ЕВРОПЕЙСКИ ПАРЛАМЕНТ PARLAMENTO EUROPEO EVROPSKÝ PARLAMENT EUROPA-PARLAMENTET
EUROPÄISCHES PARLAMENT EUROOPA PARLAMENT ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΟΒΟΥΛΙΟ EUROPEAN PARLIAMENT
PARLEMENT EUROPÉEN PARLAIMINT NA hEORPA PARLAMENTO EUROPEO EIROPAS PARLAMENTS
EUROPOS PARLAMENTAS EURÓPAI PARLAMENT IL-PARLAMENT EWROPEW EUROPEES PARLEMENT
PARLAMENT EUROPEJSKI PARLAMENTO EUROPEU PARLAMENTUL EUROPEAN
EURÓPSKY PARLAMENT EVROPSKI PARLAMENT EUROOPAN PARLAMENTTI EUROPAPARLAMENTET

NOTE

Policy Department B
Structural and Cohesion Policies

The Consequences of the ‘cut off’ Criteria for Pesticides: Alternative Methods of Cultivation

AGRICULTURE

2008

EN

Directorate General Internal Policies of the Union

Policy Department Structural and Cohesion Policies

AGRICULTURE AND RURAL DEVELOPMENT

The Consequences of the ‘cut off’ Criteria for Pesticides: Alternative Methods of Cultivation

NOTE

Content:
Commission proposal for a Regulation to replace Council Directive 91/414/EEC is currently being negotiated. The current Directive provides the framework for the authorisation and marketing of agricultural pesticides. The Regulation will update the human and environmental safety ‘cut off’ criteria by which plant protection products are approved. This may result in the prohibition of a significant number of synthetic chemical pesticide products. Various non-chemical control methods can make valuable contributions to crop protection. The aim of this briefing note is to provide information on technologies that complement, or can be used as alternatives to, the application of synthetic chemical pesticides.

IP/B/AGRI/IC/2008_168 **01/12/2008**

PE 408.962 **EN**

This note was requested by the European Parliament's Committee on Agriculture and Rural Development

This paper is published in the following language:
- Original: EN

Author: Dr Dave Chandler (Coordinator)[1]
University of Warwick

Responsible Administrator Mrs Ekaterini Stavridi
Policy Department Structural and Cohesion Policies
European Parliament
B-1047 Brussels
E-mail: ipoldepb@europarl.europa.eu

Manuscript completed in December, 2008.

This note is available on the Internet at:
http://www.europarl.europa.eu/activities/committees/studies.do?language=EN

Brussels, European Parliament, 2008.

[1] Co-authors: G. Bending, J. Clarkson, G. Davidson, S. Hall, P. Mills, D. Pink, D. Skirvin, P. Neve, R. Kennedy, J. M. Greaves, W. P. Grant & R. H. Collier

Executive summary

Commission proposals for a Regulation to replace Council Directive 91/414/EEC are currently being negotiated. The current Directive provides the framework for the authorisation and marketing of agricultural pesticides. The Regulation will update the human and environmental safety ‘cut off’ criteria by which plant protection products are approved. This may result in the prohibition of a significant number of synthetic chemical pesticide products. The aim of this briefing note is to help decision makers understand some of the consequences of the 'cut off' criteria for landscape preservation and EU agriculture. In particular, we were asked to provide information on technologies that complement, or can be used as alternatives to, the application of synthetic chemical pesticides.

Pests (invertebrates, plant pathogens and weeds) are major constraints to agricultural production. There is an urgent requirement for systems of pest management with greater levels of sustainability. These must be capable of increasing or maintaining food productivity and have positive outcomes for environmental services. This would be a significant way forwards for improving yields and continued access for EU citizens to reasonably priced, healthy and good quality food. The main pathway for achieving this is through Integrated Pest Management (IPM).

Chemical pesticides are a vital part of crop protection and they need to be used more within the framework of IPM. At the time of writing, under Commission cut-off criteria, loss of herbicides would jeopardise production of minor crops such as carrot, parsnip and onion and fungicide loss might result in 20-30% yield losses in wheat. There would also be implications for pest, disease and weed control in other crops. It is difficult to predict the extent to which altered pesticide use would have a direct impact on biodiversity. If crop yield per hectare declines then more land may be made over to cultivation, which is likely to lead to a reduction in biodiversity. It is unlikely that organic farming could be used to substitute for conventional agriculture because it typically produces smaller yields. However, it has much to offer in terms of its emphasis on renewable resources, ecology and biodiversity.

The Commission proposals are likely to reduce the range of pesticide modes of action available. This is likely to result in a reduced ability to manage resistance in pest populations.

Various non-chemical control methods can make valuable contributions to crop protection. These include physical and cultural controls, natural compounds, biological control, plant breeding and other genetic methods. In some situations, a combination of methods may be able to replace synthetic pesticides, for example where a pest has developed pesticide resistance. But in most cases the most practical way forward is to use them with chemicals in a fully integrated programme.

Crop rotation is one of the oldest strategies for managing pests and is particularly useful for controlling pest species with limited dispersal ability and host range. Other physical and cultural control methods have a role to play in IPM strategies for one or sometimes several pests. Much research has been devoted to identifying ‘natural’ compounds for pest control and many have been used successfully for pest insect monitoring. There are fewer examples of compounds that have been used successfully for pest control and considerable research and development investment would be required to expand this portfolio.

Biological control can be a very successful part of IPM. Biocontrol agents tend to have a narrow activity spectrum. This is attractive from an environmental perspective but it also makes them niche market products, which can act as a barrier to their commercialisation. There are significant differences in the biological control strategies used in, and the amount of success obtained with, glasshouse vs. outdoor crops. More investment in research and development is needed, particularly for biocontrol in field crops.

The growing of resistant varieties is often promoted as an alternative to the use of pesticides. Although there has been some work to breed for resistance to invertebrate pests, the majority of effort has been directed at resistance to microbial plant pathogens. Many hundreds of pathogen resistance genes have been identified in crop species. However, no plant variety is resistant to all diseases and pests, and the choice of variety is always a balance between different traits. Moreover, most resistance is ephemeral due to the ability of pathogen populations to overcome it through natural selection. Host resistance must be used, therefore, as part of IPM in order to achieve durable crop resistance.

There is evidence that GM crops can provide economic and environmental benefits. However if the technology is not used according to IPM principles then sustainability gains may be lost. If there are large-scale effects from GM then they should become apparent in the 8 countries outside the EU that are now growing over 1 million ha of GM crops. The ethical issues surrounding GM are complex and there may be specific concerns for Europeans. Scientists can provide valuable knowledge about GM but policy making is the responsibility of Governments. Effective engagement between all members of the policy network is vital.

The best way to make crop protection more effective and durable is by using Integrated Pest Management. IPM is a systems approach that combines a wide array of crop production practices with careful monitoring of pests and their natural enemies. The aim of IPM is not pest eradication; rather it is the more realistic goal of reducing a pest population below its economic injury level. The uptake of IPM in Europe varies significantly depending on the type of crop grown. IPM is being used widely in glasshouse crops and some sophisticated systems have been developed. Some components of IPM are used in field vegetable crops including crop rotation, careful pest monitoring and resistant varieties when available. IPM strategies in orchard crops are largely based on not using sprays of broad spectrum pesticides to preserve natural enemies of the main pests. There is considerable scope for IPM in arable crops but it does not appear to be used widely. The majority of schemes are based on pest forecasting, monitoring and varietal resistance rather than on biological control.

IPM can play a significant role in making farming more environmentally, economically and socially sustainable: it can help to maintain biodiversity, reduce pollution, lower the build up of pesticide resistance, maintain the security of food supply, increase yields, and improve consumer confidence in the agri-food industry. The manufacture of biocontrol agents and related products is a small-scale activity that can boost high quality employment opportunities in rural areas. However the adoption of different crop protection technologies has a strong market and regulatory dimension. Regulatory systems can act as barriers to new technologies and approaches. There is a need for distinctive regulatory arrangements that recognise the particular character of ‘alternative’ products and makes use of their contribution to sustainability objectives.

Finally, we wish to emphasis that global agriculture is in a period of tremendous change. There is increasing tension between the need to produce food and protect other ecosystem services. Europeans have not paid enough attention to the long-term future of farming and the overwhelming requirement for a sustainable agri-food system. We make a number of recommendations including:

- The need for more detailed impact assessments of the ‘cut-off’ criteria across the EU including economic, environmental and social impacts.
- Ensuring farmers have access to a variety of pesticides with different modes of action.
- Placing IPM at the centre of crop protection policy.
- Providing significantly more funding for research and development. This should include studies of pest and natural enemy biology (including interactions with other components of farming ecosystems), the development of new crop protection tools and their practical use. Promoting the availability of alternatives through research and manufacture should be legitimate grounds for funding under Pillar 2 rural development programmes.
- The need for innovations to overcome regulatory and market barriers.
- More information must be obtained on the practical ways in which farmers and growers are already using non-chemical pesticide methods as part of IPM.
- Work currently being undertaken by OECD offers the potential for the development of a global harmonised system for microbial pesticide regulation.
- Many member states no longer have state extension services that could have provided guidance and assistance to farmers and growers. There is a case for providing funding to facilitate innovation in the use of ‘alternative’ crop protection methods by farmers and growers, e.g. by co-funding the purchase of consultancy advice.

Contents

1. Introduction

Commission proposals for a Regulation to replace Council Directive 91/414/EEC are currently being negotiated. The current Directive provides the framework for the authorisation and marketing of agricultural pesticides. The Regulation will update the human and environmental safety 'cut off' criteria by which plant protection products are approved. This may result in the prohibition of a significant number of synthetic chemical pesticide products. The aim of this briefing note is to help decision makers understand some of the consequences of the 'cut off' criteria for landscape preservation and EU agriculture. In particular, we were asked to provide information on technologies that complement, or can be used as alternatives to, the application of synthetic chemical pesticides.

1.1. The importance of pests for European agricultural production

Pests are organisms that reduce the availability, quality or value of a human resource [1]. Agricultural pests include plant pathogens (e.g. fungi, oomycetes, bacteria, viruses, nematodes), weeds, arthropods (primarily insects and mites), molluscs (slugs and snails) and a small number of vertebrates. They reduce the yield and quality of produce by feeding on crops, by transmitting diseases, or by competition with crop plants for space and other resources (weeds, for example). There are estimated to be about 67,000 different pest species worldwide, of which c. 10% are classed as major pests [2]. They are a significant constraint on agricultural production, responsible for around 40% loss of potential global crop yields [2,3]. Of this, 15% is caused by arthropods, 12 - 13% by plant pathogens and 12 – 13% by weeds. A further 20% loss is estimated to occur post harvest [2]. These losses occur despite the considerable efforts made at pest control, and they suggest that improvements in pest management are significant way forward for improving yields and access to food.

Pest problems are an almost inevitable part of agriculture. They occur largely because agricultural systems ('agro-ecosystems') are simplified, less stable modifications of natural ecosystems. The creation and management of agricultural land disrupts the ecological forces that regulate potential pest species in natural ecosystems: these include physico-chemical conditions, food availability, predation, and competition. Thus, growing crops in monoculture provides a concentrated food resource that allows pest populations to achieve far higher densities than they would in natural environments. New food resources for pests are provided when a crop is introduced into a country. Cultivation can make the physico-chemical environment more favourable for pest activity, for example though irrigation or the warm conditions found in glasshouses. Finally, using broad spectrum pesticides will destroy natural predators that help keep pests under control.

Some of the most important problems are caused by alien (i.e. non-native) species that are accidentally introduced to a new country or continent and which escape their co-evolved natural predators [4,5]. More than 11,000 alien species have been documented [6]. About 15% are thought to cause economic damage and a further 15% harm biological diversity[6]. Economic losses to crops from alien invasive pests are estimated at €4.5 billion per annum in the UK alone (approximately €75 per person) [7]. There are also threats from emerging pests. For example, Ug99, which is a new strain of the wheat stem rust fungus *Puccinia gramninis* f.sp. *tritici*, evolved in Uganda and is now spreading towards Asia and Europe. It is able to overcome the resistance gene bred into standard wheat lines, and as a result it is highly virulent, capable of causing 100% yield loss. The only control option at present is to use fungicide sprays, but sufficient stocks may not be available [8].

1.2. Synthetic chemical pesticides: benefits and costs

Crop protection was revolutionised by the development of the first synthetic chemical pesticides in the 1940s. Systematic advances in pesticides and other technologies such as nitrogenous fertilizers, plant breeding, irrigation and mechanisation have increased agricultural production in Europe by 68% since the 1960s [9]. Today, most farmers and growers in the EU rely on chemical pesticides. Only approved products can be used and many of these compounds have excellent characteristics in terms of efficacy and human and environmental safety [10]. But while this approach to farming – which emphasises the intensive use of non renewable resources combined with new technologies - has delivered immense benefits in terms of increased commodity production, there are also significant external costs [11]. The injudicious use of some pesticides, in combination with other aspects of agricultural systems, can be a source of environmental harm [12,13]. There is also a perception among some consumers and pressure groups that pesticide residues are detrimental to health. There is pressure on growers from retailers and others to reduce the levels of residues in produce, but this needs to be done without sacrificing yield and by minimising reductions in crop quality.

