	Mediterranean	Arnó *et al.*, 2009; Urbaneja *et al.*, 2009
Dicyphus maroccanus	Mediterranean	Mollá *et al.*, 2010
Pentatomidae		
Podisus nigrispinus	South America	Vivan *et al.*, 2002
Berytidae		
Metacanthus tenellus	South America	Oliver and Bringas, 2000
Nabidae		
Nabis sp.	South America	Vargas, 1970
N. pseudoferus	Mediterranean	Cabello *et al.*, 2009
Hymenoptera		
Vespidae		
Polistes sp.	South America	Vargas, 1970
Protonectarina sylveirae	South America	Bacci *et al.*, 2008
Brachygastra lecheguana	South America	Leite *et al.*, 1998
Polybia sp.	South America	Medeiros, 2007
Neuroptera		
Chrysopidae		
Chrysoperla externa	South America	Carneiro and Medeiros, 1997
Thysanoptera		
Phlaeothripidae	South America	Miranda *et al.*, 1998

*This genus is known to cause dermatitis in humans. Consequently, its use as biological control agent is not recommended (Cunha *et al.*, 2006).

of *T. absoluta*, although they consume a higher number of eggs than larvae. The number of eggs fed upon each day by one *M. pygmaeus* or *N. tenuis* adult may exceed 100 eggs in laboratory conditions, whereas c. two first-instar larvae are preyed upon each day. Nymphs of *M. pygmaeus* consumed fewer eggs than nymphs of *N. tenuis* or adults of both Mirid species (Urbaneja *et al.*, 2009; Arnó *et al.*, 2009b). *N. tenuis* was able to complete its nymphal development with high survival by feeding on *T. absoluta* alone (Mollá *et al*., 2010) and was able to limit *T. absoluta* population growth at high pest densities (Nannini, 2009). In greenhouse exclusion cage experiments, when *T. absoluta* was released where predators were well-established, *N. tenuis* was able to reduce the pest populations better than *M. pygmaeus* (98% versus 66%, respectively) (Mollá *et al*., 2009, 2010). Similarly, Calvo *et al*. (2010) found that the inoculation of *N. tenuis*, either by release in seedling nurseries or in the crop, could maintain populations of *T. absoluta* under control.

M. pygmaeus and *N. tenuis* are among the most abundant natural enemies in tomato greenhouses and open fields in the Mediterranean region, and they are especially abundant in IPM tomato crops that are not heavily sprayed with chemical pesticides (Gabarra *et al*., 2008). Field data in commercial IPM cultivations showed that when Mirid bugs are well established in the crop, they can be an important control agent of *T. absoluta*. Abundance of galleries and damage in young tomato fruits were four times higher in crops managed with pesticides than in those where inoculation or conservation of *M. pygmaeus* and *N. tenuis* was used as a pest control strategy (Arnó *et al*., 2009b).

Fig. 6.12. Adult of *Macrolophus pygmaeus* preying on *Tuta absoluta* eggs.

Fig. 6.13. Adult of *Nesidiocoris tenuis* preying on *Tuta absoluta* eggs.

In the Mediterranean region, predation on *T. absoluta* has also been observed by *Nabis pseudoferus* Remane (Hemiptera: Nabidae) (Cabello *et al*., 2009a), *Dicyphus maroccanus* Wagner (Hemiptera: Miridae), *Amblyseius cucumeris* Oudemans and *A. swirskii* (Athias-Henriot) (Fig. 6.14) (Acari: Phytoseiidae) (Mollá *et al*., 2010) on tomato, and by *Orius majusculus* (Reuter) and *O. laevigatus* (Fieber) (Hemiptera: Anthocoridae) on potato (Gabarra & Arnó, unpublished data).

All *T. absoluta* predators that have been identified so far in Europe and North Africa prey only on eggs and very young larvae. This means that predators can only control the pest for a short period of its development, and therefore, high populations of these natural enemies are needed to reduce damage. To achieve these high densities while controlling the pest it will be necessary to release *T. absoluta* parasitoids and/or spray with *B. thuringiensis* early in the season before the full establishment of the predators (Mollá *et al*., 2010; Gabarra and Arnó, 2010; González-Cabrera *et al*., 2011).

Fig. 6.14. *Amblyseius swirskii* preying on *Tuta absoluta* larva.

Entomopathogens

Several researchers have attempted to establish the basis for an effective control of *T. absoluta* with such biocontrol agents. Rodríguez *et al.* (2006) have shown that applications of *Beauveria bassiana* (Bals.) Vuill. as well as *Metarhizium anisopliae* (Metsch.) Sorok. sprayed on third instar larvae resulted in >90% mortality; however, this percentage decreased to 68% when larvae were fed leaves previously sprayed with Conidia (Rodríguez *et al.*, 2006). In Brazil, the combination of moderately resistant tomato varieties with applications of *B. bassiana* or *B. thuringiensis* has resulted in additive or synergistic effects, causing significant mortality in larvae from all four instars (Giustolin, 1996; Giustolin *et al.*, 2001a, b). Furthermore, screening programs in Chile showed that it is possible to improve effectiveness of Bt-based commercial formulations. Two newly isolated strains have demonstrated higher toxicity against neonate larvae than that of the Bt strain in the commercial product, Dipel® (Niedmann and Meza-Basso, 2006). Moreover, the expression of toxins in other *Bacillus* species naturally colonizing the phylloplane can result in longer persistence of the toxins (up to 45 days), which increases the chance for the larvae to ingest a lethal dose (Theoduloz *et al.*, 2003). This approach should be further studied as a new delivery system, as it may help reduce the number of treatments necessary for control. In Brazil, a granulovirus isolated from the potato tuber moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae), was also highly virulent to *T. absoluta*, leading to significant mortality, delayed larval growth and inhibited pupation (Mascarin *et al.*, 2010).

In the Mediterranean region, *T. absoluta* control has relied mostly on chemical pesticides, but safety issues as well as low residue levels authorized in fresh fruits have triggered the development of more environmentally sound control strategies. Despite the proven efficacy of Bt-based formulations against other Lepidopterans (González-Cabrera and Ferré, 2008), their use for controlling *T. absoluta* was initially recommended only when infestation levels were relatively low (Monserrat, 2009b, 2010); however, the results obtained in Spain from laboratory, greenhouse and open-staked tomato field assays have shown that Bt is effective against all instar larvae, reducing damage by up to 90% compared to controls when sprayed at 180.8 MIU/l (millions of international units per liter) (Fig. 6.15). Moreover, it was also shown that weekly sprays at 90.4 MUI/l can control *T. absoluta* throughout the growing season without any additional treatment, even at very high infestation levels (González-Cabrera *et al.*, 2011). Recent greenhouse assays have shown that treatments performed every other week at 90.4 MUI/l (which lowered the cost) are enough to reach an optimum control of the pest. In these assays it was also shown that products based on *B. thuringiensis* var. *kurstaki* can be combined with those based on *B. thuringiensis* var. *aizawai* to obtain similar efficacy while reducing the risk of resistance development in insect populations. Furthermore, the integration of Bt treatments with releases of *N. tenuis* resulted in a very promising strategy. The assays performed in greenhouses showed that Bt applied in conjunction with *N. tenuis* can provide control of *T. absoluta* while the predator is established in the crop. Thereafter, the Bt treatments can be discontinued and *N. tenuis* alone is able to control the pest (Mollá *et al.*, 2011).

The combination of Bt treatments and *B. bassiana* was also tested in open tomato fields in Spain, where it proved to be more effective than the fungi alone in terms of *T. absoluta* mortality observed per plant; however, there was variability in the protection of fruits during the experiment (Torres Gregorio *et al.*, 2009). Further experiments should clarify the best way to integrate these two entomopathogens for controlling *T. absoluta*.

The suitability of three species of entomopathogenic nematodes for controlling *T. absoluta*

Fig. 6.15. Third instar larvae of *Tuta absoluta* killed by Bt.

was also tested under greenhouse conditions. These assays showed that nematodes were highly effective at killing larvae (up to 100% mortality), but they had almost no effect on pupae (<10% mortality). Additionally, the high level of parasitism reached (77.1–91.7%) was evidence that nematodes are able to kill the larvae inside the galleries, so that this approach could be integrated with other control strategies to reach better and more efficient control of the pest (Batalla-Carrera *et al*., 2010). Currently, pest control worldwide is moving toward an IPM strategy which includes biological, cultural or biotechnological methods. Thus, entomopathogens should play an important role in this global effort.

6.7.2 Semiochemical management

T. absoluta is an example of how, in the absence of an efficient conventional control, an immature pheromone technology for insect control can be firmly established (Witzgall *et al*., 2010). The use of pheromone-lured traps as a key tool to monitor (Attygalle *et al*., 1996; Michereff *et al*., 2000a,b; Benvenga *et al*., 2007), manage and control *T. absoluta* in Europe and North Africa has resulted in a global demand of >2,500,000 *T. absoluta* lures per annum. The availability of a more economical pheromone active ingredient is fostering the development of novel control techniques that use pheromone more intensively, such as attract-and-kill, and mating disruption (Stoltman *et al*., 2010).