And while pesticides will remain an important tool for farmers and growers, they are not a panacea for crop protection. The negative effects of broad spectrum pesticides on natural predators are well documented, leading to resurgence and secondary pest issues [10]. The development of pesticide resistance is a major issue. Insecticide resistance often evolves within 10 years and herbicide resistance within 10 – 25 years of introduction of a new compound [14]. Worldwide, over 500 species of arthropod pests have resistance to one or more insecticides [15] (Fig. 1). Serious problems for European horticulture have occurred in the last 20 years from invasive insect species that are also pesticide resistant, such as the western flower thrips *Frankliniella occidentalis* and the silverleaf whitefly *Bemisia tabaci*. And worldwide, bee keeping has suffered greatly from the varroa mite *Varroa destructor*. Problems associated with resistance to fungicides by plant pathogens have been recognised for some while [16 – 18]. However, to put this in context, most fungicides are still very effective against the target organisms for which they were developed and fungicide resistance occurs only in a few pathogens. Nevertheless, there is a challenge for pesticide developers to stay one step ahead of the ability of pests to evolve resistance. Unfortunately, the development of new active compounds is expensive (c. $200 million) and time consuming (about 10 years) [10].

There is an urgent requirement for systems of pest management with greater levels of sustainability. These must be capable of increasing or maintaining food productivity and have positive outcomes for environmental services. They must also be long lasting and resilient to future shocks [9]. The main pathway for achieving greater sustainability is through Integrated Pest Management.

1.3. Pesticide regulation in the EU

EU pesticide regulation is done as a two tier system involving both comitology at the EU level and the member states. Directive 91/414 was one of the first major items of legislation to anticipate not only the principle of subsidiarity, but also the precautionary principle. An extensive dossier containing information on the active substance is submitted by a company to a Rapporteur Member State. The pesticide authority in that member state carries out a risk assessment and distributes the Draft Assessment Report (DAR) with a recommendation to the applicant and the other member states. Since 2002 the EFSA has been responsible for risk assessment, which it does through a scientific peer review. This leads to the production of a guidance document for the Working Group (legislation) of the European Commission's Standing Committee on the Food Chain and Animal Health. Member state representatives decide whether to approve the active substance and, if successful, it is added to Annex 1 of Directive 91/414. Product authorisations are considered at a national level using harmonised criteria for data requirements laid down in EU legislation.

2. Some of the possible consequences of the ‘cut-off’ criteria

At the time of writing, the Commission cut-off criteria would probably result in 6-10% of insecticides, 8-32% of fungicides and 4-10% of herbicides not being approved (however the situation is fluid and is likely to change before a final decision is taken). Candidates for substitution would be 38, 20 and 24% of current active ingredients respectively. Impact assessments have not be undertaken in many member states, however, the assessment undertaken in the UK [19, 20] suggests that under the Commission proposals, production of minor crops such as carrot, parsnip and onion might be particularly affected, mainly because the majority of herbicides approved for these crops would no longer be approved. Crop sensitivity to herbicides means that alternative herbicides may not be suitable. Fungicide availability could be reduced as a result of the endocrine disruptor criteria, which might result in 20-30% yield losses in wheat, due to an inability to control *Septoria tritici*. The loss of pendimethalin as a pre-emergence treatment would jeopardise weed control in cereals. Non-approval of potential endocrine disruptors would jeopardise disease control on oilseed rape leading to significant yield loss. Loss of warfarin would affect amenity woodland and forestry and lead to increased mortality of native trees due to grey squirrel damage. There would also be implications for pest, disease and weed control in other crops. An EPPO workshop held to consider the impact of proposals concluded that there was no reason to believe that the impact of the proposals throughout northern Europe would be very different to that in the UK [21]. This is because the range of pests and pesticides are similar throughout this area. Agriculture in the south of the EU will face different problems. For example, pest insects are more prevalent. The impact of herbicide losses would be less severe due to different crops and the warmer climate. The impact of the loss of some fungicides, particularly under the commission proposals might be so severe that some crops could no longer be grown in the EU.

Under Commission cut-off criteria, loss of herbicides would jeopardise production of minor crops and fungicide loss might result in 20-30% yield losses in wheat. There would also be implications for pest, disease and weed control in other crops.

2.1. Nature conservation (preserving the landscape, forestry, weed destruction)

Many of the direct and quantifiable negative impacts of agriculture on biodiversity are due to habitat loss [22] or to farming practice other than pesticide use [23]. Nevertheless, by definition, pesticides affect species diversity, at least in the area in which they are applied [22]. An overall reduction in pesticide use would have benefits for non-target species such as insects, birds and wild plants. However, the cut-off criteria are not directed at reducing environmental impact and a reduction in the diversity of pesticides may not reduce pesticide use *per se*. Less appropriate pesticides may be applied more frequently to maintain levels of pest control. Badly-chosen biological control agents can also have a negative impact on biodiversity such as the coccinellid *Harmonia axyridis* [24].

Maintaining natural and semi-natural ecosystems within Europe is vital for the provision of environmental goods and services, such as clean air, water and waste absorption. The ecological footprint of Western Europe is currently twice that of global biocapacity [25]. Recent research indicates that the durable protection of biodiversity requires 30 – 40% of an area to be given over to nature conservation [25, 26]. Many EU member states have a high proportion of their land area devoted to agriculture already (Table 1). If pesticide withdrawals result in lower yields, and more land is made over to cultivation, there is likely to be a further loss of our few remaining natural lowland habitats with a consequent reduction in biodiversity. This could happen through the direct effects of habitat destruction [27, 28] or by reducing the connectivity between habitats that is essential for wildlife movement [27]. In Europe, this is most likely to be the case for areas devoted to arable production, since under the Commission proposals, the yields of wheat and oilseed rape are likely to decline.

Pesticide use can also have positive impacts on biodiversity. Alongside other methods, pesticides play a key role against alien species. In terms of nature conservation and landscape, the most damaging are probably invasive weeds such as *Rhododendron ponticum*, which can out-compete native plants over large areas, or new pathogens of native plants, such as *Phytophthora ramorum*, which causes sudden oak death [29-31]. Direct impacts on European biodiversity and landscape will occur if the pesticides used to combat these species are lost. Classical biological control can be used as an alternative for some invasive species; it has had notable successes outside of Europe but it is not being used to any degree within the EU for alien weed control [32].

It is difficult to predict the extent to which altered pesticide use would have a direct impact on biodiversity. However, if crop yield per hectare declines then more land may be made over to cultivation, which is likely to lead to a reduction in biodiversity. Pesticides are used to control alien invasive species, which often have a negative impact on biodiversity.

2.2. What is the future role of organic farming? Can it enable the EU to farm without pesticides?

Certified organic farming accounts for 3 – 5 million ha of land use in Europe [9,33] and is currently a niche activity. There is an obvious question of whether organic farming, which prohibits the use of a number of crop protection technologies including synthetic chemical pesticides, can be expanded and adopted as the standard method of cultivation across the EU. Organic farming in European systems typically produces significantly lower (up to 50%) crop yields than conventional agriculture [34,35] and hence it is unlikely to be able to substitute directly. However, organic farming has much to offer sustainable farming in terms of its emphasis on renewable resources, ecology and biodiversity. There is a requirement to avoid attitudes to farming becoming increasingly polarised into ‘organic’ versus ‘conventional’ standpoints. Instead, the debate must be framed in terms of the best practices that can be adopted from all farming systems to make crop protection more sustainable. Thus, according to Pretty (2008) sustainable agriculture ‘*does not mean ruling out any technologies or practices on ideological grounds. If a technology works to improve productivity for farmers and does not cause undue harm to the environment, then it is likely to have some sustainability benefits*’[9].

Organic farming in European systems typically produces lower crop yields than conventional agriculture and hence it is unlikely to be able to substitute. However, organic farming has much to offer sustainable farming in terms of its emphasis on renewable resources, ecology and biodiversity.

2.3 How could the ‘cut off’ impact on our ability to anticipate and prevent the development of resistance to synthetic chemical pesticides?

All living species show genetic diversity that arises from naturally occurring mutations. When pesticides are used, natural selection will favour individuals that are less susceptible to these pesticides. These may survive the treatment and reproduce to give a progressive build up of this particular genetic trait in the population. This becomes apparent as control failures as these resistant pests start to dominate the population. The occurrence of pesticide resistance depends on a number of factors, including genetic variability and the selection pressure applied during pesticide use. It is not always easy to predict whether a pest species will, or will not, become resistant to a certain pesticide. However, the risk of resistance developing invariably becomes greater if pest control relies on the repeated use of pesticides with the same mode of action.

The Commission proposals are likely to reduce the diversity and range of modes of action available to farmers and growers in the EU. This is likely to result in a reduced ability to manage resistance in pest populations that currently contain a high proportion of resistant genotypes and also to increase selection pressure for the development of new instances of resistance. One such example would be insecticide resistance management in populations of *Myzus persicae*, an aphid pest and virus vector in a diverse range of crops such as potato, sugar beet, brassica, lettuce, pepper. Individuals of this species may currently demonstrate resistance to carbamate (pirimicarb), organophosphorus and pyrethroid insecticides [36]. At present, resistance in this species is managed through the use of newer insecticides with different modes of action (e.g. neonicotinoids, pymetrozine). However, some of these newer insecticides may well be lost as a result of the cut off criteria and this pest species will be very hard to manage with the insecticides that remain. Whilst biological control strategies may be effective against this pest in greenhouse crops, there are currently no viable alternative control options for field crops. New instances of insecticide resistance have been identified recently in pollen beetle (*Meligethes* spp.) (now widespread in Europe) whose control has relied almost solely on one group of insecticides (pyrethroids) [37] and *Thrips tabaci* (UK) [38], whose control was again reliant on pyrethroids.

Problems of resistance to fungicides continue to emerge with serious economic and environmental consequences [39]. Practical experience combined with experimentation, indicates that the risk of resistance depends not only on the inherent risk of a particular fungicide-pathogen combination, but also on the conditions of fungicide use. This includes the number of repeated applications of the at-risk fungicide; the more frequently the treatment is applied to selectable populations of the pathogen, the more rapid the selection of resistant mutants resulting in control failure [40]. The overall strategy to manage fungicide resistance is to minimize use of the at-risk fungicide without reducing disease control. This has been accomplished by using the at-risk fungicide with other fungicides and with non-chemical control measures, such as disease resistant cultivars, in an integrated management program.

The proposals made as part of the EU strategy are likely to reduce the diversity and range of modes of action available to farmers and growers in the EU. This is likely to result in a reduced ability to manage resistance in pest populations that currently contain a high proportion of resistant genotypes and also to increase selection pressure for the development of new instances of resistance.

3. Examination of ‘alternative’ methods of crop protection

The crop protection industry is dominated in market size terms by synthetic pesticides, but there are a wide range of other methods that are being used by farmers and growers. They include cultural practices and physical methods (e.g. crop covers), natural compounds, biological control and plant breeding. These are often described as ‘alternative’ methods of crop protection. This term must be used with care, because it has more than one meaning. In the context of this report, ‘alternative’ means giving farmers and growers a choice of different crop protection methods. However, it can also refer to two choices being mutually exclusive. In the case of Integrated Pest Management, this is misleading. ‘Alternative’ can also relate to practices that offer a substitute for conventional ones and, in common parlance, it has connotations of being leftfield and outside the mainstream. There is a danger that labelling a crop protection technology as ‘alternative’ could deter farmers from using it.

There are a number of other caveats about non-pesticide methods of pest control that must be borne in mind. (1) These methods are generally not like-for-like replacements for synthetic chemical pesticides. (2) They have different modes of action and, thus, different strengths and weaknesses. (3) Many have lower efficacy than synthetic pesticides, are slower to act or are vulnerable to breakdown. (4) Many are affected by environmental conditions. (5) They often cost more to buy than synthetic pesticides and they require specialist knowledge to use them. (6) There are also many remaining scientific and technical challenges to their development, not helped by under-investment in crop protection research throughout the EU. (7) Some of the features that make them attractive from an environmental standpoint can be a problem in economic terms. For example, the narrow prey spectrum of many biological control agents means that they are only appropriate for niche markets, with individual agents often earning less than €1 million per product per annum, which discourages companies from developing them. To quote Gelernter (2005) ‘*The features that made most BCPs [Biological Control Products] so attractive from the standpoint of environmental and human safety also acted to limit the number of markets in which they were effective*’[41].