Mass trapping

The Southern European and North African invasion of *T. absoluta* increased the demand for pheromone monitoring lures, which were then used in mass-trapping campaigns for greenhouse pest management. Mass trapping can be an effective management tool in isolated and controlled spaces such as greenhouses. For *T. absoluta* in a tomato greenhouse setting, at least one trap per 500 m^2 has been used to reduce moth populations significantly as part of an integrated pest management program (Stoltman *et al*., 2010). Mass-trapping programs must be deployed early in the plant growth cycle, when *T. absoluta* populations are present at low densities, otherwise the program is likely to fail.

Traditional paper and plastic delta traps can also be used in a mass-trapping program. These traps may be preferred in larger operations due to their relatively low cost, ease of deployment and disposal. Paper delta traps come with sticky interior walls and are designed for one-time use. They should be disposed of once the trap becomes saturated. Conversely, plastic delta traps come with removable sticky liners. Liners can be replaced after they are filled. One problem with the sticky traps is that the glue liner of the trap becomes rapidly saturated under high *T. absoluta* population densities, and requires frequent replacement.

In order to reduce the cost of mass trapping, and also avoid trap saturation, growers have started using water traps in their mass-trapping programs. Trap designs vary and can be as simple as deep plastic trays filled with soapy water and with the pheromone lure suspended over the centre of the tray, just above the water line, so that attracted moths are trapped when they touch the soapy water (Fig. 6.16).

Mating disruption

Mating disruption is the practice of continuously dispensing synthetic sex pheromones into an area to limit the male's ability to locate and subsequently fertilize the calling females. Under pheromone disruption by competitive attraction, female moths compete with sources of synthetic pheromone for the male's response, a density-dependent phenomenon. Non-competitive mechanisms are density-independent phenomena, where the presence of the synthetic pheromone in the field modulates the male's ability to perceive, or to respond to, natural blends due to desensitization by adaptation and habituation, sensory imbalance or camouflage of the plume.

The potential for using *T. absoluta* sex pheromone for control through mating disruption was first studied by Michereff *et al*. (2000b) in small plots (0.01 ha of fresh-market tomatoes using doses up to 80 g/ha of the major pheromone component alone. Some of the treatments achieved an impressive 90% trap shutdown in these exceedingly small plots, but there was no direct correlation between trap catch suppression and protection of the tomato crop. Failure in protecting these experimental plots was attributed to the use of the incomplete blend and/or to the strong edge effect resulting from high *T. absoluta*

Fig. 6.16. Water trap used in mass-trapping strategy attracts *Tuta absoluta* with a sex pheromone lure and a light source (photo courtesy of Rodrigo Oliveira Silva and Daniela Fernanda Klesener).

populations in neighboring fields. Since females are not affected by pheromone treatments, it is possible that migrating mated females invaded the pheromone-treated area (Michereff *et al.*, 2000b). New efforts of mating disruption in greenhouses have demonstrated the feasibility of the technique for controlling the pest, despite cost constraints and availability of the pheromone (Navarro-Llopis *et al.*, 2010). In both studies, lack of an economic scale-up synthesis of the *T. absoluta* sex pheromone precluded larger, more elaborated mating disruption trials.

When the economic scale-up synthesis of the major component of the *T. absoluta* sex pheromone was developed by ISCA Technologies, Inc. (Stoltman *et al.*, 2010), it allowed researchers to create larger experimental field trials using a higher number of point sources and doses of pheromone active ingredient per treated area.

Attract and kill

Attract and kill is a density-dependent phenomenon that inherently requires substantially less pheromone than other non-competitive mating disruption formulations designed to achieve habituation/adaptation, sensory imbalance and camouflage, which prevent location of both natural and synthetic sources by overwhelming the male with pheromone. Attract and kill requires well balanced pheromone lures that not only elicit upwind flight behavior of the male, but also promote sustained contact with the point source.

Recently, ISCA Technologies began working on the development of an attract-and-kill formulation for *T. absoluta*. Preliminary field data indicate that this formulation has a longer field life than a similarly formulated mating disruption formulation, perhaps because of its sustained deleterious effect on attracted males (Stoltman *et al.*, 2010) (Fig. 6.17).

6.7.3 Plant resistance

The highest levels of plant resistance to *T. absoluta* have been observed in non-commercial (wild-type) genotypes of tomato; however, there are studies reporting resistance in commercial genotypes as well as in hybrids resulting from crossings between wild-type and commercial genotypes. França *et al.* (1984) performed greenhouse assays to evaluate plant resistance in 22 tomato genotypes, including *Lycopersicon hirsutum* f. *typicum*, *L. hirsutum* f. *glabratum* and

Fig. 6.17. A dollop used for attract-and-kill of *Tuta absoluta* males in tomato (photo courtesy of Lyndsie Stoltman and Ya-Ting Yang).

L. pennellii. They observed a non-preference effect in *L. pennellii* leading to a high level of resistance to *T. absoluta*. In addition, *L. hirsutum* f. *typicum* and f. *glabratum* showed antibiosis and non-preference, respectively. Lourenção *et al.* (1984, 1985) found that plants of *L. peruvianum*, infested with *T. absoluta*, showed significantly lower losses (measured as damaged foliar area) than more susceptible genotypes. Barona *et al.* (1989) also found a high level of resistance in lines of *L. peruvianum* and *L. hirsutum* and also in *L. pimpinellifolium*.

Castelo Branco *et al.* (1987) evaluated varietal resistance in F2 plants (*L. pennellii* × *L. esculentum*) based on morphological (velvety leaves, very hairy) and physiological (strong exudation) characteristics. Comparisons between susceptible and selected populations indicate that it is possible to select insect-resistant plants on the basis of morphological and physiological leaf traits, but exposure of these plants to insect infestation is also recommended for plant selection.

Giustolin and Vendramim (1996b) observed that larvae reared on *L. hirsutum* f. *glabratum* showed longer development, lower viability, lighter pupae and lower fecundity compared to those reared on a susceptible cultivar of *L. esculentum* (Santa Cruz Kada). In addition, several authors reported similar results when assessing plant age as a resistance factor, and found that *T. absoluta* larval stages lasted longer and larvae suffered greater mortality on older plants of *L. hirsutum* f. *glabratum* and *L. esculentum* (Picanço *et al.*, 1995; Leite *et al.*, 1998; Suinaga *et al.*, 1999).

Segeren *et al.* (1993) reported evidence of segregation for resistance to *T. absoluta* and the capacity to overcome the incompatibility barrier between tomato species by obtaining interspecific hybrids via embryo culture.

Giustolin and Vendramim (1996b) tested the effect of two allelochemicals on plant resistance. They used 2-tridecanone (2-T) and 2-undecanone (2-U), present in type VI trichomes of *L. hirsutum* f. *glabratum*. Larval mortality was 100% when fed with an artificial diet supplemented with mixtures of these two allelochemicals at concentrations ranging from 0.15% to 0.30% and 0.03% to 0.06%, respectively. Furthermore, there was concentration-dependent behavior when the diet was supplemented with 2-U. At 0.06% 2-U, there was high larval mortality (91.4%), while at 0.03% there was stimulation of insect development. Experiments performed with seven genotypes of two species (*L. esculentum*, *L. hirsutum* f. *glabratum*) and the F1 hybrid showed that *T. absoluta* oviposition and plant damage was greater in those genotypes with lower 2-T contents (Maluf *et al.*, 1997). Supporting this finding, Labory *et al.* (1999) concluded that high levels of 2-T are associated with a non-preference for oviposition and with resistance mechanisms to feeding. According to Leite *et al.* (1999), 2-T production increases from the base to the top of the plant, and the authors associated *T. absoluta* oviposition with an antibiotic effect. Although genotypes of *L. hirsutum* f. *typicum* have shown lesser infestation levels by *T. absoluta* compared to *L. esculentum*, including less success in biological development, this material does not contain the 2-T and 2-U allelochemicals (Ecole *et al.*, 2000). Leite *et al.* (2001) observed a higher mortality with increasing plant age. Their observation is most likely correlated with trichome density, which probably increases with age, resulting in a rise in the 2-T level and consequently a longer larval developmental period or high mortality.

Zingiberene is a sesquiterpene present in the glandular trichomes, especially in *L. hirsutum* f. *hirsutum*. Azevedo *et al.* (2003) found that crossing *L. esculentum* and *L. hirsutum* f. *hirsutum* results in an increase in zingiberene, which regulates resistance since it has a deterrent effect on *T. absoluta* oviposition and feeding.

Acyl sugars present in *L. pennellii* play an important role in the resistance of the tomato plant to *T. absoluta* (Resende *et al.*, 2006; Pereira *et al.*, 2008; Oliveira *et al.*, 2009b). Oliveira *et al.* (2009a) discovered a positive correlation between tetracosane and hexacosane and the percentage of mined leaves. Similar results were obtained with acyl sugars by Gonçalves Neto *et al.* (2010) and Maluf *et al.* (2010).

6.7.4 Cultural practices

Prophylaxis is one of the most effective and cheapest ways of reducing pest infestation (Berlinger *et al.*, 1999). Consequently, this is the aim of most of the cultural practices recommended for *T. absoluta* control. The adoption of prophylactic methods could be the key to success in controlling this pest, particularly in greenhouses, and as a result, there are several recommendations for cultural control (Arnó and Gabarra, (2010), and the online Endure Information Centre[i]).

One of the most accepted cultural methods for reducing *T. absoluta* populations is crop isolation. This can be achieved in greenhouses by screening vents and installing double doors. Monserrat (2009a) advised the use of mesh of at least 6 × 9 threads/cm^2 to exclude *T. absoluta* adults. One consideration, however, is that screening the greenhouse will reduce its ventilation, so measures to encourage air movement are essential to avoid adverse effects on the crop. In addition, nets will also hamper biological control, since they will prevent pest immigration and colonization by parasitoids and predators (Berlinger *et al.*, 1999).

Reducing early pest infestations is very important. Seedlings, especially, must remain pest-free. Therefore, extreme control measures are advised for transplant producers. When the pest damage is low, particularly at the beginning of the growing season, it is important to remove leaves, stems and fruits affected by the presence of *T. absoluta* larvae or pupae, by placing the materials in sealed plastic bags exposed to direct sunlight. Also, before planting, and throughout the growing season, removal of weeds that may also host *T. absoluta* is also advised. Furthermore, it is recommended that infested crop residues should be removed either during the growing season, or immediately following harvest, by burying the residue or placing the material in closed containers covered with a transparent plastic film to allow fermentation. In Almería (south-eastern Spain), covering crop residues with plastic for no less than 3 weeks reportedly reduced the number of adult *T. absoluta* by 94% during the fall (Tapia *et al.*, 2010). Crop residues can also be eliminated by burning or grinding combined with insecticide sprays (Robredo and Cardeñoso, 2008), although these methods may require a permit for burning, and involve the high cost of grinding.

Crop rotation with non-host crops is also imperative. In highly specialized farms where tomatoes are intensively produced, it is recommended that greenhouses should be emptied between crop cycles and sealed for 4–8 weeks, depending on the temperature (Monserrat, 2009b, 2010). Under these conditions, all adults emerging from the soil will die or will be captured by pheromone or light traps. In some situations, chemical treatments may be applied in order to reduce *T. absoluta* levels in soil. Soil solarization has been advised in warm climates, to kill pupae that remain in the soil after the harvest. To our knowledge, the impact of many of these measures on the infestation level of *T. absoluta* has not been quantified, but a broad consensus indicates that they may be useful as general prophylactic measures.

The use of genetic resistance may also be an alternative for controlling this pest, since some sources of resistance to *T. absoluta* have been reported in some wild tomato species. The two mechanisms of resistance detected so far have been antixenosis and antibiosis (Oliveira *et al.*, 2009a, b).

In Brazil, sprinkler irrigation has been shown to have a significant impact on populations of *T. absoluta* eggs and larvae. This type of irrigation can lead to a 62% reduction in the number eggs on the plant, depending on plant age and intensity of irrigation (Costa *et al.*, 1998). According to the same authors, water also negatively affects the number of larvae and galleries, although to a lesser extent (17–22%). To prevent *T. absoluta* fruit damage, Jordão and Nakano (2000) studied the use of paper bags covering the tomato, in combination with repellents to the pest. They concluded that the use of paper bags reduced damage caused by two Lepidopteran pests, *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) and *Neoleucinodes elegantalis* (Guenée) (Lepidoptera: Crambidae), but not by *T. absoluta*.

6.7.5 Chemical control

Many insecticides have traditionally been employed to control *T. absoluta* populations.

When the first pest outbreaks appeared in South America, organophosphate products (OP) and cartap were used, and were later substituted by pyrethroids in the 1970s (Desneux *et al*., 2010). In the 1980s, alternate applications of cartap and pyrethroids/thiocyclam were made (Lietti *et al*., 2005). New insecticides were introduced in the 1990s, such as acylurea, spinosad, abamectin, tebufenozide and chlorfenapyr. In addition, new pyrethroid molecules have been shown to be very efficient in Brazil (Silvério *et al*., 2009). The efficiency of OP products fell after 1980 with the development of resistance to such products by *T. absoluta* in Brazil and Chile, as well as resistance to cartap, abamectin and permethrin in Brazil (Siqueira *et al*., 2000, 2001), and to pyrethroids in Chile (Salazar and Araya, 1997) and Argentina (Lietti *et al*., 2005). This resistance raised doubts over insecticide use, but heavy chemical applications to control *T. absoluta* in these countries are still common. Recent research on plant extracts has demonstrated the efficiency of extracts of *Trichilia pallens* (Cunha *et al*., 2005, 2006, 2008) or neem (Gonçalves-Gervásio and Vendramim, 2007) on *T. absoluta*, but such products are rarely used in South America.

Since *T. absoluta* was detected in the Mediterranean region, the most common control practice has been based on the use of chemical insecticides (Bielza, 2010). Nevertheless, these treatments may disrupt existing IPM programs in tomato crops based on biological control (van der Blom *et al*., 2009) and may lead to resistance (Bielza, 2010), as it occurred in the area of origin of this pest. Therefore, there was an immediate need to choose pesticides which fulfilled two main objectives: (i) effectiveness against *T. absoluta*; and (ii) selectiveness, in order to preserve natural enemies in tomato crops. In addition to spinosad and indoxacarb, which were the two first available insecticides in the Mediterranean region, new effective and selective insecticides are currently available to control *T. absoluta*, such as flubendiamid, emamectin, rynoxapir, abamectin or etofenprox (Araujo-Gonçalves, 2010; Torné *et al*., 2010; Espinosa, 2010; Robles, 2010; López *et al*., 2010; Astor, 2010; Gutiérrez-Giulianotti, 2010). Moreover, azadiractine (neem) and sulfur treatments may also help to reduce *T. absoluta* incidence, although efficacies are much lower (Monserrat, 2009a). However, repeated applications should be conducted each season in order to control *T. absoluta* exclusively by chemical means. Rotation of these active ingredients is compulsory to prevent resistance development (Ortega *et al*., 2008; Bielza, 2010), as well as the use of insecticides compatible with biological control, and integration with other control tactics.

6.8 Final Considerations

Given our knowledge of the behaviour and incidence of *T. absoluta* in tomato crops, and based on the information available on its control, it is impossible to control this pest with a single method. Therefore, to successfully manage this pest it is necessary to integrate several control strategies. The first step in *T. absoluta* management is to adopt the cultural practices described above, particularly in greenhouses. Second, methodical and periodical sampling methods should be adopted with the use of pheromone traps to monitor the incidence of adult males, and by direct damage assessments of the crop by means of plant sampling. Based on the data obtained from these samplings, appropriate control methods should be adopted. Preventive methods, such as the use of systematic *B. thuringiensis* treatments, alone or in conjunction with sex pheromone formulations for mating disruption or attract-and-kill, can prevent or significantly delay crop damage. Furthermore, the conservation and promotion of natural enemies in the system, especially combined with entomopathogens or selective insecticides, may contribute to suppression of *T. absoluta* populations. Further studies are needed to identify the most effective complement of environmentally sound management methods to control this pest. Finally, curative treatments with approved insecticides should be applied when necessary. In summary, the current impact of *T. absoluta* in tomato crops makes it necessary to adopt an IPM strategy to control and reduce its incidence.

Note

[i] www.endureinformationcentre.eu, accessed 14 July 2012.

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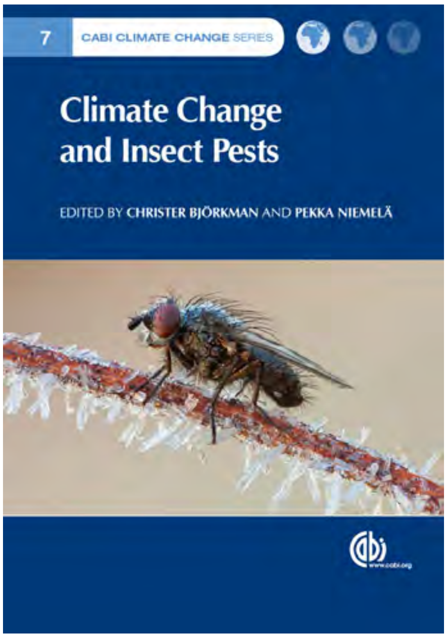

Climate Change and Insect Pests

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2 Species Distribution Modelling in Predicting Response to Climate Change

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Abstract

Species distribution modelling comprises a range of widely used tools for predicting potential changes in insect pest species distributions with climate change. We review the current literature to see the effectiveness of different approaches, particularly in comparing predictions based on current distribution data (correlative or 'environmental niche models') and those based on life-history traits and determination of thermal limits (mechanistic models). We review new developments in implementing processes such as dispersal and biotic interactions within species distribution models and how these could be used to develop management strategies incorporating natural enemies into climate change predictions. We propose that species distribution models should be linked with key trait data where possible to inform better of response to climate change.

2.1 Introduction

Many species of invertebrates not only cause huge losses to biodiversity through competition and disruption to ecosystem function (Ostberg *et al*., 2013; Zhou *et al*., 2013), but also represent some of the most recognized causes of agricultural crop loss through both herbivory and competition, and as vectors of disease (Ziska *et al*., 2010). Further to this, there are many invertebrate species that pose serious concerns for human health, particularly mosquito vectors (Bai *et al*., 2013; Lee *et al*., 2013) and ticks (Morin and Comrie, 2013; Porretta *et al*., 2013). Climate change will result in a range of potential impacts on pest invertebrates (reviewed in Harrington and Woiwood, 1995), including changes in population dynamics such as growth rate and overwintering success, as well as an increase in the number of generations per year and changing interactions with other species (Van der Putten *et al*., 2010; Sutherst *et al*., 2011). Greater risks are likely to come from changes in geographic distributions of pests and invasions by new pests (Harrington and Woiwood, 1995). For example, the distribution shifts and greater outbreak potential of the coffee borer beetle, *Hypothenemus hampei* Ferrari, in Africa (Jaramillo *et al*., 2009), and the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, in North America (both Coleoptera: Curculionidae) (see de la Giroday *et al*., 2012), and the pine processionary moth, *Thaumetopoea pityocampa* Schiff (Lepidoptera:

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Thaumetopoeidae), in Europe (Battisti *et al.*, 2005), are all linked to climate change.