Many of the perceived ‘weaknesses’ of non-pesticide agents are based on comparison with the performance of synthetic chemicals. The unsuitable adoption of a chemical pesticide development model for these agents can lead to false and unrealistic expectations of chemical-like performance. However, the very fact that ‘alternative’ crop protection methods do not function in the same way as synthetic chemical pesticides means that they can be used to compensate for the weaknesses of the latter. Biological control agents are able to reproduce within the pest population, giving various levels of self-perpetuating control. Many biological control agents are also able to actively locate their prey, making them highly useful where pests occupy cryptic habitats. Biological control, plant breeding and cultural controls generally do not require the same level of protective equipment to be used as for chemical pesticides. The lack of a toxic residue on crops and, therefore, the absence of a pre-harvest application interval, can be a real benefit. Using knowledge of the causes of pest outbreaks (section 1.1) it is possible to use conservation management, plant breeding, physical methods and cultural techniques to help prevent the build up of pest populations in a ‘total systems’ approach [42]. Moreover, the wide variety of crop protection methods available means that different combinations can be put together in complementary ways. This is vital if we are to achieve effective, sustainable pest management. There is ample evidence that the various non-chemical pesticide methods can make valuable contributions to crop protection as part of Integrated Pest Management [43,44]. In some situations, a combination of these methods may be able to replace synthetic pesticides, for example where a pest has developed pesticide resistance. But in most cases the most practical way forward is to use them in combination with chemicals in a fully integrated programme.

Compared to synthetic chemical pesticides, the current market size for ‘alternative’ crop protection products is small. For example the global market for biologically based plant protection products represents just 2.5% of the global chemical pesticide market, is currently valued at €60 million and is predicted to grow to be worth 4.2% of the global chemical pesticide market by 2010 [45]. At present products based on beneficial microorganisms make up the majority of the market share for biological control agents [41]·(Table 2). However, market size alone undoubtedly underestimates the contribution these methods can make to improving sustainability, for example by reducing the resistance pressure on chemical pesticides.

Various non-chemical pesticide methods can make valuable contributions to crop protection as part of Integrated Pest Management. In some situations, a combination of methods may be able to replace synthetic pesticides, for example where a pest has developed pesticide resistance. But in most cases the most practical way forward is to use them with chemicals in a fully integrated programme.

3.1. Physical and cultural controls

Physical control methods are non-chemical measures that destroy the pest, disrupt its development or activity, or modify the environment to a degree that is unacceptable or unbearable to the pest [46]. For weeds, mechanical in-crop cultivations are possible in crops with wide row spacings (e.g. horticultural crops but not arable crops) and developments continue to be made in vision guidance systems for greater precision and intra-row weed control [47]. Mechanical weeding requires more passes per field than pesticide application. Equipment has been developed to burn off weeds or kill weed seeds through steaming the soil, but this may be costly. In some high value and organic vegetable crops, hand weeding is practiced, though this is associated with very high labour costs.

Crop covers made of fine mesh netting are used to prevent pest insects reaching their host crop [48]. This technique has been used quite widely for the production of swede in the UK since the revocation of chlorfenvinphos for control of the cabbage root fly *Delia radicum*. Disadvantages include cost, a risk of yield reduction, increased difficulties with weed and disease control and waste disposal. Polythene and plastic mulches have been used for weed control and bio-degradable alternatives have potential [47]. There has been recent interest in erecting fences on the perimeter of vegetable fields to exclude certain pest insects [49]. This requires further evaluation.

Cultural methods of pest control generally involve the manipulation of an agro-ecosystem to decrease the success of the pest species within it [10]. Crop rotation is one of the oldest strategies for managing pests and is particularly useful for controlling pest species with limited dispersal ability and host range (e.g. potato cyst nematode [50]). Rotation with non-host crops can break a pathogen’s life-cycle. Crop rotation may prevent the build up of weed species that are adapted to any single crop or cropping system [47]. Rotation does not work for pests that disperse by flight or are carried over considerable distances by the wind, that infect or feed on many host crops or are capable of long-term survival in the soil Crop rotation is a desirable practice for other reasons including increasing soil fertility [51] and should form the basis of an IPM strategy.

Other cultural control methods involve good crop management, such as destruction of crop residues. Irrigation may contribute to pest control by washing insects from plants or enhancing the development of outbreaks of entomopathogenic fungi [52]. The manipulation of sowing or harvesting dates to ‘avoid’ key periods in pest life-cycles can be effective [53]. Pre-crop cultivation can be effective for weed control and in some cases stale seed beds are prepared in advance of planned sowing dates.

Most crops are grown as monocultures. Techniques such as intercropping, undersowing and companion planting may reduce colonisation by certain insects, pathogens and weeds [54,55,47]. Problems that have been encountered include the effects of inter-specific competition on crop yield and additional costs for management and seed. Crops that consist of more than one cultivar may also be less susceptible to pest insects and pathogens [56].

The aim of using a trap crop is to concentrate pests in a specific area, ideally arrest or destroy them, and thereby prevent them colonising a more valuable crop. Again there are additional costs, associated with the loss of potentially productive land. To date there are few examples where this approach has been used successfully in practice [57].

Crop rotation is one of the oldest strategies for managing pests and is particularly useful for controlling pest species with limited dispersal ability and host range. It is a desirable practice for other reasons including increasing soil fertility and should form the basis of an IPM strategy. Other physical and cultural control methods have a role to play in IPM strategies for the control of one or sometimes several of the key crop pests. However many of the methods have additional economic or environmental costs.

3.2. Natural compounds

Chemical compounds are the basis of life and living organisms produce and use them in a great diversity of processes. Much research has been devoted to identifying ‘natural’ compounds for pest control. Some of these products may be toxic to certain species e.g. rotenone, pyrethrum, and have been used as ‘natural pesticides’ for many years. However, their limited use within Europe suggests that, overall, the ‘natural’ pesticides that have been registered to date have limited efficacy. This is likely to be due to their relative instability, lower potency and greater price when compared with synthetic insecticides [10]. This does not mean that more effective products may not be developed in the future, provided there is sufficient investment in research and development. For example, the insecticide Spinosad is an effective and widely-used ‘natural’ product. Even so, Spinosad may be a candidate for substitution according to Commission cut-off criteria.

Semiochemical is a generic term used for a chemical substance or mixture that carries a message. The use of pheromones (used for intra-specific communication in insects and other animals) for insect management has been particularly successful. Pheromones are used widely to monitor pest insect populations in Europe and elsewhere and they have had limited application for insect control, either alone (mass trapping, mating disruption) or in conjunction with the targeted use of insecticides (lure and kill). Identification, synthesis and subsequent development of control methods using insect pheromones requires extensive research [10]. Not all insect species produce pheromones that can be exploited in this way and, for certain species that use pheromones, there may be behavioural and ecological limitations restricting the development of control methods. However, substantial research investment may provide successful control methods for certain pests. Other types of semiochemicals, mainly of plant origin, might loosely be termed as ‘attractants’ and ‘repellents’. There are examples of the successful use of attractants (e.g. host plant volatiles) to monitor pests but there is conflicting information in the literature about the value of repellents (e.g. garlic). Attractants (including pheromones) and repellents might be used to push or pull insects, or their predators, in certain directions. However, there is little evidence that this approach has been used consistently on a large scale in commercial situations [58]. Overall, adoption of behavioural manipulation methods has been limited and their cost and species specificity may be limiting factors [59].

Much research has been devoted to identifying ‘natural’ compounds for pest control and many have been used successfully for pest insect monitoring. There are fewer examples of compounds that have been used successfully for pest control and considerable research and development investment would be required to expand this portfolio.

3.3. Biological control.

Biological control is the use by man of a natural enemy to regulate the population density of a pest organism. Natural enemies are organisms that kill or debilitate another organism. Biological control programmes operate throughout the world in agriculture and forestry. Biological control agents (BCAs) include the following: (1) predatory insects and mites, which eat their prey; (2) parasitoids, which are insects with a free living adult stage and a larval stage that is parasitic on another insect; (3) parasites and microbial pathogens, such as nematodes, fungi, bacteria, viruses and protozoa, which cause lethal infections [60,61]. In Europe, typical examples of where these agents are being used include: (1) the application of parasitoids to control whiteflies in glasshouses; (2) parasitic nematodes against slugs; (3) mycoparasitic fungi to control plant diseases of horticultural crops; (4) use of viruses to control codling moth in apple orchards; and (5) building habitats on farms to increase natural populations of predators and other beneficial organisms. Some further examples of microbial control agents are given in Table 3.

Natural enemies represent a large component of the world’s biodiversity, e.g. parasitoids account for 10% of the world’s species [62]. It has been estimated that each agricultural pest species is fed upon by 50 – 250 species of natural enemies [63]. However, only a small proportion of the available species have been investigated for crop protection. Thus, while c. 750 species of insect pathogenic fungi are known, less than 20 have received serious attention as control agents of insect pests [64,65]. The natural enemies inhabiting an agro-ecosystem play a key role in preventing pests reaching damaging levels; it has been suggested that about 99% of all potential pests are controlled by natural enemies [10].

The ways in which biological control agents are used vary according to the type of pest (plant, microorganism, vertebrate or invertebrate), the biological characteristics of the control agent, as well as the agricultural setting. There are three broad biocontrol strategies: Introduction (release of an alien control agent to control an alien pest), augmentation (application of natural enemies that already live in the area of use), and conservation (manipulating agricultural practices or the environment to enhance natural control). People who use biocontrol are bound by the FAO code of conduct on the import and release of biological control agents [66] as well as national legislation on releases into the environment. The use of microbial agents is governed by Plant Protection Product regulations, in which authorisations proceed along similar lines to those for chemical pesticides although there are also some specific schemes.

BCAs have a range of attractive properties that include host specificity, lack of toxic residue, no phytotoxic effects, human safety, and the potential for pest management to be self sustaining. Many are able to actively locate their prey. BCAs can also be produced locally which can be important in terms of choosing and matching natural enemies to small scale needs [67]. Successful use requires fundamental knowledge of the ecology of both the natural enemy and the pest [60,68]. When this condition is satisfied, and the agent is used firmly within IPM, then biological control can sometimes be more cost effective than purely chemical control [69,70] (Table 4). However, under the present market system, many biological control products have not competed well with less expensive and more effective synthetic pesticides [41]. The down sides of BCAs are that most are niche products, pest control is not immediate, there can be lack of environmental persistence, and efficacy can be low and unpredictable particularly in outdoor environments. The approvals process used for microbial agents results in significantly greater authorisation costs than for macro- agents.

3.3.1. Augmentation biological control

Augmentation refers to the use of a species of BCA that lives naturally in the country of use. Selected species are mass produced by commercial companies and then sold to farmers or growers. The BCA may be used with the expectation that it will reproduce in the pest population and thereby give a degree of self sustaining control (this is known as inoculation). Another approach is to apply the BCA in very large numbers to give rapid pest control, usually on a short term basis (this is referred to as inundation) [71,72].

Augmentation biocontrol is currently used on 160,000 km^2 around the world, representing approximately 0.4% of land under crop production [63]. In Europe, about 80 species of arthropod (predator and parasitoid) natural enemies are commercially available [73]. There are also about 10 species of micro-organisms and about 60 different microbial products registered on Annex I. n comparison there are more than 200 registered products in the USA [74]. Most of the augmentation biocontrol in Europe is done in protected crops (glasshouses and poly-tunnels) where the environment suits BCA activity and natural enemies are prevented from escaping. The focus is generally on the biocontrol of insect and mite pests. A large number of BCAs are available, with several different types for a single pest, and this helps make biological control programmes stable and reliable [75]. Economic methods for mass production have been developed and considerable expertise has been built up by the various biocontrol companies. Predators and parasitoids are supplied on an as-needed basis and applied by a number of different methods, for example they can be sprinkled directly over a crop or sold in permeable sachets that are hung onto leaves and stems. Insect pathogenic nematodes (used against weevils, thrips and fly larvae) and microbial agents, such as the insect pathogenic fungi *Beauveria*, *Isaria* and *Lecanicillium* (used against thrips, capsids, aphids and whitefly) can be applied with conventional spray apparatus or in irrigation equipment.

The outdoor environment is far more complex than the controlled conditions within a glasshouse, which makes the development of augmentative strategies more difficult. Success outdoors can be achieved when there is a good understanding of the ecology of the natural enemy and its pest [76]. The egg parasitoid *Trichogramma*, for example, is used on more than 32 million ha in over 30 countries [63]. However, augmentation biocontrol on outdoor crops has not been adopted widely by European farmers in comparison to their counterparts in Central and South America or China. There are some exceptions; for example a granulovirus is being used to control codling moth in apple orchards, but there is potential for more.

Twenty species of microbial agent for control of plant pathogens are currently listed on Annex I. For example the mycoparasitic fungus *Coniothyrium minitans*, marketed in the EU as ‘Contans’, is applied to the soil to kill *Sclerotinia sclerotiorum*, an important disease of many agricultural and horticultural crops such as oilseed rape, lettuce, carrots, beans and brassicas. Another fungus, *Trichoderma*, can be applied to soil to control a wide range of plant pathogens [77]. A product based on the bacterium *Bacillius subtilis*, called ‘Serenade’, can give good control of foliar diseases. However there are still significant barriers to uptake, including lower efficacy than chemical fungicides, short persistence and a narrow activity spectrum.