Pest invertebrate species cause extensive damage to a wide range of economically important industries such as fruit and horticulture, pasture and broadacre crops including oilseeds, cereals and pulses. While drivers such as changes in pesticide use and increased irrigation are likely to be associated with some shifts in species distributions, climate change is likely to be driving shifts in the geographic distribution of some pest invertebrate species (Hoffmann *et al.*, 2008). With changes in distribution come changes to phenology and persistence that ultimately lead to pest outbreaks and spread of vector-borne plant pathogens. Some species, such as armyworm (Lepidoptera: Noctuidae), may be responding negatively to climate change (Hoffmann *et al.*, 2008). Others, such as the slug, *Milax gagates*, which perform better in arid conditions, may benefit from drier conditions under climate change (Nash, 2008; Domisch *et al.*, 2011; Jiang *et al.*, 2013), and so too the transmission of plant viruses, such as Yellow dwarf by aphid vectors (Parry *et al.*, 2012). Clearly, pest species will respond to climate change differently, and it is thus important to investigate individual species' responses through a framework that is broadly applicable.

To meet the challenges that climate change will impose on food production, we need to be able to predict accurately how pest species will respond. To date, research on how invertebrate pests will respond to climate change is relatively rare (Mika *et al.*, 2008; Ziter *et al.*, 2012). Such research could help in the development of management recommendations to be used by growers to aid crop protection in the future (Steffen *et al.*, 2011; Turner *et al.*, 2011). For this to be achieved, a good understanding is required of how species have adapted in the past, how they respond to current variability in weather, and when and how this is likely to lead to pest outbreaks across agricultural landscapes. An essential component of this is to predict species distributions across the landscape.

2.1.1 Predicting distributions of pest insects

The link between insects and climate was researched widely even before the field of ecology was formally recognized. When Uvarov (1931) reviewed this subject, he cited over 1000 papers, many of which dated back to the 19th century or earlier. At this time, the field of 'climatic analysis of insect distribution' was first formulated. Meteorological data were available to ecologists and the understanding of how large-scale climatic variables influenced distributions was becoming apparent (e.g. Grinnell, 1917). While there existed a few studies that studied the effect of climatic variables on pest insects: for example, alfalfa weevil (Ball, 1917), green bug, *Schizaphis graminum* Rond. (Ruggles and Wadley, 1927), and Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann) (Gjullin, 1931), it was William C. Cook who outlined methods of predicting the distributions of pest invertebrate species (Cook, 1931). Within these methods, Cook (1929) described how weather station data could be used initially to determine climatic zonations for pest insects. He explained how these zones could be correlated with the frequency of limiting climatic conditions and thus provide maps describing where outbreaks of species such as the pale western cutworm, *Porosagrotis orthogonia* Morr. (Cook, 1924), and the true armyworm, *Cirphis unipuncta* (now *Mythimna unipuncta* (Haworth)) (Cook, 1929), were more likely to occur. Cook went on to describe a framework for predicting insect distributions that tied weather data to insect distributions and known physiological parameters (Cook, 1931). While the effects of 20th century climate change were not apparent at this time, and the field of invasion biology was just emerging, this provided a robust framework for predicting the distributions of pest invertebrates in relation to climate. (For another account of Cook's contribution to the field of predicting pest insect distributions in relation to climate, a recent paper by Sutherst (2014) gives further detail.)

There have been many other advances in the field of pest ecology and distributions since the time of Cook (e.g. Messenger, 1959; Andrewartha and Birch, 1982), but predicting the distribution of a pest species still remains an essential component of understanding the potential effects of climate change. Today, we are faced with enormous challenges posed by a changing climate and increasing introductions of insect pests through global trade and tourism, and we require tools, methods and competent practitioners to meet them.

In this chapter, where we review the prediction of pest invertebrate response to climate change through the use of modern tools, it is still useful to consider the ideas of Cook (1931). Central to predicting potential distributions for pest insect species and response to climate change is the concept of the *niche*.

2.2 Niche Concept

2.2.1 Niche definitions

The niche is an ecological concept that ties biotic and environmental elements together (Keller and Golley, 2000) to define the distribution or functional role of a species. To describe the niche for a given species accurately would involve measuring every environmental condition, biotic interaction and resource that an organism requires (Porter and Kearney, 2009). In reality, this is an impossible task; however, the niche as a concept still serves as a useful tool for understanding species' requirements across space and time (Soberón and Nakamura, 2009; Wiens *et al*., 2009). In terms of predicting the distribution of species, there are different and equally important interpretations of the niche that need to be defined when investigating processes and traits that determine niche boundaries (Colwell and Rangel, 2009; Porter and Kearney, 2009; Wiens *et al*., 2009).

The first formal definition of the niche was provided by Joseph Grinnell, who described the niche in terms of areas of distributions of species and the different variables that govern the range of species (Grinnell, 1914, 1917). That is to say, that the spatial extent of the range and geographical expression of a species' niche are approximately the same (Tingley *et al*., 2009). This provides a somewhat restricted definition of the niche, employing broad, non-interacting ecological variables (Soberón and Nakamura, 2009) to set the range limits of species (Wiens, 2011). This simplicity allows for an operational and straightforward niche concept (Soberón and Nakamura, 2009) and, when employed, can provide strong explanations of species' range boundaries (Tingley *et al*., 2009). Such an interpretation of the niche lends itself to being particularly useful in understanding biogeographical patterns (Wiens, 2011).

While the Grinnellian niche encapsulates broad environmental processes, Charles Elton defined the niche in terms of biotic interactions and resource limitations that shaped the distribution of a species (Elton, 1927; expanded by Soberón, 2007). This interpretation of the niche presents the species as playing a functional role within a community (Wiens *et al*., 2009), and is thus a much finer-scale concept than that of Grinnell. The Eltonian niche employed axes of resource utilization and provided the foundation for later elaborations by Hutchinson (1957) and MacArthur (1972), to become widely used in ecological studies (Wiens *et al*., 2009). This interpretation of the niche allows for understanding of the biophysical requirements of the species to be measured and associated with landscape features, to define niche boundaries.

In later development of the niche concept, George Evelyn Hutchinson (1957) presented a niche–distribution duality that provided perhaps the most important distinction of niche concepts termed fundamental and realized niches. Hutchinson described the niche as taking both the form of the *fundamental* niche – the direct physiological requirements of a species – and the *realized* niche – the proportion of the fundamental niche actually occupied by the species at a particular time, due to limits set by both biotic and abiotic interactions (Wiens *et al*., 2009). This Hutchinsonian definition of the niche allows for both the Grinnellian and Eltonian niche interpretations to be employed in a suite of species–environment relationships within physical (environmental) and geographical (biotope) space (Colwell and Rangel, 2009; Wiens *et al*., 2009).

The growth of species distribution model use has seen the advent of the *potential* niche. This describes the area that might permit population persistence and growth, but to which the species has not yet dispersed (Soberón, 2007; Soberón and Nakamura, 2009). This concept is particularly important for pest and other invasive species that are not in equilibrium with the environment.

2.2.2 Niche conservatism

When measuring the response of pest insects to climate change, it is important to understand how the species–environment relationships are likely to persist or change. A species that occupies geographical regions corresponding to regions of niche space set by the fundamental niche is said to have displayed niche conservatism (Colwell and Rangel, 2009). Conversely, niche 'shifts' describe transgression between species–environment relationships across ranges (e.g. Broennimann *et al*., 2007; Fitzpatrick *et al*., 2007) or over time (e.g. Kharouba *et al*., 2009). For studies of climate change, niche conservatism refers to species that track climatic change to preserve species–environment relationships: species must undergo elevational and/or latitudinal range shifts to stay within their favourable climate zones (Colwell and Rangel, 2009). This process can cause problems for species not able to disperse as fast or as far as the changing climate dictates.

Niche shifts may occur if the native range holds only a subset of the full range of the fundamental niche due to interspecific competition (the presence of predators and pathogens), or a geographical barrier, or a limited set of possible environments – the species in its invasive range might simply be expressing other parts of the fundamental niche (Broennimann *et al*., 2007; Rödder and Lötters, 2009; Alexander and Edwards, 2010; Medley, 2010). Alternatively, the species may have adapted, resulting in a change in a species' response to environmental variables over time (Broennimann *et al*., 2007; Ficetola *et al*., 2010). A niche shift may also arise through species dispersal and colonization, driving expansion geographically into new environmental habitats (Alexander and Edwards, 2010). These processes of range expansion may be facilitated by changes in climatic conditions, land use or through evolutionary adaptation.

Measuring niche conservatism can give insight into predicted pest insect response to processes such as climate change and biological invasion, including the interaction of these two. In this chapter about modelling insect pests and climate change, we describe tools to measure niche conservatism geographically and look at examples from both biological invasions and climate change research, as these fields are highly relevant to one another. One way in which we can study the process of niche shifts and niche conservatism in response to climate change is to construct different types of species distribution models. These models can be used to inform which environmental variables and traits may limit the niche, and the level of niche conservatism displayed in species invasion and response to climate change.

2.3 Species Distribution Models

Species distribution models are increasingly popular tools for describing the niche of a species and detecting niche shifts. There are a number of modelling methods available that have varying advantages and explicabilities, and which utilize different interpretations of the species niche. Commonly used in conservation biology research (Pearson *et al*., 2007; Habel *et al*., 2011), species distribution models may also be applied to invertebrate pest species, especially when questions need to be asked of species invasion or climate change impacts. Importantly, the choice of which type of model to use relies heavily on the type of data you have available. It is also crucial that as much information about the species as possible is included to ground some of the choices during the modelling process.

Table 2.1 gives examples of recent research showing the application of species distribution models for a variety of pest insects. At present, the majority of pest insect distribution models determine potential areas for species invasions, though more are starting to address responses to climate change.

Much of the recent advance in species distribution modelling has been made possible by the increasing availability of global weather station data and the computational power to process these. This has allowed for the formation of geospatial databases that offer high-resolution layers of averaged monthly climate data (e.g. WorldClim (Hijmans *et al*., 2005), ANUCLIM (v6.1, Fenner School of Environment and Society, Australian National University)). These data can be transformed into biologically relevant trends and patterns of rainfall, temperature, humidity and solar radiation (e.g. BIOCLIM variables (Nix and Busby, 1986)), and used to determine limiting factors to species distributions (Elith and Leathwick, 2009). Instead of models being restricted to a few sites, it is possible to project models across entire countries, continents or globally, to understand the macroecological processes of invasion and climate change (Peterson, 2003; Araújo *et al*., 2005; Elith and Leathwick, 2009). There is also a range of future climate models (global circulation models – GCMs) that are based on different scenarios of the severity of climate change. These allow for future forecasts of climate change to be incorporated into species distribution models. Choice of climate change scenario can alter model outputs, so this needs to be taken into consideration when building models, to determine which scenarios are likely to be relevant to the models (Beaumont *et al*., 2008; Mika and Newman, 2010). As no one model may be considered the 'best' (Beaumont *et al*., 2008), an ensemble forecast of a range of GCMs can outperform single GCMs and provide greater confidence in model outputs (Fordham *et al*., 2011).

While the toolbox is increasing for species distribution modelling, there is little chance that automation will ever take hold (see Sutherst, 2014), and generalizations are likely to be only for large-scale studies rather than for effective management at the landscape level (e.g. general poleward movements; Bebber *et al*., 2013). Selection of the most appropriate model requires careful consideration of the species and the data available for the species, which will be different in terms of forms and amount. There is no 'one size fits all' approach for modelling pest insect species, and this needs to be taken into consideration. The range of models presently available are suited to different tasks and use types of data in different ways, and it may often be that applying different types of models to the same species, allowing for determining congruence between predictions, is a better approach (Venette *et al*., 2010).

There is a wealth of literature on the application of different species distribution models, and there are many debates surrounding the application and validation of such models. Here, we present a brief overview of the currently popular methods of species distribution models being applied to questions surrounding pest insects and climate change; ecological niche models, mechanistic models and a semi-mechanistic approach, CLIMEX (see Fig. 2.1).

2.3.1 Ecological niche models

Species distribution models that attempt to characterize the niche by correlating known distribution points with environmental predictor variables, or covariates, are typically referred to as ecological niche models (ENMs) (Jiménez-Valverde *et al*., 2011; Wiens, 2011). ENMS investigate something close to the realized or potential niche of a species by correlating limiting variables identified from the landscape the species is found in to suitable habitat in appropriate geographic areas (see Elith

Table 2.1. Examples of species distribution models for pest invertebrate species.

Common name	Species	Models	Type	Use	Locality	Reference
Fig fly	*Zaprionus indianus*	MAXENT/GARP/ Mahalanobis distances	Correlative	I	Global	da Mata *et al*., 2010
Western corn rootworm	*Diabrotica virgifera virgifera*	ENFA/Mahalanobis distances	Correlative	I/C	Northern hemisphere	Aragón and Lobo, 2012
Yellow-legged hornet	*Vespa velutina nigrithorax*	Ensemble modelling	Correlative	I/C	Global/Europe	Barbet-Massin *et al*., 2013
Mediterranean fruit fly/ Natal fruit fly	*Ceratitis capitata/Ceratitis rosa*	GARP/PCA	Correlative	I	Africa/Europe/global	De Meyer *et al*., 2008
Asian tiger mosquito	*Aedes albopictus*	CLIMEX/MAXENT	Semi-mechanistic/ correlative	I/C	Australia/global	Hill *et al*., 2014
European grapevine moth	*Lobesia botrana*	Physiology/demographic	Mechanistic	I	California/USA	Gutierrez *et al*., 2012
Light brown apple moth	*Epiphyas postvittana*	Temperature/demographic	Mechanistic	I	California	Gutierrez *et al*., 2010
Light brown apple moth	*Epiphyas postvittana*	CLIMEX/MAXENT	Semi-mechanistic/ correlative	I	Global	Lozier and Mills, 2011
Bird cherry-oat aphid	*Rhopalosiphum padi*	CLIMEX	Semi-mechanistic	I	Global	Macfadyen and Kriticos, 2012
Pea leafminer	*Liriomyza huidobrensis*	CLIMEX	Semi-mechanistic	I/C	North America	Mika and Newman, 2010
Swede midge	*Contarinia nasturtii*	CLIMEX	Semi-mechanistic	I/C	North America	Mika *et al*., 2008
Spruce budworm	*Choristoneura fumiferana*	Ecophysiology/temperature	Mechanistic	C	North America	Régnière *et al*., 2012
Brown marmorated stink bug	*Halyomorpha halys*	MAXENT	Correlative	I	North America/global	Zhu *et al*., 2012

Note: I = invasion risks; C = response to climate change.

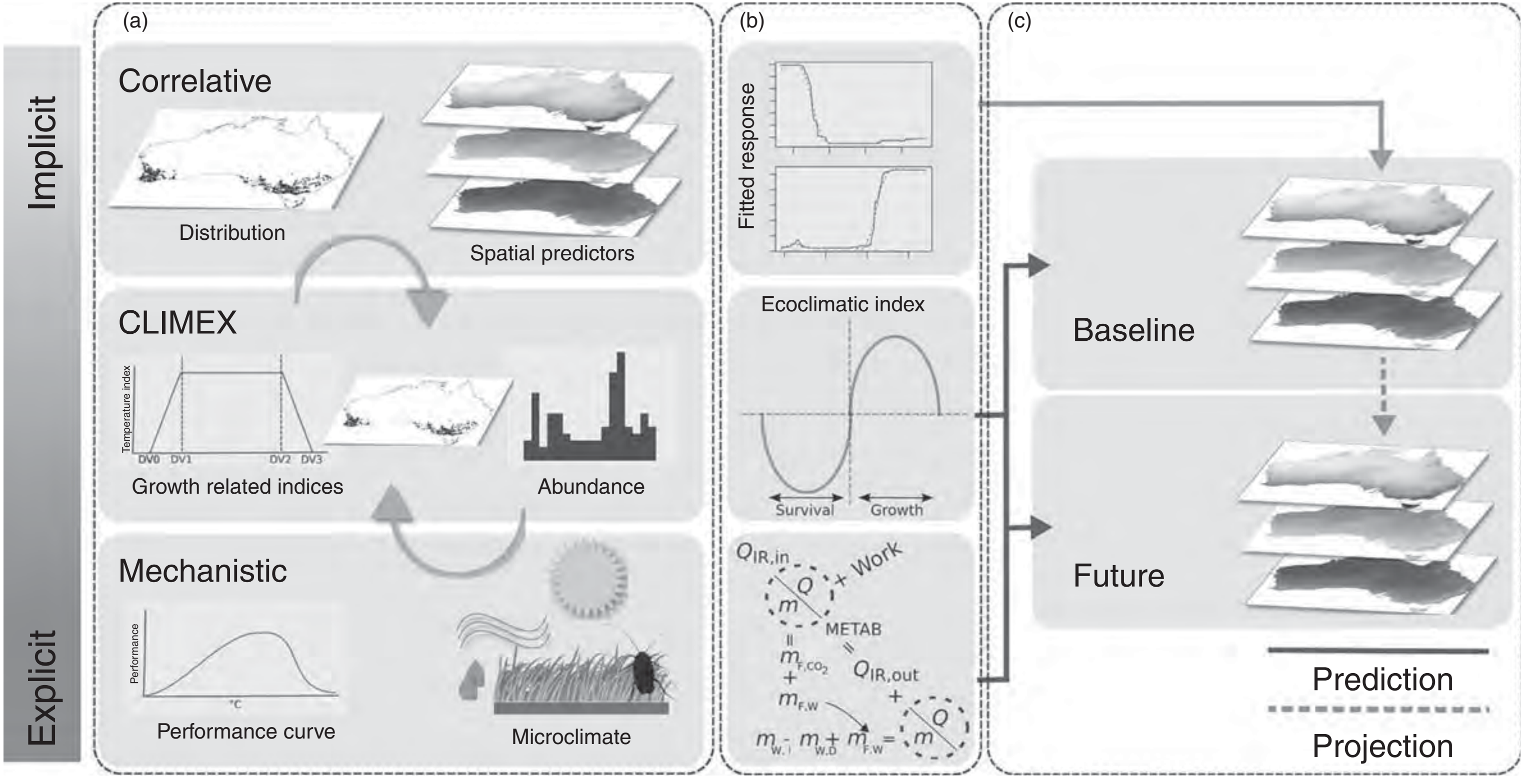

Fig. 2.1. Schematic illustration showing general differences between types of species distribution models (SDMs) used in predicting the response of insect species to climate change. (a) Displays the different categories of SDM mentioned in this chapter and the data sets they incorporate. (b) Displays how those data are fitted in the model. (c) Displays how the fitted models are then either spatially predicted or projected to new climate surfaces. Explicit and implicit scale is adapted from the review in Kearney and Porter (2009). *Correlative models* (typically called *ecological niche models*) combine known localities of species (presence-only or presence-absence records) with spatial predictors at each of these locality points to model species–environment relationships. Fitted functions for response to incorporated variables are then combined to determine the species–environment relationships, and then this can be predicted to the spatial data the model was trained on, or projected (extrapolated) on to new spatial predictors, such as climate change scenarios.

continued

et al., 2011 for a more detailed explanation). Using such models, it is possible to predict pest insect species range boundaries and project these models into future climate change scenarios (extrapolation) to investigate how changing climate space may influence broad-scale species–environment relationships.