Symbiotic associations between arbuscular mycorrhizal (AM) fungi and plant roots are widespread in nature and improve plant nutrition, drought tolerance and pest resistance [78]. Many agricultural crops are mycorrhizal and there is widespread if equivocal evidence that crops benefit from an AM association [79]. Intensively managed agroecosystems are generally impoverished in AM fungi. However new approaches could be developed to reverse this, including changes to farm management practices or applications of fungal inoculum to the soil.

Microbial control products can also be used against weeds. No products are currently available in Europe, but two fungal products, ‘Collego’ and ‘DeVine’, have been used in the USA since the 1980s. These are based on strains of *Colletotrichum gloeosporioides* and *Phytophthora palmivora* respectively and typically control 85% of northern joint vetch in rice and soybean (‘Collego’), and 90% of milkweed vine in citrus groves (‘DeVine’) [80].

Because the effects of augmentation BCAs are dose dependent, any negative impact on non-target species should be temporary and last for as long as the agent persists. Accumulated experience by researchers and growers with agents such as entomopathogenic fungi appear to back this up, with no detectable detrimental environmental impact [81,82]. Such experience is clearly relevant to risk evaluation, but it is not to say that evaluation of new products is not required [83]. If augmentation control becomes used more widely, then the amount of environmental perturbation might increase. There is a lack of formal meta-analyses of the long-term environmental impact, particularly for microbial products. Providing this would be of considerable benefit to regulatory authorities.

3.3.2. Biopesticides

Some of the plant protection agents discussed in previous sections are referred to as ‘biopesticides’. There is no formally agreed definition of the term, but our definition of a biopesticide is a mass-produced, biologically based agent used for the control of plant pests. This definition describes the type of agent and how it is used. They can be divided into two main types [84]: (1) living organisms used for inundation biological control (predatory insects, parasitoids, nematodes or micro-organisms); (2) natural compounds. There are about 70 biopesticide products listed on Annex I (Table 5). In some countries, such as the USA, genetically modified plants that express introduced genes conferring protection against pests or diseases are also classed as biopesticides (so called plant incorporated products). Microbial agents and natural products are regulated under Plant Protection Products legislation. Biopesticides are being used on increasing scales; for example, the management of IPM in protected edible crops in the UK and the Netherlands is now done with a strong emphasis on using biopesticides supplied by specialised companies [85].

3.3.3. Introductions of non native natural enemies: classical control and augmentation

Classical biological control is the intentional introduction of an alien natural enemy for permanent establishment and control of an alien pest [71]. It is implemented mainly through government-funded programmes. It is usually associated with perennial crops where the stable nature of the ecosystem enables a permanent relationship between pest and natural enemy to become re-established [60]. Today, classical biological control of insects is used on 350 million ha worldwide, equivalent to 10% of the total global area of cultivated land, and is reported to have a cost benefit ratio in the range of 1 : 20 – 500 [60]. Since classical control is based on the deliberate introduction of a non-indigenous natural enemy with the aim of permanent establishment, determination of host specificity is paramount to ensure that agents released do not have negative effects on non-target organisms. There are well-established systems for risk assessment and host range testing of classical control agents, led largely by researchers working on weed control [86]. Around 2,000 natural enemy species have been introduced worldwide leading to the permanent reduction of 165 pest species [87]. There are estimated to have been about 130 examples of classical introductions against insect pests in Europe but no agents have been released against weed pests in the EU [88] despite their use against 133 target weeds elsewhere. Data collected on alien weeds in some EU countries suggest that they cause considerable economic damage (Table 6).

It has been argued that there is still a lack of long term, quantitative and objective monitoring of classical control programmes [89]. This may be because few apparent problems have been encountered with classical control [87]. However, where pre-release risk evaluation procedures are inadequate or ignored, environmental damage can occur. A prominent recent example in Western Europe concerns the harlequin ladybird, *Harmonia axyridis*. This species is native to Asia and has been used as a control agent of aphids in glasshouses in Europe and North America. It has been intentionally introduced in nine European countries since 1982 [24], although a retrospective analysis identified it as having high environmental risk [90] and thus it should not have been released [91]. It is now established in 13 European countries from Denmark to southern France and is predicted to spread further. It is able to out-compete native ladybirds, will predate on some beneficial insects, and there is evidence that it has a significant negative impact on other native arthropod species. This episode has undoubtedly cast a shadow over classical biological control in Europe. This is unfortunate, because it remains the only method for permanent ecological management of many alien species. It has been proposed that legislation is enacted within the EU in line with the Convention on Biological Diversity to enable releases of classical control agents based on EPPO standards [88].

Non native arthropod natural enemies are also used in northern Europe for augmentation biological control in glasshouses. Approximately 50% of insect and mite predators and insect parasitoids used in glasshouses are alien species [92]. Licenses for use are granted based on environmental risk assessments where it can be established that the agent cannot overwinter outdoors.

3.3.4. Conservation biological control

Conservation biological control is the practice of enhancing natural enemy efficiency through modification of the environment or of existing pesticide practices [71]. Although there is a large body of evidence suggesting that provision of floral resources, alternative food and shelter habitats can increase natural enemy abundance and diversity, there is as yet limited evidence that this leads to decreased pest damage or increased yields [93]. However successful conservation biocontrol of pest insects has been demonstrated for outdoor lettuce and grapes [94 – 96]. Thus, while conservation biocontrol has the potential to provide a range of benefits including lower production costs and enhanced yield, careful economic evaluation is needed[97]. Because it entails habitat management, it could provide additional public goods, such as biodiversity conservation, ecological restoration and tourism [98]. Wine producers in New Zealand, for example, are now growing flowers in between vines in order to lure and retain naturally occurring parasitoids; these floral displays also attract tourists to the region and are being used to market the wine as a premium, environmentally-friendly, brand [99].

Biological control can be a very successful component of IPM. Biocontrol agents tend to have a narrow activity spectrum. This is an attractive property from an environmental perspective but it also means that they are usually niche market products, which can act as a barrier to their commercialisation. There are significant differences in the biological control strategies used in - and the amount of success obtained with - glasshouse vs. outdoor crops. Classical control has much to offer, but if the systems of environmental risk assessment developed by scientists are not followed then problems can occur. More investment in research and development is needed, particularly for biocontrol in field crops.

3.4. Plant breeding

The growing of resistant varieties is often promoted as an alternative to the use of pesticides. Although there has been some work to breed for resistance to invertebrate pests, the majority of effort has been directed at resistance to microbial plant pathogens. Many hundreds of pathogen resistance genes have been identified in crop species. However, no plant variety is resistant to all diseases and pests, and the choice of variety is always a balance between different traits; generally disease resistance is a lower priority than quality / market acceptability. Moreover, most resistance is ephemeral due to the ability of pathogen populations to overcome it through natural selection [100].

Release of new resistant varieties which depend on only a single resistance gene is the most common commercial situation; indeed several varieties all sharing the same resistance gene is becoming the norm as the expense of finding new genes is shared between breeding companies. This increases the chances of a new virulent pathogen isolate evolving. For some crop / pathogen combinations, e.g. lettuce downy mildew, over 30 resistance genes have been 'wasted' and breeders are now searching for new genes in wild relatives. Various strategies have been promoted to preserve the longevity of resistance, including 'pyramiding' resistance genes (incorporating more than one gene in a variety) or deploying a mixed set of genes in a crop as a variety mixture. However, these have generally proved costly and have not been adopted by breeding companies. The biggest successes with variety mixtures have been in centralised economies where authorities can dictate to farmers their choice of varieties. An alternative form of resistance exists which is determined by several genes. This can be (but is not always) more durable than single gene resistance. However, it is more difficult to handle in a breeding programme and is often partial, i.e. some disease still develops. The former is now being overcome with new technology such as marker assisted breeding [101], the latter may not be an issue if some yield reduction is acceptable. However, in fruit and vegetables, where marketable yield is determined by quality, any disease blemishes may be unacceptable.

Host resistance must be used as part of IPM to achieve durable crop resistance. Resistant varieties should be combined with other measures such as biological control, targeted pesticide use and cultural techniques. This will reduce the chances of pathogens overcoming plant resistance, but will also lower the probability of them evolving resistance to pesticides. However, reducing the availability of some pesticides could limit options for putting IPM programmes into place.

3.5. Genetic methods

The sterile insect technique involves the release of very large numbers of sterilised insects (usually males) into the vicinity of the crop, so that they will mate with 'wild' insects and so prevent them producing young. The insects to be released are sterilised using irradiation or chemicals. The release ratio ranges from 10:1 up to 100:1 sterile: wild insects. The technique will work better if sterile insects are as 'fit' as wild insects, the species only mates once and it has a limited ability to disperse. The technique is expensive, mainly because large numbers of insects must be reared and it usually requires releases over large areas. It has been used successfully to eradicate the screw-worm fly (*Cochliomyia hominivorax*) in areas of North America. There have also been many successes in controlling species of fruit flies, most particularly the medfly (*Ceratitis capitata*) [10], and the technique has been used to manage onion fly in the Netherlands.

3.6. Genetically Modified (GM) crops

To date, GM maize, cotton, soya bean and oilseed rape crops have been commercialised for management of weeds, insects, or both. There are several examples of GM-incorporated herbicide tolerance including glyphosate resistance (known as 'GR'). GM maize and cotton plants resistant to insect attack contain genes of the insect pathogenic bacterium *Bacillus thuringiensis* that express proteins toxic to caterpillar pests (known as 'Bt' crops). The same bacterium is also used as a BCA against caterpillars as a foliar spray. GM crops are grown in 23 countries over 114 million ha worldwide, equivalent to c. 5% of global cultivated land [102]. These include 8 EU states; Spain, France, Czech Republic, Portugal, Poland, Germany, Slovakia and Romania, although the area of cultivation in these countries is generally less than 0.05 million ha.

It is undoubtedly the case that the development of policies on GM crops in Europe has been affected by a lack 'upstream' engagement between governments, regulators, farmers, pressure groups, industry, the media, and other members of civil society. There has been a loss of confidence in scientific experts by the general public over issues of risk. While scientific expertise and evidence can help answer specific questions about GM crops, it cannot be the sole tool for developing policy. People entering the debate about GM have different points of view and hence a resolution may not be possible. Agriculture in Europe has its own distinctive social dimension and hence Europeans may well have different concerns about GM compared to citizens elsewhere. The ethical issues surrounding GM crops are many and complex, and include general welfare (i.e. the responsibility of governments to protect the interests of citizens), consumer choice and rights, principles of justice, and the boundary between what is considered natural / unnatural [103].

Those in favour of GM argue that transgenic crops can help increase yields (for example by reducing losses due to pests), can have improved nutritional content, require fewer inputs and have less post harvest spoilage and wastage. Arguments against GM crops include possible harm to human health, concerns that the technology consolidates the industrialisation of agriculture, that it is not natural, and that it may damage the environment (for example by having effects on natural enemies and other non target species). In Europe and elsewhere, detailed environmental risk analysis of potential effects of GM crops based on laboratory and field experiments is made before licences to release the technology are granted. For example, UK Farm Scale Evaluations have been conducted that compared the effects on farmland biodiversity of growing conventional and GR sugar beet, maize and oilseed rape. It was found that the species of crop grown (i.e. beet, maize or rape) had a greater impact on biodiversity than whether the crop was GR or conventional [104]. Only minor differences were observed between the GR and conventional versions of the same crop species. Critics have argued that even farm scale trials cannot predict the effects of GM crops when grown at very large scales. Eight countries now grow > 1 million ha of GM crops (USA, Canada, China, India, South Africa, Paraguay, Argentina, Brazil) [102] and hence, if negative effects do occur from GM crops, then it is reasonable to expect that they will become apparent soon if they have not done so already. In the case of Bt crops, laboratory and field studies have shown either no impact or only a transient effect on natural enemies, which is mainly due to a reduction in the number of target pests as prey [105]. Resistance management is a concern [106] as resistance has developed to Bt foliar sprays. A strategy has been devised based on the cultivation of areas of non Bt crops as refugia to maintain susceptible alleles within the pest populations [107]. Surveys of farmers' pesticide use indicates that growing Bt crops can result in significantly reduced applications of conventional insecticides, up to 70% in some cases [108,109]. However there are exceptions. Secondary pest problems caused by mirid bugs have occurred on Bt cotton grown in China [110]. These bugs were controlled previously by broad spectrum pesticides but are not controlled by Bt cotton. Problems with mirids in China did not occur until a few years after the widespread uptake of Bt cotton (i.e. there was a time lag between adoption of Bt cotton and the onset of secondary pest problems). The unfortunate result is that some farmers growing Bt cotton in China are having to make more pesticide applications than before in order to control mirid outbreaks, with a net reduction in revenue compared to conventional cotton [109]. Secondary pest outbreaks are a well-known phenomenon in agriculture, but without more evidence it is difficult to say whether this particular problem could have been foreseen. One lesson is clear; if GM crops, or any other new technologies, are to be used in ways that increase the sustainability of crop production, then they must be treated on a case by case basis and utilised according to basic IPM principles.

GM crops can give economic and environmental benefits. However if they are not used according to IPM principles then sustainability gains may be lost. If there are large-scale effects then they should become apparent in the 8 countries outside the EU that grow over 1 million ha of GM crops. The ethical issues surrounding GM are complex and there may be unique concerns for Europeans.