There is an increasing variety of correlative methods available to predict the distribution of species, ranging from regression methods such as GLMs (generalized linear models) and GAMs (general additive models), bioclimatic methods such as BIOCLIM and ENFA (environmental niche factor analysis) and through to more recently developed machine-learning methods, MAXENT (maximum entropy) and BRTs (boosted regression trees). A prerequisite for using all these types of ENMs is having sufficient distribution data to characterize the species–environment relationships across the geographical ranges that are likely to determine the distribution. In turn, good distribution data provide a clear advantage of a robust model being built, with little knowledge of the species' ecology and biology required (although to present a model in isolation of this will provide little benefit). One of the key points of using distribution information is that these points are the result of many different ecological processes (Sutherst, 2014). That is, when applying correlative models, the data being included could represent any number of possibilities that translate into a presence point. Presence points do not always represent population persistence, and thus it is imperative to understand which data are useful to the modelling process.

Different forms of distribution data will again dictate which of these model types is most appropriate to the species question in hand, including amount of distribution points, the prevalence of those points across a given area and whether there is absence data as well as presence data. For instance, MAXENT and ENFA require presence-only data (with an ecologically defined background, or study area), whereas BRTs can employ presence and true (surveyed) absence data. What ENMs all have in common, however, is the requirement of well-sampled and unbiased data to construct models that encapsulate as broad a range of species–environment relationships as possible. Ideally, species–environment relationships in both the native and invasive ranges need to be characterized (Beaumont *et al*., 2009; Jiménez-Valverde *et al*., 2011). For many pest insect species, the only data available are for where a species has been found (e.g. outbreaks) or abundance data, thus the correlative models in Table 2.1 are all based on presence-only data. These data need to be checked closely for errors, and often require expert opinion to confirm the validity of distribution data. For more information on spatial biases and sampling errors and how they influence models, Dormann *et al.*

Fig. 2.1. *continued*

CLIMEX draws from different knowledge domains (e.g. physiological response, distribution data and abundance data) to determine an ecoclimatic index that is a combination of growth and stress indices (redrawn from Sutherst *et al*., 2004). This is run across weekly values throughout a year and then combined into a yearly summary of population growth and survival seasons (adapted and redrawn from Sutherst, 2003). In this way, models can be run for a given locality or across gridded spatial predictors, to produce maps of geographic suitability based on the ecoclimatic index. By running the model on future climate scenarios, CLIMEX is able to avoid the inherent issues of extrapolation that correlative models incur.

Mechanistic models take physiological information measured on the species to define limits to distributions based on processes and ecophysiological profiles. While mechanistic or process-based models can take many forms, the stylised one here combines performance curves and information about the microclimate (adapted, with parts redrawn from Kearney and Porter, 2009). Models can be based on how the species experiences the environment, how this affects metabolic rate and what this ultimately means to distributions and phenology under both current (baseline) and future conditions. Additionally, mechanistic models may be able to incorporate biotic interactions as explicit processes to examine the effects of climate change on pest insects and competitors/predators (see text for more detail).

(2007) and Elith and Leathwick (2009) provide reviews.

Because biotic and abiotic factors, and dispersal constrain the niche, ENMs can provide only partial information on the full range of environmental conditions that the species may survive (i.e. not estimating the fundamental niche, or even the potential niche) (Jiménez-Valverde *et al*., 2011). Related to this there are two main criticisms when using correlative models for measuring biological invasion and response to climate change.

The first of these criticisms is that environmental limits may be different between populations (particularly across both native and invasive ranges), inhibiting the ability of models to describe both ranges (Randin *et al*., 2006). For instance, when characterizing the realized niche of the native range, the species may be inhibited by a range of barriers, including biotic and abiotic factors that do not exist in the invasive range (Beaumont *et al*., 2009), resulting in underestimation of the potential invasive niche. Further, insect pest species are often not in a state of equilibrium with their environment, particularly within novel, invaded ranges (Václavík and Meentemeyer, 2009). This may translate into geographic range expansions as species continue to spread to fill their potential niche (Soberón, 2007; Soberón and Nakamura, 2009) and give rise to issues with ENM predictions. However, there are some techniques to help with these issues; see Elith *et al*. (2010) and Hill and Terblanche (2014) for examples of using presence-only data for range-expanding species. This non-equilibrium may be further exacerbated through climate change.

The second group of criticisms surrounds the use of ENMs as reliable tools for extrapolating into new space or time. Some degree of caution must be taken when projecting ENMs, as the relationship of variables projected may result in underprediction of areas that will contain non-analogue climates. Therefore, when ENMs are used to measure niche conservatism and response to climate change, they inherently encompass a broad range of factors and include the possibility that niche shifts are not a result of change in the fundamental niche (Hill *et al*., 2012). A good primer on the application of the transferability of correlative species distribution models is found in Elith and Leathwick (2009).

In the absence of strong biotic interactions, as is often the case for pest insect species, it is possible to explore modelled responses and apply ENMs in an attempt to account for unstable relationships with climate, and as yet unencountered environmental conditions (e.g. Elith *et al*., 2010) such as climate change. Given good distribution data in both native and invasive ranges (characterizing the realized niche as much as possible), correlative models have been demonstrated to be valuable tools for modelling pest insect distributions in relation to climate change.

2.3.2 Mechanistic models

Mechanistic models are often referred to as process-based (Morin and Thuiller, 2009) or trait-based (Kearney *et al*., 2008) models and use explicit biological processes built on species-specific observations (Morin and Thuiller, 2009). In this regard, mechanistic models are often able to overcome some of the main issues associated with using ENMs, such as when they are employed to investigate species response to climate change, they are not extrapolating from inferred relationships measured through distribution data but rather aim to translate morphological and physiological traits of a species with key environmental variables and the terrain (Kearney *et al*., 2008; Kearney and Porter, 2009). This means that mechanistic models require little to no information about the distribution of a species to construct the model (Kearney *et al*., 2008), which may be much more suited to a pest insect species of which little is known about the origin or geographic distribution but there is the ability to characterize life tables and trait data.

While mechanistic models are not always used for species distributions, they can be projected on to spatial data (e.g. GIS data), like those used as predictor variables in correlative models, to determine the probability of a given location, or grid cell, to meet the organism's resource requirements (Kearney and Porter, 2004). Information regarding physiological response to climatic variables can be compiled into a framework to understand activity, reproduction and survival thresholds. Mechanistic models that may be most useful for the prediction of pest invertebrate distributions include life history and phenology models (e.g. Gutierrez *et al*., 2008, 2010, 2012) or thermodynamic niche models (e.g. Kearney *et al*., 2008; Kearney and Porter, 2009). Like correlative ENMs, they can be interpreted through the Hutchinsonian niche duality, but instead characterize axes of the fundamental Eltonian niche. Mechanistic models can also include information about the microclimate – the environmental conditions an individual of a species will experience and utilize (Kearney *et al*., 2009).

The downside of using mechanistic models in pest insect species distribution modelling is that this avenue is often data intensive, and thus a single species requires much research attention. This may be possible for established pest species that often have a long history of research interest, resulting in data accumulation (e.g. light brown apple moth, *Epiphyas postvittana* Walker, pine processionary moth, gypsy moth, *Lymantria dispar* L., mosquitoes including *Anopheles* and *Aedes* spp., and others), but not so much for emerging pests that require immediate attention. When sufficient data are available though, mechanistic models are very appropriate and allow for more in-depth analyses of species response to climate change. This is particularly evident for species that are in a state of flux or range expansions (filling potential niche), or through adaptive changes in physiological or morphological traits. Species that are in the process of such adaptive shifts (e.g. the cane toad, *Bufo marinus*) may prove challenging to apply ENMs (Kearney *et al*., 2008), unless different weightings and model complexity parameters are explored, grounded on other biological information (Elith *et al*., 2010). This is important in terms of understanding the effects of climate change on pest invertebrates, as research should aim to include both phenotypic and genotypic flexibility (Bale *et al*., 2002). Mechanistic models can incorporate levels of variation or plasticity in distribution-limiting traits (Kearney and Porter, 2009; Kearney *et al*., 2009; Kolbe *et al*., 2010), which allows for hypotheses of adaptive shifts to be estimated under selective conditions such as climatic change.