4. Integrated Pest Management

There is little doubt that the best way to make crop protection more sustainable is by using Integrated Pest Management (IPM). IPM is a systems approach that combines a wide array of crop production practices with careful monitoring of pests and their natural enemies. IPM practices include resistant varieties, timing of planting, physical methods, cultivation, biological controls, and judicious use of pesticides to control pests. The aim of IPM is not pest eradication; rather it is the more realistic goal of reducing a pest population below its economic injury level. In industrialised economies, IPM is seen as technologically based and is focused on using a suite of complementary control options in combination with pest monitoring and economic action thresholds. In some developing nations, however, a different IPM model has been developed, based on training farmers to better understand the importance of natural biological control and to rely on their own observations in order to decide when to spray pesticides [43,67]. However, in both situations, the goal is the same; namely to achieve a flexible and durable system that minimises impacts on other components of the agro-ecosystem [111].

IPM does not rule out the use of synthetic chemical pesticides. However, they are only used when systematic monitoring indicates a need. Other forms of pest management are used to keep chemical interventions to a minimum. This includes biological, cultural and physical controls, host plant resistance, and decision support tools. In the last decade, there have also been recommendations to restore the ecosystem function of pest management, so that the agricultural landscape itself becomes resistant to the development of pest populations, for example by growing pest-resistant crop varieties and increasing populations of natural predators, parasites and parasitoids [60,42].

IPM can reduce reliance on agrochemical inputs and provide environmental and economic benefits [112]. Figures for the estimated area of crops under IPM for different crop types are given in Table 7. In an analysis of 62 IPM initiatives in 26 industrialised and developing countries, over 60% of initiatives resulted in a reduction in pesticide use and an increase in yields [9]. Sixteen percent of projects resulted in an increase of both yield and pesticide use. These were conservation farming projects that incorporated zero tillage and thus tended to result in greater use of herbicides for weed management. Approximately 20% of projects resulted in a reduction in yield with lowered pesticide use. These mainly consisted of cereal production projects in Europe, where falls in pesticide use resulted in typically 80% reduction in yield. Because cereal production is a significant component of European agriculture, this finding has important implications for policy.

4.1. IPM in glasshouse crops

Glasshouse growers are able to produce high value crops on a small area of land. Unfortunately, glasshouse crops also provide an excellent environment for pest insects, mites and plant pathogens. Pesticide resistance evolved in some key glasshouse pests as long ago as the 1960s, prompting the early development of biocontrol. This was followed by the widespread adoption of bumblebees for pollination, which required growers to stop using broad-spectrum insecticides. Some sophisticated and effective IPM programmes have been developed for glasshouse crops (Table 8). These were mainly instigated through publicly funded research and involved close working between research scientists, growers and industry. IPM is now used in over 90% of glasshouse tomato, cucumber and sweet pepper production in the Netherlands [85] and is standard practice for glasshouse crops in the UK. It uses a combination of biological and physical controls, selective pesticides and resistant varieties. It has been adopted widely because it has clear benefits for the grower. These include reliable pest control, lack of phytotoxic effects, better fruit set, and the fact that staff do not have to be excluded from the glasshouse so often for pesticide applications. Most of the biological control used in glasshouses is concerned with managing insect and mite pests. Some BCAs are available against plant pathogens and can be integrated with selective pesticides [113] but a greater range of products is required. Many of the main plant diseases are tackled using resistant crop cultivars. Typically, pesticides will be used at the start of the season as a clean up for insect and mite pests before switching to inundative applications of predators, parasitoids, parasitic nematodes and insect pathogens. Short persistence pesticides are used on an at-need basis to knock back pest populations if they start to outstrip the ability of the biological control agents to regulate them. Recent research has shown that insect pathogenic fungi can also be used as a second line of defence when using predators against thrips and spider mites [114,115]. The ability to use pesticides and microbial control agents as fast acting remedial treatments can make the difference between success and failure in glasshouse IPM (R. Jacobson, personal communication). Europe-wide, the industry is supported by about 25 biological control companies – including the world’s three largest - that supply natural enemies and technical support [85]. The costs of IPM are reported to be competitive with chemically-based control [85].

4.2. IPM in field vegetable crops & orchards

European retailers and consumers demand vegetables that are relatively uniform in size and shape and free from blemishes and pest-related debris. Field vegetables generally have a higher value than cereals, but a lower value than glasshouse crops. Because of the emphasis on quality, the risk of producing an unmarketable crop is relatively great. Vegetable growers are, therefore, generally risk averse. Components of IPM that are well-developed in field vegetables include crop rotation (with some exceptions), good crop management (removal of plant residues, application of fertilisers and irrigation) and careful crop monitoring for pest problems. This may often involve the use of pest or disease forecasts [116], traps or other management tools. Growers walk their crops regularly and make decisions based on their findings, but ‘research-based’ thresholds are used relatively rarely in Europe compared with, for example, the USA [117]. Pest and disease resistant cultivars are grown where available and if the cultivars meet other market requirements. Lettuce with resistance to downy mildew are grown widely. Lettuce varieties with resistance to the aphid *Nasonovia ribisnigri* have been increasing, although this has now been overcome in several locations in Europe. Use of physical methods of pest control is increasing. Mechanical weed control can be effective and covers or mulches have been used to control pest insects and weeds. Biological control with microbials or arthropods is relatively undeveloped. This is due to a combination of factors: lack of environmental ‘control’ and ‘confinement of released natural enemies’ compared with protected crops, the relatively high cost of biological control methods compared with the value of the crop, reduced and variable efficacy compared with pesticides and the limited research and development input in this area.

European retailers also have high quality standards for orchard crops. IPM strategies in orchards are largely based on stopping sprays of broad spectrum pesticides and allowing natural enemies to re-establish[60]. The development of decision support tools (pest thresholds, monitoring, models) has allowed the targeted application of specific pesticides or microbial control agents (e.g codling moth granulovirus) or the application of parasites and parasitoids [118,119].

4.3. IPM in arable crops

Arable crops generally have high economic thresholds for pest management interventions, meaning that low densities of many pests can be tolerated (the exceptions are for pre- and post-harvest fungal diseases, some of which pose a serious hazard to human health). There is, therefore, good scope for IPM, but it is not yet being used widely in Europe. For example, it is estimated that only 10% of cereal production is done under IPM [120]. The majority of IPM schemes are based on pest forecasting, monitoring and host-plant resistance rather than on biological control. A notable exception is the use of the parasitoid *Trichogramma* to control outbreaks of the European corn borer, *Ostrinia nubilalis* on maize [121]. The use of conservation biological control methods, such as wildflower headlands and beetle banks, is promoted through various agri-environment schemes but in the UK, for example, most of these have had a very low uptake [122]. There is greater use of IPM techniques within organic arable production, but even here there is limited use of biological control, with the majority of integrated crop management schemes relying on improved monitoring and reduced applications of approved chemical controls [123].

5. Regulation and the market: the case of biopesticides

The adoption of different crop protection technologies has a strong market and regulatory dimension. Regulatory systems can act as barriers to new technologies and approaches. In the case of biopesticides governed by Plant Protection Products legislation (i.e. microbial control agents and natural products), the regulatory system has tended to follow a chemical pesticide model which is often not relevant in the questions that it poses and does not facilitate the efficient authorisation of products. The authorisation process therefore raises entry costs to the market that are particularly onerous for the small to medium sized enterprises that make up the bulk of the biopesticides industry.

The wider adoption of biopesticides in the United States in part reflects the existence of a large internal market that makes it commercially viable to produce niche products. The US has also been proactive in encouraging the development of BCAs. Within the EU, the efficiency of member state regulatory agencies is recognised to be highly variable, although there are examples of best practice. Unfortunately there is no internal market for biopesticides because mutual recognition between member states has yet to work effectively. A fundamental tension also arises from the fact that, because of their role and their training, regulators tend to be conservative and risk averse, whereas entrepreneurs developing new products are risk takers. This creates a basis for mutual misunderstanding with biopesticides producers perceiving the conservatism of the regulatory system as an incomprehensible hurdle. It requires a very special combination of circumstances for regulatory innovation to occur at all. What can be done in the EU is constrained by state aid rules in terms of 'near market' aid. However, it is possible to take actions that assist firms through the registration process, for example the Genoeg scheme in the Netherlands (GEwasbeschermingsmiddelen van Natuurlikje Oorsprong Effictief Gebruiken, which translates colloquially as 'effective use of natural pesticides'). The UK developed a pilot scheme followed by a permanent Biopesticides Scheme intended to facilitate registration. This in part reflected a willingness on the part of Government to allow resources to be devoted to such a scheme. The main features of the scheme are pre-registration meetings with applicants to clarify what is required in the dossier; substantially reduced registration fees; and the development of an informal network within PSD with relevant expertise. Effective working relationships have been developed with the trade association, the International Biocontrol Manufacturers Association (IBMA) as a means of reviewing procedures and reaching out to potential registrants. The scheme has led to an increase in the number of products registered or being considered for registration.

6. Conclusions and recommendations

Global agriculture is in a period of tremendous change. There is increasing tension between the need to produce food and protect other ecosystem services. Europeans have not paid enough attention to the long-term future of farming and the overwhelming requirement for a sustainable agri-food system.

Pests (invertebrates, plant pathogens and weeds) are major constraints to agricultural production. There is a clear and present need to develop integrated systems of pest management with greater levels of sustainability across all crop types. This would be a significant way forwards for improving yields and continued access for EU citizens to reasonably priced, healthy and good quality food. Looking ahead, IPM will be essential for climate change adaptation and mitigation, including decreased reliance on fossil fuels.

Chemical pesticides are a vital part of crop protection and they need to be used more within the framework of IPM. More impact assessments need to be done on the consequences of the ‘cut-off’ criteria. It is likely that a loss of key herbicides would jeopardize production of some minor crops hile fungicide loss would result in significant yield decline in wheat and other arable crops. There may well be effects on nature conservation. It is well known that chemical pesticides can affect species diversity, at least in the area to which they are applied. However, if loss of fungicides means that more land has to be put over to cultivation in order to increase cereal production, then there could be significant negative effects on biodiversity through loss of natural habitats. It is unlikely that organic farming could be used to substitute for conventional agriculture because it typically produces smaller yields. However, it has much to offer to the development of sustainable farming in Europe in terms of its emphasis on renewable resources, ecology and biodiversity.

In this document we have appraised a wide range of non-chemical pesticide methods for crop protection: physical and cultural controls, natural compounds, biological control, plant breeding and genetic methods. These methods have a wide range of attractive properties and can all make valuable contributions to crop protection as part of IPM. In most situations the best way forward is to use them with chemicals in a fully integrated programme. In the case of glasshouse and other protected crops, some sophisticated and effective ways of doing this are already in place. However in outdoor crops, IPM does not appear to be used widely.

Agriculture has many functions. It not only produces commodities, it also provides essential public goods and services. IPM can play a significant role in making farming more environmentally, economically and socially sustainable: it can help to maintain biodiversity, reduce pollution, lower the build up of pesticide resistance, maintain the security of food supply, increase yields, and improve consumer confidence in the agri-food industry. The manufacture of biocontrol agents and related products is a small-scale activity that can boost high quality employment opportunities in rural areas. However, many of the features of non-chemical pesticide methods that make them attractive in terms of human safety and the environment also limit them to niche markets. At present, there are definite regulatory and market barriers that are preventing these ‘alternative’ crop protection agents from being taken up more widely. The development of inundative biological control agents, for example, has followed a chemical pesticide model that does not exploit fully the favourable biological properties of the agents [67]. There are also significant scientific and technical challenges to be addressed, but these are being hampered by a chronic under-investment in research and development.

Finally, we emphasise that IPM should be tailored to local conditions [9]: the species of pest, the type of crop, climate and weather, production practice, and skills and knowledge of farmers and growers. The ability to do this successfully will depend on there being effective institutions, policies and partnerships in place to enable and sustain innovation [9]. This may require fundamental shifts [11]. Shared goals must also be developed by the chemical pesticide sector and the producers of other products, a process that appears to be under way in Europe already

[45]. When this happens, IPM can be embraced rapidly. For example, the area of edible horticultural crops grown under IPM in Almeria, Spain, has increased from just 250 ha to 7000 ha since 2005 [45]. This offers hope for the future.

Our recommendations are as follows:

- More assessments are needed of the impact of the 'cut-off' criteria across the EU. This must be wide ranging and include the consequences not just for crop yields but also for pesticide resistance, nature conservation, the management of alien species and the development of IPM.
- European farmers and growers must be given access to a variety of pesticides, with different modes of action, as a vital method for IPM and for pesticide resistance management.
- If key pesticides are withdrawn too rapidly then the market will be unable to fill the gap in time.
- IPM should be at the centre of EU crop protection policy. Effective policies should be in place to facilitate its development and uptake. There is not enough information about the current status of IPM in different crops and farming systems across the EU.
- Significantly more funding is needed for research and development. This must include research to better understand pest biology and the interactions between the different components of agro-ecosystems. More work should be funded on the development, use and integration of crop protection tools: synthetic chemicals, biological controls, natural products, physical and cultural methods, decision support, plant breeding and other genetic techniques including GM. This must be focused on making agriculture more sustainable. The link between farmers / growers and the crop protection industry could be developed to better target product development and to support development of data for national product registration.
- Research is needed on why augmentation biocontrol is not being used much on outdoor crops in Europe, including possible ecological, technical, environmental, economic and social barriers.
- There is a strong case for making better use of ecological theory in biological control that includes environmental risk evaluation. This should lead to better biocontrol and enable regulators and others to respond better to future developments such as tensions between stakeholders (for example conservationists vs. food producers and retailers).
- More information must be obtained on the practical ways in which farmers and growers are already using non-chemical pesticide methods as part of IPM. There should be more effective ways of exchanging this knowledge. Other members of the policy network should be included.
- Innovations are required that overcome regulatory and market barriers to the adoption of non-chemical pesticide methods while still protecting human and environmental safety. The regulatory process needs to have an inbuilt preference for alternatives rather than being constructed and operated in a way that presents them with additional barriers. The registration process for alternatives needs to be made more accessible, more specific, faster and less expensive.
- Promoting the availability of alternatives through research and manufacture should be legitimate grounds for funding under Pillar 2 rural development programmes.
- Work currently being undertaken by OECD offers the potential for the development of a global harmonised system for microbial pesticide regulation. This would permit companies to secure larger markets and economies of scale and hence enhance their viability. However, sufficient resource support in terms of expert time needs to be available for this process.
- Many member states no longer have state extension services that could have provided guidance and assistance to farmers and growers. There is a case for providing funding to facilitate innovation in the use of 'alternative' crop protection methods by farmers and growers, e.g. by co-funding the purchase of consultancy advice.

Annex I: References

[1.] Flint, M.L. & van den Bosch, R. (1981). Introduction to integrated pest management. Plenum Press, New York, USA.

[2.] Pimentel, D. (1997). Techniques for reducing pesticides: environmental and economic benefits. John Wiley and Sons, Chichester, UK.

[3.]. Oerke, E.C., Dehne, H.W., Schnbeck, F. & Weber, A. (1994). Crop production and crop protection: estimated losses in major food and cash crops. Elsevier, Amsterdam, The Netherlands.

[4.] Torchin, M.E., Lafferty, K.D., Dobson, A.P., McKenzie, V.J. & Kuris, A.M. (2003). Introduced species and their missing parasites. *Nature*, **421**, 628 – 630.

[5.] Mitchell, C. E. & Power, A. G. (2003). Release of invasive plants from fungal and viral pathogens. *Nature*, **421**, 625 – 627.

[6.] Delivering Alien Invasive Species Inventories for Europe (DAISIE). European Commission Sixth Framework Programme (Contract Number: SSPI-CT-2003-511202). http://www.europe-aliens.org/

[7.] Pimentel, D., McNair, S., Janecka, J., Wightman, J., Simmonds, C., O’Connell, C., Wong, E., Russel, L. Zern, J., Aquino, T. & Tsomondo, T. (2001). Economic and environmental threats of alien plant, animal, and microbe invasions. *Agriculture, Ecosystems and Environment,* **84**, 1 – 20.

[8.] MacKenzie, D. (2007). Billions at risk from Wheat super blight. *New Scientist*, *2598,* 6-7.

[9.] Pretty, J. (2008). Agricultural sustainability: concepts, principles and evidence. *Philosophical Transactions of the Royal Society B*, **363**, 447-465.

[10.] Thacker, J.R.M. (2002). An introduction to arthropod pest control. Cambridge University Press, Cambridge, UK.

[11.] Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R. & Polasky, S. (2002). Insight. *Nature*, **418**, 671 – 677.

[12.] Tilman, D. (1999). Global environmental impacts of agricultural expansion.: the need for sustainable and efficient practices. *Proc. Natl Acad. Sci. USA,* **96**, 5995-6000.

[13.] Millennium Ecosystem assessment (MEA) (2005). Eccosytems and well-being. Island Press, Washington, DC, USA.

[14.] Palumbi, S.R. (2001). Humans as the world’s greatest evolutionary force. *Science*, **293**, 1786-1790.

[15.] Hajek, A. (2004). Natural enemies: an introduction to biological control. Cambridge University Press, Cambridge, UK.

[16.] Skylakakis, G. (1987). Changes in the composition of pathogen populations caused by resistance to fungicides. In: Populations of plant pathogens: their dynamics and genetics. Wolfe M.S., Caten C.E. (Eds). Blackwell Publishing, Oxford, UK, pp 227–237.

[17.] Milgroom, M.G., Levin, S.A. & Fry, W.E. (1989). Population genetics theory and fungicide resistance. In: Plant disease epidemiology. 2. Genetics, resistance and management. Leonard, K.J. & Fry, W.E. (Eds). McGraw Hill, New York, USA, pp 340-367.

[18.] De Waard, M.A., Georgopoulos, S.G., Hollomon, D.W., Ishii, H., Leroux, P., Ragsdale, N.N., Schwinn, F.J. (1993). Chemical control of plant diseases: problems and prospects. *Ann. Rev. Phytopathol.,* **31**, 403-421.

[19.] Pesticides Safety Directorate. (2008). Assessment of the impact on crop protection in the UK of the 'cut-off criteria' and substitution provisions in the proposed Regulation of the European Parliament and of the Council concerning the placing of plant protection products in the market. Pesticides Safety Directorate, York, UK http://www.pesticides.gov.uk/environment.asp?id=1980&link=%2Fuploadedfiles%2FWeb%5FAssets%2FPSD%2FImpact%5Freport%5Ffinal%5F%28May%5F2008%29%2Epdf

[20.] Pesticides Safety Directorate. (2008).plant protection products regulation: agronomic implications of proposals in the EU. Pesticides Safety Directorate, York, UK http://www.pesticides.gov.uk/environment.asp?id=1980&link=%2Fuploadedfiles%2FWeb%5FAssets%2FPSD%2FPPPR%5FAgronomic%5Fimplications%5Fof%5Fproposals%5Fin%5Fthe%5FEU%2Epdf

[21.] European and Mediterranean Plant Protection Organization (EPPO) (2008). http://archives.eppo.org/MEETINGS/2008_conferences/active_substances.htm#pres

[22.] McLaughlin, A. & Mineau, P. (1995). The impact of agricultural practices on biodiversity. *Agriculture, Ecosystems and Environment*, **55**, 201-212.

[23.] Benton, T.G., Vickery, J.A. & Wilson, J.D. (2003). Farmland biodiversity: is habitat heterogeneity the key? *Trends in Ecology and Evolution*, **18**, 182-188.

[24.] Brown, P.M.J., Adriaens, T., Bathon, H., Cuppen, J., Goldarazena, A., Hagg, T., Kenis, M., Klausnitzer, B.E.M., Kovar, I., Loomans, A.J.M., Majerus, M.E.N., Nedved, O., Perdersen, J., Rabitsch, W., Roy, H.E., Ternois, V., Zakharov, I.A. & Roy, D.B. (2008). *Harmonia axyridis* in Europe: spread and distribution of a non-native coccinellid. *BioControl*, **53**, 5 – 21.

[25.] Kitzes, J., Wackernagel, M., Loh, J., Peller, A., Goldfinger, S., Cheng, D. & Tea, K. (2008). Shrink and share: humanity's present and future ecological footprint. *Philosophical Transactions Of The Royal Society B*, **363**, 467-475.

[26.] Svancara, L.K., Brannon, R., Scott, J.M., Groves, C.R., Noss, R.F., Pressey, R.L. (2005). Policy-driven versus evidence-based conservation: A review of political targets and biological needs. *Bioscience*, **55 (11)**, 989-995.

[27.] Fahrig, L. (2003). Effects of habitat fragmentation on biodiversity. *Annual Review of Ecology, Evolution and Systematics*, **34**, 487-515.

[28.] Scherr, S.J. & McNeely, J.A. (2008). Biodiversity conservation and agricultural sustainability : towards a new paradigm of ‚ecoagriculture' landscapes. *Philosophical Transactions of the Royal Society B*, **363**, 477-495.

[29.] Dehnen-Schmutz, K., Perrings, C. & Williamson, M. (2004). Controlling *Rhododendron ponticum* in the British Isles: an economic analysis. *Journal of Environmental Management*, **70**, 323–332.

[30.] Dawson, F.H. & Holland, D. (1999). The distribution in bankside habitats of three alien invasive plants in the U.K. in relation to the development of control strategies. *Hydrobiologia*, **415**, 193-201.

[31.] Brasier, C., Denman, S., Brown, A. & Webber, J. (2004). Sudden Oak Death (*Phytophthora ramorum*) discovered on trees in Europe. *Mycological Research*, **108**, 1108-1110.

[32.] Sheppard, A.W., Shaw, R.H. & Sforza, R. (2006). Top 20 environmental weeds for classical biological control in Europe: a review of opportunities, regulations and other barriers to adoption. *Weed Research*, **46**, 93 – 117.

[33.] Lampkin, N.H. (2004). Certified and policy supported organic and in-conversion land area in Europe. http://www.organic.aber.ac.uk/statistics/euroarea03.htm

[34.] Lampkin, N.H. & Padel, S. (Eds). (1994,). The economics of organic farming. an International perspective. CAB International, Wallingford, UK.

[35.] Mader, P., Fliebach, A., Dubois, D., Gunst, L., Fried, P.& Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science*, **296**, 1694-1697.

[36.] Foster, S.P., Denholm, I. & Devonshire, A.L., (2000). The ups and downs of insecticide resistance in peach-potato aphids *(Myzus persicae)* in the UK. *Crop Protect*, **19**, 873-879.

[37.] European and Mediterranean Plant Protection Organization (EPPO) (2007. *Ad hoc* EPPO Workshop on insecticide resistance of *Meligethes* spp. (pollen beetle) on oilseed rape. Berlin, 2007-09-03/05 http://archives.eppo.org/MEETINGS/2007_meetings/meligethes/meligethes_workshop.htm

[38.] Defra (2006). Evaluating the response of UK strains of *Thrips tabaci* to deltamethrin. Final report of Project PS2710.

[39.] Van den Boschm, F. & Gilligan, C.A. (2008). Models of Fungicide Resistance Dynamics. *Annual Review of Phytopathology*, **46**, 123–147.

[40.] Brent K.J. & Hollomon, D.W. (2007). Fungicide resistance; the assessment of resistance. FRAC Monograph No.2 second, (revised) edition

[41.] Gelernter, W.D. (2005). Biological control products in a changing landscape. The BCPC *International Congress Proceedings: 2005*. Volume 1, pp. 293-300. The British Crop Protection Council, Hampshire, UK.

[42]. Lewis, W.J, van Lenteren, J.C., Pathak, S.C. & Tumlinson, J.H. (1997). A total systems approach to sustainable pest management. *Proc. Natl Acad. Sci. USA*, **94**, 12243-12248.

[43.] Dent, D. (2000). Insect pest management. CABI publishing , Wallingford, UK.

[44.] Gurr, G. & Wratten, S. (Eds).(2000). Biological control: Measures of success. Kluwer Academic Publishers, The Netherlands.

[45.] Evans, J. (2008). Biopesticides: from cult to mainstream. *Agrow*, **October 2008**, 11 – 14. www.agrow.com

[46.] Vincent, C., Hallman,G., Panneton,B. & Fleurat-Lessard, F. (2003). Management of agricultural insects with physical control methods. *Annual Review of Entomology*, **48**, 261–81.

[47.] Bond, W. & Grundy, A.C. (2001). Non-chemical weed management in organic farming systems. *Weed Research*, **41**, 383-405.

[48.] Leatherland, M. (1995). The great pest cover up. *New Farmer & Grower*, **Summer 1995**, 30-31.

[49.] Meadow, R. & Johansen, T.J. (2005). Exclusion fences against brassica root flies (*Delia radicum* and *D. floralis*). *IOBC/WPRS Bulletin*, **28**, 39-43.

[50.] Minnis, S.T., Haydock, P.P.J., Ibrahim, S.K. Grove, I.G. Evans, K. & Russell, M.D. (2002). Potato cyst nematodes in England and Wales - occurrence and distribution. *Annals of Applied Biology*, **40**, 187-195.

[51.] Wibberley, J. (1996). A brief history of rotations, economic considerations and future directions. *Aspects of Applied Biology*, **47**, 1-10.

[52.] Shah, P.A. & Pell, J.K. (2003). Entomopathogenic fungi as biological control agents. *Applied Microbiology and Biotechnology*, **61**, 413-423.

[53.] Ellis, P.R., Hardman, J.A., Cole, R.A. & Phelps, K. (1987). The complementary effects of plant resistance and the choice of sowing and harvest times in reducing carrot fly (*Psila rosae*) damage to carrots. *Annals of Applied Biology*, **111**, 415-424.