Mechanistic models that incorporate trait variability (e.g. Kearney *et al*., 2009) provide an alternative to using an ENM-centred framework. However, while mechanistic models that characterize the thermodynamic niche (e.g. Kearney *et al*., 2013) provide comprehensive detail, these require many parameters and extensive empirical research. By having a mechanistic understanding of how climate affects life-history traits such as emergence (e.g. Kearney *et al*., 2010), and number of generations, it may be possible to translate these into guidelines for control measures. Finally, as they are based on explicit processes, mechanistic models are also able to take directly into account other environmental processes, such as biotic interactions. We talk more about this later.

2.3.3 CLIMEX

One of the most common modelling tools used for pest insect distributions is CLIMEX (Sutherst and Maywald, 1985). This tool uses a process-fitted or semi-mechanistic approach to examine the relationship between climate, species distributions and patterns of growth (Macfadyen and Kriticos, 2012). Importantly, CLIMEX models can be fitted using a combination of empirically measured parameters, abundance and point distribution records. These data types are often complementary for insect pest species and allow for knowledge gaps to be bridged when constructing informative models. Hence, CLIMEX is ideal for modelling distributions of pest insects, as it often is that data are 'patchy' across abundance, distribution information and physiological information (such as life-table studies).

The CLIMEX model works through a series of weekly growth and stress indices that are combined to produce an ecoclimatic index (EI). The EI describes regions that are unsuitable for the species to persist, through to those that provide a 'perfect' environment for the species. This is interpreted within a scale of 0–100 (Olfert *et al*., 2011), with an EI over 20 considered to convey ideal conditions (Sutherst *et al*., 2004) and below 10 an unfavourable environment, though rating interpretations will be species specific to some extent. The strength of CLIMEX lies in its ability to project models to new environments without relationships between variables confounding projections. CLIMEX also has a lot of flexibility; for example, when abundance patterns are not well known, they can be inferred from development rate experiments or observations and these become methods of validation (Kocmánková *et al*., 2011; Macfadyen and Kriticos, 2012).

The coupling of demographic parameters with spatial distribution information and other different data types gives CLIMEX certain advantages over SDMs and allows for basic physiological information (e.g. response to temperature, moisture) to be incorporated into climate change projections. CLIMEX is able to avoid some of the issues involved with transferability associated with ENMs, due to the model being built on climate change data rather than being extrapolated. This makes CLIMEX suited to predicting new geographical regions for invasive invertebrate species, and also responses to climate change. However, the stress indices are normally derived from the realized distribution and, due to the nature of the climate data used, CLIMEX models do not capture microclimate effects. In this way, CLIMEX is closer to a correlative approach, an important consideration when employing this model type.

Another advantage to using CLIMEX is that it is also able to investigate evolutionary adaptation indirectly by adjusting parameters based on information about changes in physiological tolerances. For example, Hill *et al*. (2014) looked at the mosquito vector of Dengue fever, *Aedes albopictus*, and incorporated different physiological profiles (based on experimental data on adaptive change) to examine how the species might respond to climate change given a shift in temperature tolerance.

2.3.4 Other models

Besides the main types we have just presented, there is a range of other models available to model insect pests and their response to climate change. One that looks particularly applicable is the Insect Life Cycle Modeling (ILCYM) software (Sporleder *et al*., 2009), which can be used to determine the number of generations in a given geographical area under different climatic conditions (Kroschel *et al*., 2013). A phenology model like ILCYM could determine if suitable climate space determined by ENM methods would translate into faster population growth for different pest insect species. This coupling of methods would provide some valuable insight into pest insect species and climate change.

As climate change is likely to affect processes beyond what any one modelling process can capture, it may be important to combine multiple modelling methods (e.g. ENM, semi-mechanistic, phenological and thermodynamic mechanistic models). Using combinations of models to assess the response of pest insects to climate change may translate into more targeted management decisions. For example, using CLIMEX alongside ENMs allows for areas of congruence to be assessed (e.g. Lozier and Mills, 2011; Hill *et al*., 2014).

2.4 Current Developments/Future Directions

So far in this chapter, we have considered species in isolation, and without considering dispersal ability. Both the interactions with other species and the ability of species to move both actively and passively are likely to play major roles in determining response to climate change. Here, we review current developments in each of these categories and suggest ways in which they may be incorporated in predictive modelling of pest insect species.

2.4.1 Biotic interactions

One of the main limitations when applying SDMs to a single species is that each species is considered in isolation and as a single population. Species, of course, do not exist free from interactions with other species, nor are they homogeneous in response to environmental stressors. Interactions such as competition, predation and parasitism are all likely to be impacted by climate change, resulting in species composition shifts and biocontrol failures (Sutherst *et al*., 2007; Thomson *et al*., 2010). Ecologists increasingly recognize the importance of species interactions for mediating the effects of climate change (reviewed in Tylianakis *et al*., 2008; Gilman *et al*., 2010; Walther, 2010; Yang and Rudolf, 2010).

Biotic interactions (e.g. competition and predation) may restrict the spread of pest invertebrate species (i.e. a new predator encountered in an invasive range, or competitive interactions between species) under present climatic conditions, but these interactions may mismatch through shift under climate change, resulting in altered pest invertebrate distributions. Biotic interactions also impact on population abundance across time, limiting species distributions spatially. In terms of biocontrol, beneficial (predators and parasitoids) species may respond to climate change in completely different ways than the pest invertebrate they attack (Thomson *et al*., 2010). Thus, the influence of biotic interactions and their success under a changing climate needs to be considered, and at what spatial scale these interactions are important. For instance, it may be argued that for some species models that incorporate broad climatic variables, biotic interactions may not be important in shaping the distribution at that scale, only at a finer, landscape level. Further, some pest insect species are highly successful competitors and biotic interactions are unlikely to limit distributions outside their native range (e.g. *Bactrocera invadens*; Hill and Terblanche, 2014).

Incorporating interactions in species distribution models has proved a challenging area of research. Species interactions are currently incorporated in ENMs at a basic level, including covariates of competitive interactions (Pellissier *et al*., 2010; Meineri *et al*., 2012) and available prey items (Hof *et al*., 2012), to look at how these interactions affect modelling outcomes. Another approach that looks promising is to nest a community of species spatially within a modelling framework that incorporates co-occurrence indices (Boulangeat *et al*., 2012). Population processes such as dynamic ranges and dispersal parameters can also be incorporated into ENMs. Developments in this area include dynamic range models (DRMs) to estimate spatial population dynamics (Pagel and Schurr, 2012; Schurr *et al*., 2012) and other dynamic species distribution models that can incorporate stochastic processes such as dispersal, growth and competition within a Bayesian framework (Marion *et al*., 2012). Processes such as biotic interactions and dispersal could also be linked explicitly within a mechanistic modelling framework, and there are simple interaction parameters available for CLIMEX models to examine changes in the EI under climate change (Sutherst *et al*., 2007).

In considering pest invertebrates and climate change, it is important to consider the types of biotic interactions that may play a role in shaping responses. These may include competition, natural enemies' interactions and host shifts. Some of the avenues for incorporating biotic interactions within SDM frameworks are presented in Kissling *et al*. (2012), highlighting an exciting area of SDM research that will enhance greatly climate change predictions for pest insect species.

Competition

The varying success with which a pest invertebrate species outcompetes endemic and/or other pest species has implications for predicting distributions accurately, both currently and under climate change. The potential importance of competition in determining distributions is demonstrated by the highly successful invasive ladybird beetle, *Harmonia axyridis* (Pallas), where its success in interspecific competition is implicated in adverse ecological impacts through North America and Europe (Roy *et al*., 2012). Further, the thrips species, *Frankliniella occidentalis* (Pergande), is a highly invasive pest that has spread from its original range (the western states of the USA) to a worldwide distribution. Despite this, it is largely absent in the eastern states, where a native thrips, *Frankliniella tritici* (Fitch), successfully outcompetes in larval competition (Paini *et al*., 2008). While there are currently limited examples for pest insects, there are some recent studies looking to incorporate competition into SDM, particularly ENM, approaches. For example, Brame and Stigall (2014) used ENM modelling to reconstruct ecological niches for 11 genera of marine invertebrates over geological time and found taxa adjusted to increased competition by altering aspects of their niche. These types of studies may serve as valuable road maps for incorporating competition into climate change predictions for insect pests.

Predators/parasitoids or natural enemies

The impact of predators and parasitoids on invertebrate pests is well documented, and the presence or absence of natural enemies has been demonstrated to exert a controlling influence on pest insect species distributions (Thomson *et al*., 2010; Culik *et al*., 2013). In the absence of parasitism, a mechanistic SDM predicted a wide geographic istribution of glassy-winged sharpshooter (*Homalodisca vitripennis* (Germar)) in the USA and Mexico. Including the interaction with its egg parasitoids (*Gonatocerus ashmeadi* Girault and *Gonatocerus triguttatus* Girault) in the model changed distribution predictions (and abundance) dramatically (Gutierrez *et al*., 2011). In a well-studied species, more complex interactions may present themselves; for example, parasitoid attacks may induce different host immune responses, and some parasitoids may also make facultative response by adjusting life-history parameters. Larvae of the moth *Lobesia botrana* (Denis & Schiffermuller) can accelerate their development rapidly and reach maturity earlier in response to cues perceived at a distance from parasitoids. Such a phenotypically plastic life-history shift, induced by the perception of deadly enemies in the environment, is likely to be an adaptive defensive strategy to prevent parasitoid attack, and has important implications in host–parasite dynamics (Vogelweith *et al*., 2013). A possible corollary of range shift moving from parasitoids extends to phenological change; loss of the cue allows longer development time of the moth. As hosts that mature earlier are smaller, which is often correlated with low fecundity and reduced longevity, maybe this is an advantage in a new environment, whether range change or invasion. Marini *et al*. (2013), in a long-term study aimed at identifying the role of predation and parasitism on bark beetles, concluded a limited effect. These kinds of complex interactions are largely unconsidered for pest insect SDMs, although they comprise key components in understanding the response to climate change and provide many opportunities for future research.