[54.] Finch, S. & Collier, R.H. (2000). Host-plant selection by insects – a theory based on 'appropriate/inappropriate landings' by pest insects of cruciferous plants. *Entomologia experimentalis et applicata*, **96**, 91-102.

[55.] Theunissen, J. & Schelling, G. (1996). Pest and disease management by intercropping: suppression of thrips and rust in leek. *International Journal of Pest Management*, **42**, 227-234.

[56.] Brophy, L.S. & Mundt, C.C. (1991). Influence of plant spatial patterns on disease dynamics, plant competition and grain yield in genetically diverse wheat populations. *Agriculture, Ecosystems & Environment*, **35**, 1-12.

[57.] Shelton, A.M. & Badenes-Perez, F.R. (2006). Concepts and applications of trap cropping in pest management. *Annual Review of Entomology*, **51**, 285–308.

[58.] Cook, S.M., Khan, Z.R. & Pickett, J.A. (2007). The Use of Push-Pull Strategies in Integrated Pest Management. *Annual Review of Entomology*, **52**, 375–400.

[59.] Foster, S.P. & Harris, M. O. (1997). Behavioral manipulation methods for insect-pest management. *Annual review of Entomology*, **42**, 123-146.

[60.] Bale, J.S., van Lenteren, J.C. & Bigler, F. (2008). Biological control and sustainable food production. *Philosophical Transactions of the Royal Society B*, **363**, 761 – 776.

[61.] Bellows, T.S. & Fisher, T.W. (Eds) (1999). Handbook of biological control. Academic Press, San Diego, USA.

[62.] Begon, M., Townsend, C.R. & Harper, J.L. (2006). Ecology: From individuals to ecosystems. Blackwell Publishing Ltd, USA.

[63.] Van Lenteren, J.C. (2000). Success in biological control of arthropods by augmentaion of natural enemies. In Gurr, G. & Wratten, S. (Eds.), Biological Control: measures of success, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 77 – 103.

[64.] Hawksworth, D.L., Kirk, P.M., Sutton, B.C. & Pegler, D.N. (*1995). (Ainsworth and Bisby's) Dictionary of the fungi (Eighth Edition).* CAB International, Wallingford, UK.

[65.] Copping, L.G. (2004). The Manual of Biocontrol agents. British Crop protection Council, Farnham, UK.

[66.] FAO, (1996). Code of conduct for the import and release of exotic biological control agents. International standard for phytosanitary measures, no. 3. Secretariat of the International plant protection Convention, FAO, Rome, pp21. See http://www/ippc.int

[67.] Waage, J.K. (1997). Biopesticides at the crossroads: IPM products or chemical clones? In H.F. Evans (Chair), Microbial insecticides: novelty or necessity?. *British Crop Protection Council Symposium Proceedings* **No.68**, Farnham, UK, pp11-20.

[68.] Collier, T. & Van Steenwyck, R. (2004). A critical evaluation of augmentative biological control. *Biological Control*, **31**, 245-256.

[69.] Tisdell C.A. (1990). Economic impact of biological control of weeds and insects. In Critical issues in biological control. Mackauer, M., Ehler, L.E. & Roland, J (Eds), Intercept, Andover, UK, pp.301-316.

[70.] Van Driesche, R.G. & Bellows, T.S. (1995) Biological Control. Chapman & Hall, New York, USA.

[71]. Eilenberg, J., Hajek, A. & Lomer, C. (2001). Suggestions for unifying the terminology in biological control. *BioControl*, **46**: 387-400.

[72.] Whipps, J.M. (2001). Microbial interactions and biocontrol in the rhizosphere. *Journal of Experimental Botany*, **52**, 487 – 511.

[73.] European and Mediterranean Plant Protection Organization (2002). List of biological control agents widely used in the EPPO region. *EPPO Bulletin*, **32**, 447 – 461.

[74.] Kabaluk, T. & Gazdik, K. (2005). Directory of microbial pesticides for agricultural crops in OECD countries. Agriculture and Agri-Food Canad. http://www.agr.gc.ca/env/pdf/cat_e_pdf

[75.] Albajes, R.. Gullimo, M.L., van Lenteren, J.C. & Elad, Y. (Eds) (1999). Integrated pest and disease management in greenhouse crops. Kluwer Academic Publishers, Dordrecht, The Netherlands.

[76.] Wright, M.G., Kuhar, T.P., Diez, J.M. & Hoffman, M.P. (2005). Effective augmentative biological control – importance of natual enemy dispersal, host location and post-release assessment. *Proceedings of the Second International Symposium on Biological Control of Arthropods* pp. 495-500.

[77.] Howell, C.R. (2003). Mechanisms employed by Trichoderma species in the biological control of plant diseases: the history and evolution of current concepts. *Plant Disease*, **87**, 4–10.

[78.] Bending, G.D., Aspray T.A. & Whipps, J.M. (2008) Significance of microbial interactions in the mycorrhizosphere. *Adv. Appl. Microbiol*., **60**, 97-132.

[79.] Gosling, P., Hodge, A., Goodlass, G., and Bending, G. D. (2006). Arbuscular mycorrhizal fungi and organic farming. Agric. Ecosyst. Environ. 113, 17–35.

[80.] Charudttan, R. (1990). The mycoherbicide approach with plant pathogens. In Microbial Control of Weeds. D.O. TeBeest (Ed). Chapman and Hall, London, p. 24 – 57.

[81.] Goettel, M.S., Hajek, A.E., Siegel, J.p. & Evans, H.C. (2001). Safety of fungal biocontrol agents. In Fungi as biocontrol agents:progress, problems and potential.Butt, T.M, Jackson, C.W. & Magan, N. (Eds.). CABI Publishing, Wallingford, UK, pp.347-376.

[82.] Vestergaard, S., Cherry, A., Keller, S. & Goettel, M. (2003). Safety of hyphomycete fungi as microbial control agents. In *Environmental impacts of microbial insecticides.* Hokkanen, H.M.T. & Hajek, A.E. (Eds.). Kluwer Academic Publishers, Dordrecht The Netherlands, pp. 35–62.

[83.] Jackson, T.A. (2003). Environmental safety of inundative application of a naturally occurring biocontrol agent, *Serratia entomophila*. In *Environmental impacts of microbial insecticides.* Hokkanen, H.M.T. & Hajek, A.E. (Eds.). Kluwer Academic Publishers, Dordrecht The Netherlands, pp. 169 – 176.

[84.] Copping, L.G. & Menn, J.J. (2000). Biopesticides: a review of their action, applications and efficacy. *Pest Management Science*, **56 (8)**, 651-676.

[85.] Van Lenteren, J.C. (2000) A greenhouse without pesticides. *Crop Protection*, **19**, 375-384.

[86.] Andersen, M.C., Ewald, M. & Northcutt, J. (2005). Risk analysis and management decisions for weed biological control agents: Ecological theory and modelling results. *Biological Control*, **35**, 330-337.

[87.] Van Lenteren, J.C., Bale, J., Bigler, F., Hokkanen, H. M. T. & Loomans, A. J. M. (2006). Assessing risks of releasing exotic biological control agents of arthropod pests. *Annual Review of Entomology*, **51**, 609 – 634.

[88.] Sheppard, A.W. Shaw, R.H. & Sforza, R. (2006). Top 20 environmental weeds for classical biological control in europe: a review of opportunities, regulations and other barriers to adoption. *Weed Research*, **46**, 93-117.

[89.] Thomas, M.B. & Read, A.F. (2007). Can Fungal Biopesticides Control Malaria? *Nature Reviews Microbiology*, **5**, 377-383.

[90.] Van Lenteren, J.C. Babendreier, D., Bigler, F., Burgio, G., Hokkanen, H., Kuske, S., Loomans, A., Menzler-Hokkanen, I. Van Rijn, P. Thomas, M., Tommassini, M. & Zeng, Q-Q. (2003). Environemntal risk asessment of exotic natural enemies used in inundative biological control. *BioControl*, **48**, 3-38.

[91.] Van Lentern, J.C., Loomans, A. J. M., Babendreier, D. & Bigler, F. (2008). *Harmonia axyridis*: an environmental risk assessment for Northwest Europe. *BioControl*, **53**, 37 – 54.

[92.] De Clercq, P. (2002). Dark clouds and their silver linings: exotic generalist predators in augmentative biological control. *Neotrop. Entomol*., **31**, 169–176.

[93.] Jonsson, M., Wratten, S.D., Landis, D.A. & Gurr, G.M. (2008). Recent advances in conservation biological control of arthropods by arthropods. *Biological Control*, **45**, 172-175.

[94.] Chaney, W.E. (1998). Biological control of aphids in lettuce using in-field insectaries. *In: Enhancing Biological Control: Habitat Management to Promote Natural Enemies of Agricultural Pests,* Pickett, C.H. & Bugg, R.L.(Eds). University of California Press, USA, pp. 73 -83.

[95.] Berndt, L.A. & Wratten, S.D. (2005). Effects of alyssum flowers on the longevity, fecundity and sex ration of the leafroller parasitoid *Dolichogenidae tasmanica*. *Biological Control*, **32**, 65-69.

[96.] Berndt, L.A., Wratten, S.D. & Scarratt, S.L. (2006). The influence of floral resource subsidies on parasitism rates of leafrollers (Lepidoptera: Totricidae) in New Zealand vineyards. *Biological Control*, **37**, 50-55.

[97.] Cullen, R., Warner, K.D., Jonsson, M. & Wratten, S.D. (2008). Economics and adoption of conservation biological control. *Biological Control*, **45**, 272 – 280.

[98.] Fielder, A.K., Landis, D.A. & Wratten, S.D. (2008). Maximizing ecosystem services from conservation biological control: The role of habitat management. *Biological Control*, **45**, 254 – 271.

[99.] Waipara Valley Wine growers. http://www.waiparawine.co.nz/

[100.] Pink, D., Bailey, L., McClement, S., hand, P., Mathas, E., Buchanan-Wollaston, V., Astley, D., King, G. & Teakle, G. (2008). Double haploids, markers and QTL analysis in vegetable brassicas. *Euphytica*, **164**, 509 – 514

[101.] Collard, B. C. Y. & Mackill, D. J. (2008). Marker-assisted selection: an approach for precision plant breeding in the twenty first century. *Philosophical Transactions of the Royal Society B*, **363**, 557 – 590. .

[102.] Plant Genomes: Science Multimedia feature. www.sciencemag.org/plantgenomes/map.html

[103.] Nuffield Council on Bioethics (1999). Genetically modified crops: the ethical and social issues. http://www.nuffieldbioethics.org/go/ourwork /gmcrops/ publication_301.html

[104.] Freckleton R.P., Sutherland A.R., and Watkinson A.R. (2003). Deciding the Future of GM Crops in Europe. *Science* **302**: 994-996.

[105.] Romeis, J., Meissle, M. & Bigler, F. (2006). Transgenic crops expressing *Bacillus thuringiensis* toxins and biological control. *Nature Biotechnology.*, **24**, 63-71.

[106.] Li, G-P., Wu, K-M., Gould, F., Wang, J-K., Miao, J., Gao, X-W. & Guo, Y-Y. (2007). Increasing tolerance to Cry1Ac cotton from cotton bollworm, *Helicoverpa armigera*, was confirmed in Bt cotton farming area of China. *Ecological Entomology*, **32 (4)**, 366-375.

[107.] Carpenter, J. E. & Gianessi, L. P. (2001). Agricultural biotechnology: updated benefit estimates. National Center for Food and Agriculture Policy http://ncfap.org/pup/biotech/updatedbenefits.pdf (cited in reference 108).

[108.] Shelton, A.M., Zhao, J-Z. & Roush, R.T. (2002). Economic, ecological, food safety and social consequences of the deployment of Bt transgenic plants. *Annual Review of Entomology*, **47**, 845 – 881.

[109.] Wang, S., Just, D.R. & Pinstrup-Andersen, P. (2006). Tarnishing silver bullets: Bt technology adoption, bounded rationality and the outbreak of secondary pest infestations in China. Selected paper prepared for presentation at the American Agricultural Economics Association Annual Meeting Long Beach, CA, July 22 – 26, 2006.

[110.] Lu, Y. H., Qiu, F., Feng, H. Q., Li, H. B., Yang, Z. C., Wyckhuys, K. A. G. & Wu, K. M. (2008). Species composition and seasonal abundance of pestiferous plant bugs (Hemiptera: Miridae) on Bt cotton in Chona. Crop Protection, 27, 465 – 472.

[111.] Kogan, M. (1998). Integrated pest management: Historical perspectives and contemporary developments. *Annual Review of Entomology*, **43**, 243-70.

[112.] Pimentel, D. & Pimental, M. (1996). Food, energy and society. Colorado University Press, Niwot, USA.

[113.] Budge S.P., Whipps J.M. (2001). Potential for Integrated Control of *Sclerotinia sclerotiorum* in Glasshouse Lettuce Using Coniothyrium minitans and Reduced Fungicide Application. *Phytopathology* **91**, 221-227.

[114.] Chandler, D., Davidson, G. & Jacobson, R. J. (2005). Laboratory and glasshouse evaluation of entomopathogenic fungi against the two-spotted spider mite, *Tetranychus urticae* (Acari: Tetranychidae) on tomato, *Lycopersicon esculentum*. *Biocontrol Science and Technology*, **15**, 37 – 54.

[115.] Jacobson, R. J., Chandler, D., Fenlon, J. & Russell, K. M. (2001). Compatibility of *Beauveria bassiana* (Balsamo) Vuillemin with *Amblyseius cucumeris* Oudemans (Acarina: Phytoseiidae) to control *Frankliniella occidentalis* Pergande (Thysanoptera: Thripidae) on cucumber plants. *Biocontrol Science and Technology*, **11**, 381 - 400.

[116.] Gilles, T., Phelps, K., Clarkson, J.P. & Kennedy, R. (2004). Development of MILIONCAST, an improved model for predicting downy mildew sporulation on onions. *Plant Disease*, **88**, 695-702.

[117.] Collier, R.H. & Finch, S. (2007). IPM case studies: brassicas. In: Aphids as crop pests. van Emden, H.F. & Harrington, R. (Eds). CAB International, Wallingford, UK, pp 717.

[118.] Cross, J. & Berrie, A. (2006) The challenges of developing IPM programmes for soft fruit crops that eliminate reportable pesticide residues. *Journal of Fruit and Ornamental Plant Research* **14 (suppl. 3):** 49-59.

[119.] MacHardy, W.E. (2000). Current status of IPM in apple orchards. *Crop Protection*, **19**, 801-806.

[120.] Van Lenteren, J. C. (Ed) (2008) IOBC Internet Book of Biological Control http://www.unipa.it/iobc/download/IOBC%20InternetBookBiCoVersion5January2008.pdf

[121.] Burn, A.J. (1987). Cereal Crops. In: Integrated Pest Management. Burn, A.J, Coaker, T.H. & Jepson, P.C. (Eds.). Academic Press, London, UK, pp209-256.

[122.] Boatman, N.D., Jones, N.E., Garthwaite, D. & Pietravalle, S. (2007). Option uptake in entry level scheme agreements in England. *Aspects of Applied Biology,* **81,** 309-316.

[123.] MacKerron, D.K.L., Duncan, J.M., Hillman, J.R., Mackay, G.R., Robinson, D.J., Trudgill, D.L. & Wheatley, R.J., (1999). Organic farming: science and belief. In: Scottish Crop Research Institute Annual Report 1998/99. Macfarlane-Smith, W.H. & Heilbronn, T.D. (Eds.), pp. 60–72.

[124] Wijden van der, W., Leewis, R. & Bol, P. 2007. Biological globalisation – Bio-invasions and their impacts on nature, the economy and public health. KNNV Publishing, Uthrecth, the Netherlands. 223 pp.

[125.] Gren, I-M., Isacs, L. & Carlson, M. 2007. Calculation of costs of alien invasive species in Sweden – technical report. SLU, Institutionen för ekonomi, Uppsala, Sweden.

[126.] Reinhardt, F., M. Herle, F. Bastiansen, and B. Streit. 2003. Economic Impact of the Spread of Alien Species in Germany. Texte Umweltbundes-amt 80/03, 1-299.

[127.] Gritten RH. 1995. Rhododendron ponticum and some other invasive plants in the Snowdonia National Park. In: Pyšek P, Prach K, Rejmánek M, Wade M. (Eds). Plant invasions: General aspects and special problems. SPB Academic Publishing, Amsterdam

ANNEX II: TABLES AND FIGURES

Figure 1: Occurrence of arthropod pests with resistance to one or more pesticides (from Hajek, 2004)[15]

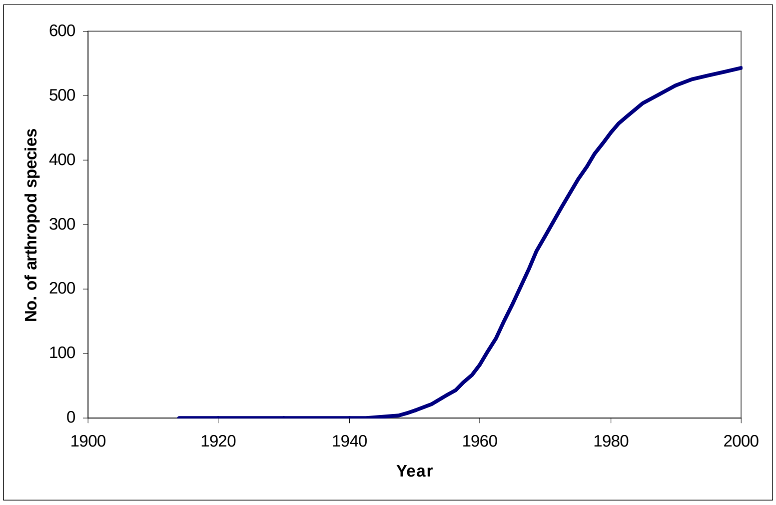

Table 1: Land use of the 27 sovereign nation states of the EU in the year 2000. Source FAO 2007

Countries	% Land area used for forest and wood	% Land area used for agriculture	Arable Land Permanent crops Pasture (% of total land area)		
Austria	47.1	41.2	17	0.9	23.3
Belgium	24.1	46.0	28.5	0.7	16.8
Bulgaria	33.3	50.5	31.9	2.3	16.3
Cyprus		15.5	10.6	4.5	0.4
Czech republic	34.1	55.4	39.9	3.1	12.4
Denmark	10.7	62.4	53.8	0.2	8.4
Estonia	48.6	13.3	9.9	0.3	3.1
Finland	72.0	7.3	7.2	0.03	0.1
France	27.9	54.1	33.5	2.1	18.47
Germany	30.8	48.9	33.8	0.6	14.5
Greece	27.9	66.2	21.3	8.6	36.3
Hungary	20.0	63.6	50	2.2	11.4
Ireland	9.6	64.0	15.6	0.03	48.4
Italy	34.0	53.1	28.8	9.5	14.8
Latvia	47.1	40.0	29.7	0.5	9.8
Lithuania	31.8	55.6	46.8	0.9	7.9
Luxembourg		49.4	23.9	0.4	25.1
Malta		28.1	25	3.1	
Netherlands	11.1	57.8	26.9	1.0	29.9
Poland	29.7	60.5	46	1.1	13.4
Portugal	40.1	43.2	19.7	7.8	15.7
Romania	28.1	64.0	40.8	2.3	21.5
Slovakia	45.3	50.8	30.2	2.6	18
Slovenia	55.0	25.7	8.6	1.5	15.6
Spain	28.8	59.7	26.9	9.8	23
Sweden	66.1	7.7	6.6	0.007	1.1
UK	11.5	70.1	24.3	0.2	45.6
World	**29.7**	**38.2**	**10.7**	**1.0**	**26.5**

Table 2: Estimated share of 2004 global product sales for biologically-based control agents
Source: Gelernter, 2005 [41]

Class of product	**% market share**
Microbial biopesticides	65 - 70
Beneficial macroorganisms	15 - 16
Semiochemicals	10 - 19
Botanicals	4 - 8
Microbial soil and plant enhancers	1 - 2

Table 3: Examples of microorganisms used as control agents of agricultural pests

Organism	**Use**	**Pest**	**Target crops**
Bacteria *Agrobacterium radiobacter* *Xanthomas campestris pv. poannua*	Anti-bacterial agent Herbicide	Crown gall (*Agrobacterium tumefasciens*) Annual bluegrass	soft fruit, nuts, vines turf
Bacillus subtilis	Fungicide	*Fusarium*, *Pythium*, *Rhizoctonia* spp.	legumes, cereals, cotton
Bacillus thuringiensis	Insecticide	Various Lepidoptera, Diptera, Coleoptera	vegetables, fruit, cotton, rice, forestry
Fungi *Lecanicillium longisporum*	Insecticide	Aphids	glasshouse edible & ornamental crops
Phytophthora palmivora	Herbicide	strangler vine	citrus
Trichoderma harzianum	Fungicide	*Pythium*, *Phytophthora*, *Rhizoctonia*	orchards, ornamentals, vegetables, glasshouse crops
Protozoa			
Nosema locustae	Insecticide	grasshoppers, crickets	pasture
Viruses			
***Cydia pomonella* granulosis virus**	Insecticide	codling moth	apple, pear

For more information see Copping (2004)[65]; Kabaluk & Gazdik (2005)[74].

Table 4. Comparison of aspects related to the development and application of chemical and biological control (2004).
Source: Bale *et al*., (2008) [60]

	Chemical control	Biological control
Number of ingredients tested	>3.5 million	3000
Success ratio	1:200 000	1:20
Developmental costs	180 million US$	2 million US$
Developmental time	10 years	10 years
Benefit per unit of money invested	2.5 – 5	30
Risk of resistance	Large	Nil/small
Specificity	Low	High
Harmful side effects	many	Nil/few

Table 5: Biopesticide Plant Protection Product active substances listed on Annex 1 (including substances voted but before entry into force date, which will be by 1 May 2009)

	Insecticide	Fungicide	Herbicide	Nematicide	Repellant	Other
Microorganism	8	20	0	1	0	0
Plant extract	0	0	0	0	6	2
Baculovirus	5	-	-	-	-	-
Pheromone	27	-	-	-	-	-
Total	**40**	**20**	**0**	**1**	**6**	**2**

Source: R. Gwynn, International Biocontrol Manufacturers Association

Table 6: Estimated economic costs of some invasive weed species in different European countries

Country	Weed species	Estimated cost per year
Netherlands	Hydrocotyle	€2 – 4 million [124]
Sweden	Ambrosia	€32 million [125]
Germany	*Prunus serotina*	€20 million [126]
	Japanese knotweed	€15 – 30 million [126]
	Water hyacinth	€4 million [126]
United Kingdom: Snowdonia National Park	Rhododendron	€66 million to date [127]

Table 7: Guided and Integrated control programmes used in Europe
Source: Bale et al., 2008 [60]

Crop	Type	Elements	Area under IPM in Europe/reduction in pesticides on that area
Field vegetables	guided	Monitoring-sampling-warning Host-plant resistance diseases/pests	5% of total area 20-80% reduction
Cereals	guided	Monitoring-sampling-forecasting Host-plant resistance diseases	10% of total area 20-50% reduction
Maize	integrated	Mechanical weeding-host-plant resistance diseases-biocontrol of insects	4% of total area 30-50% reduction
Vineyards	integrated	Biocontrol of mites-host plant resistance diseases-pheromone mating disruption	20% of total area 30-50% reduction
Olives	integrated	Cultural control-biocontrol insects host-plant resistance diseases/pests monitoring-sampling-pheromones	Very limited
Orchards	guided	monitoring-sampling selected pesticides	15% of total area 30% reduction
	integrated	Monitoring-sampling-pheromones biocontrol-selective pesticides host-plant resistance diseases	7 % of total area 50% reduction
Greenhouse vegetables	integrated	Monitoring-sampling-biocontrol Pests and diseases-host-plant resistance diseases	30% of total area 50-99% reduction

Table 8: Integrated pest and disease management programme as applied in tomato in Europe. Source: van Lenteren (2000)[85]

Pests and Diseases	Method used to prevent or control pest/disease
Pests	
Whiteflies (*Bemisia tabaci, Trialeurodes vaporariorum*)	Parasitoids: *Encarsia, Eretmocerus*
	Predators: *Macrolophus*
	Pathogens: *Verticillium, Paecilomyces, Aschersonia*
Spider mite (*Tetranychus urticae*)	Predator: *Phytoseiulus*
Leafminers (*Liriomyza bryoniae, L. trifolii* & *L. huidobrensis)*	Parasitoids: *Dacnusa, Diglyphus* & *Opius* & natural control
Lepidoptera (e.g. *Chrysodeixis chalcites, Lacanobia oleracea, Spodoptera littoralis*)	Parasitoids : *Trichogramma*
	Pathogens : *Bacillus thuringiensis*
Aphids (e.g. *Myzus persicae, Aphis gossypii, Macrosiphum euphorbiae*)	Parasitoids : *Aphidius, Aphelinus*
	Predators : *Aphidoletes* & natural control
Nematodes (e.e. *Meloidogyne* spp.)	Resistant & tolerant cultivars, soilless culture
Diseases	
Gray mold (*Botrytis cinerea*)	Climate management, mechanical control & selective fungicides
Leaf mold (*Fulvia = Cladosporium*)	Resistant cultivars, climate management
Mildew (*Oidium lycopersicon*)	Selective fungicides
Fusarium wilt (*Fusarium oxysporum lycopersici*)	Resistant cultivars, soilless cultures
Fusarium foot rot (*Fusarium oxysporum radicis-lycopersici)*	Resistant cultivars, soilless culture, hygiene
Verticillium wilt (*Verticillium dahliae*)	Pathogen-free seed, tolerant cultivars, climate control, soilless culture
Bacterial canker (*Clavibacter michiganesis*)	Pathogen-free seed, soilless culture
Several viral diseases	Resistant cultivars, soilless culture, hygiene, weed management, vector control
Pollination	Bumble bees or bees