2.4.2 Dispersal ability

Further improvements to species distribution modelling may come from including dispersal information to examine how this influences response to climate change. Currently, most SDMs assume no dispersal, or unrestricted scenarios (see Travis *et al*., 2013), while others attempt to combine dispersal information to SDMs through process-based modelling approaches (see Elith and Leathwick, 2009, for examples). For pest insect species, dispersal may be in either passive or active forms and play a major role in shaping the distribution. Dispersal may also introduce new species interactions, further highlighting the importance of movement of species as an important component to understand response to climate change properly. Newer methods such as DRMs, as presented in Schurr *et al*.

(2012), are able to incorporate dynamic processes such as dispersal and look promising for pest insect SDMs. Similar to this, population processes are likely to be useful for pest insect distribution modelling (Fordham *et al*., 2013).

Current implementation of dispersal in pest insect distribution models includes the hemlock woolly adelgid (HWA; *Adelges tsugae* Annand), an invasive threat to North America (Fitzpatrick *et al*., 2012). In this study, dynamic dispersal was combined with population processes and maps, characterizing heterogeneity in climate and habitat. Fitzpatrick *et al*. (2012) found that simulations generally matched the observed current extent of the invasion of HWA, but were not able to predict accurately when HWA was observed to arrive at different geographic regions. Differences between the modelled and observed dynamics were attributed to an inability to capture the timing and direction of long-distance dispersal events, which substantially affected the ensuing pattern of spread. Other weather events such as increased cyclones or high winds may increase dispersal beyond current conditions for some pests. Such events are inherently difficult to capture using current SDM techniques and corresponding meteorological information.

2.4.3 Genetic diversity

Another avenue to improve pest invertebrate SDM predictions is to incorporate relevant genetic diversity into the models. For example, ENMs typically assume that species exist as one large population, and therefore do not include potentially important difference responses between populations. If species distribution models are applied where clear structure exists between populations (for example, geographic barriers or multiple and distinct introductions), then it could be beneficial to examine the differences in environments occupied by populations or lineages (e.g. Arteaga *et al*., 2011; Newman and Rissler, 2011). This can be achieved by identifying unique populations through measures of genetic divergence and partitioning model data into corresponding subsets, or perhaps information on dispersal and movement abilities of a species. While it is possible to measure population structure and divergence using microsatellites, for example, neutral genetic diversity and adaptive genetic diversity are often not correlated (Holderegger *et al*., 2006). This implies that adaptive niche shifts that may alter response to climate change are not likely to be detected in such population genetic studies; instead, these studies provide information to calibrate modelling procedures around genetic diversity.

2.5 Enhancing Model Predictions with Niche-limiting Traits

As was pointed out when discussing the advantages of CLIMEX, data for pest insect species are often incomplete across the different knowledge domains (e.g. distribution information, physiological studies, demographic studies). A useful approach to predicting the effect of climate change on pest insect species may be to measure niche-limiting traits and then couple this with distribution information to detect variance and/or shifts and how they may influence potential response. We feel this is a framework that will prove to be more successful and draws from different knowledge realms in an insightful way. When applied appropriately, the different types of species distribution models are able to generate hypotheses about the niche of an organism, and then direct further research towards understanding traits that limit the niche (Rey *et al*., 2012; Hill *et al*., 2013). Adaptation in limiting traits may lead to niche shifts and mediate a species response to climate change (Chown *et al*., 2010; Hoffmann and Sgrò, 2011). For the mosquito, *Aedes aegyptii*, Kearney *et al*. (2009) identified egg desiccation resistance as limiting the inland distribution of the species and incorporated this into a model predicting how adaptation in this trait could facilitate range expansion under climate change. Thus, one of the great challenges is to determine which traits may be limiting current distributions (Wiens, 2011) and then to measure these to incorporate them into predictions. Further, adaptation or persistence in changing environments may also be mediated through phenotypic plasticity: rapid phenotypic adjustment to environmental variation (see Chown and Terblanche, 2006). For invasive species, studies that measure traits in both native and invasive ranges, and across a range of environmental gradients, would be extremely beneficial, though are rare (Alexander and Edwards, 2010). The key traits that are relevant to niche shifts during invasion and under climate change are likely to be:

1. Thermal tolerance: maximum and minimum temperature limits for activity and survival. As temperature plays a large part in determining the niche of a species (Bale *et al*., 2002), understanding thermal tolerance traits can help to determine species–environment relationships (Terblanche *et al*., 2006). Thermal tolerance traits are used widely to investigate ecological and evolutionary processes for terrestrial arthropods (Hoffmann *et al*., 2005; Terblanche *et al*., 2006; Mitchell and Hoffmann, 2010; Alford *et al*., 2012). Species often exhibit differences in thermal tolerance limits across environmental gradients, including elevation and latitude (Gaston and Chown, 1999; Hoffmann *et al*., 2005), with variation across latitude, including phenotypic plasticity, more evident for lower than upper limits of terrestrial arthropods (Hoffmann *et al*., 2005; Terblanche *et al*., 2006; Alford *et al*., 2012; Hoffmann *et al*., 2013).

2. Desiccation resistance: water loss potential. For terrestrial arthropods, their small size and high surface-to-volume ratio means they are susceptible to desiccation (Johnson *et al*., 2011). Variation in desiccation resistance has been linked to distributional patterns (Kellermann *et al*., 2009). For example, tropical species of *Drosophila* have low desiccation resistance (and low heritability of this resistance), compared to widely distributed *Drosophila* species (Kellermann *et al*., 2009; Hoffmann and Sgrò, 2011).

3. Photoperiodism: physiological reaction to day or night length. While day length will not be affected by climate change, photoperiodism interacts with temperature and varies across latitude, to initiate lipid storage and diapause with the onset of winter (van Asch and Visser, 2007; Lehmann *et al*., 2012; Urbanski *et al*., 2012). Adaptation in photoperiodic response has allowed the mosquito, *A. albopictus*, to undergo range expansion in North America (Urbanski *et al*., 2012). Adaptations in photoperiodic traits may also facilitate earlier emergence (to coincide with milder winter temperatures) and increase herbivore damage under climate change (van Asch and Visser, 2007).

Photoperiodism can underlie different development patterns in a pest, which may facilitate population growth with changed temperature beyond what can be predicted with temperature modelling. Development times greater than explained by temperature differences in *L. botrana* in north-east Italy are interpreted as a means to ensure best fit of the moth to environmental conditions (Pavan *et al*., 2013).

Whereas mechanistic models can directly incorporate variation in niche-limiting traits, correlative models can determine which environmental covariates may be most important to the niche and which may limit the distribution of species across a geographic range. These can lead to hypotheses about which traits are likely to govern the distribution of the species and should be investigated empirically (e.g. Banta *et al*., 2012; Hill *et al*., 2013). This provides an opportunity to use correlative models in tandem with experiments to measure these traits, rather than building full mechanistic models, which can be time-consuming. Alternatively, a few niche-limiting traits for pest invertebrate species could be used with distribution information in CLIMEX-like models that are able to draw from multiple knowledge domains (Macfadyen and Kriticos, 2012).

For some pest insect species, it may be useful to characterize traits for other life stages, such as diapause, and look at intergenerational effects. This could form a comparison to ENMs and be projected on to the same future climate surfaces (e.g. the CliMond data set) to examine areas of model congruence.

2.6 Conclusion

Different pest insect species will respond to climate change in different ways. Species distribution models can provide important first steps in establishing hypotheses around the niche of a species, to drive hypotheses and experimental work for providing robust advice to managers and agricultural workers in the management of pests and global climate change. The type of distribution model to be employed should be based on data availability – combining from different knowledge domains where possible. When there is comprehensive and unbiased locality sampling, the increasing availability of interpolated weather station data facilitates approximation of the species realized niche using ENMs. Experimentally derived evidence allows for mechanistic models to predict response to climate change through an estimation of fundamental niche axes. The extensive data required are not always available, so tools such as CLIMEX allow for combination across data types. Generally, combining physiological, abundance and distribution data is likely to give better predictive ability.

Through measuring traits such as thermal tolerance, desiccation resistance and photoperiodism and combining this with model (e.g. ENM) predictions, valuable insights into species niche dimensions, and the added potential to investigate adaptive shifts, informs on species response to climate change.

Consideration of other drivers that shape species distributions, including biotic interaction such as competition, the presence of natural enemies and impacts of host shifts, have the potential to increase the accuracy of prediction. Predicting response to climate change for pest insect species will benefit greatly from advances in species distribution modelling to include knowledge of species dispersal ability and interactions, though all SDM work must serve as a guide to inform rather than determine management decisions under climate change.

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