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Review

Integrated pest management in faba bean

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ABSTRACT

Successful production of faba bean crops in the presence of a wide range of disease-causing fungi, parasitic weeds, nematodes, insects, mites and other pests depends on the integration of genetic resistance, hygienic management, monitoring of the target organisms and timely application of appropriate chemical and biological treatments. This paper reviews the progress in this area.

Arthropod management is still overly reliant on broad-spectrum insecticides for many pests, particularly aphids, but field assessment, tillage, sowing date, plant density and weed control can minimize pest incursions. Crop assessments, bait and pheromone traps and economic thresholds are used to predict and monitor arthropod pest populations, and biological measures (natural enemy conservation and bioinsecticides) and selective chemicals (less harmful to beneficial insects) are also used. Crop hygiene and seed bank demise is critical for management of broomrape, as much of its damage is done before the parasite is visible above ground. Mild herbicide treatments can prevent ripening of broomrape seeds with minimal damage to the faba bean crop. The main diseases caused by fungi, namely rust, ascochyta blight, chocolate spot and downy mildew, all spread rapidly when weather conditions are appropriate. Since these weather conditions are well characterized for each disease, it is possible to intervene strategically by treating with fungicide at times of high risk. Good sources of resistance are available to the key diseases, although few current cultivars are resistant to more than one disease. Root-lesion, stem and root-knot nematodes can cause severe yield losses but several cultivars and breeding lines of faba bean have good resistance to root-lesion nematodes and at least one has resistance to stem nematode and one to root-knot nematode. These groups of nematode species have broad host spectra so attention to rotations is particularly important. Chemical control of nematodes is difficult and biological control is still experimental. Control of the pathogenic fungi and nematodes requires that clean, non-infested seed be used and that the new crop does not get infected from debris and volunteer from the previous crop or adjacent fields. In the presence of continued selection pressure on the pathogens and pests, continued breeding for novel resistance genes, development of new selective chemicals, screening for new biocontrol agents and the design of new management strategies will all be necessary.

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1. Introduction

The faba bean (*Vicia faba* L.) is grown widely under a range of climatic conditions from temperate to subtropical and it hosts a wide variety of regional, native and exotic cosmopolitan insect pests, fungal pathogens and viruses as well as parasitic weeds. The three broad types of faba bean, Mediterranean-adapted, cool-temperate winter, and spring, are exposed to different pests and diseases at different times of their growth cycles. Mediterranean and winter-type faba beans are sown in autumn in conditions of abundant but declining pest activity, that then remains relatively low until temperatures increase in early spring. These types of faba bean optimize use of resources but are exposed to pests and diseases for a longer time. Spring-sown beans, on the other hand, are directly exposed to pests and diseases from emergence, and often a different suite of parasites and pathogens is involved.

Integrated Pest Management has been defined in many ways. One widely used definition was formulated by the United States Department of Agriculture in 1996, stating that IPM is "a sustainable approach to managing pests by combining biological, cultural, physical, and chemical tools in a way that minimizes economic, health, and environmental risks". The word "pests", in this definition, includes diseases and weeds as well as animals. The list of management tools often also includes genetics, i.e., resistant cultivars, and some definitions specify lack of impact on non-target organisms or mention maximizing the benefits as well as minimizing the risks. Further key aspects of IPM are the understanding of the biology of the pest, in order to model and predict outbreaks, and the concept of thresholds of damage, at which it becomes economically worthwhile to apply control methods.

Pesticides continue to play the key role in faba bean arthropod pest management but with some key species (e.g., *Heliothis armigera* Hübner) developing high levels of insecticide resistance and in the presence of human and environmental health concerns related to pesticide use, cultural techniques are increasingly being used. The combination of genetic resistance, hygiene and monitoring of crops for threshold levels of infestation, allows the most economic and effective use of chemical controls with the result that economic yields can be maximized.

In this paper we review developments in integrated management of insect pests, of parasitic broomrape plants, of the main disease-causing fungi, and of root-lesion and stem nematodes on faba bean.

2. Arthropods

2.1. The organisms

Faba bean is attractive to a large number of arthropod pests (over 70 spp.) that collectively cause damage at all stages of plant development (Table 1) (Bardner, 1983; Van Emden et al., 1988; Nuessly et al., 2004). Of these, aphids are considered the most

Table 1
Examples of key arthropod pests of faba beans, the plant stage damaged and their region of occurrence.

Name	Common name	Damage	Distribution
Aphids			
Aphis fabae Scopoli	Black bean aphid	Vegetative and podding	Europe
Aphis craccivora Koch	Cowpea aphid	Seedling	Africa, Americas, Australia
Acrythosiphon pisum Harris	Pea aphid	All	Worldwide
Other key pests			
Halotydeus destructor (Tucker)	Red-legged earth mite	Seed	Australia
Penthaleus spp.	Blue oat mite	Seed	Australia
Agrotis spp.	Cutworms	Seed	Australia
Agriotes spp.	Wireworms	Pre-emergence	Europe
Agrypnus spp.	True wireworms	Pre-emergence	Australia
Pterohelaeus spp.	False wireworm	Pre-emergence	Australia
Gonocephalum spp.	False wireworm	Pre-emergence	Australia
Delia platura Meigen	Bean seed fly	Seedling	Europe
Sitona lineatus (L.)	Pea and bean weevil	Seedling	Europe
Tipula spp.	Crane fly	Seedling	Europe
Thrips spp.	Thrips	Seedling and flowering	Worldwide
Bemisia tabaci (Genn)	Whitefly	Seedling and vegetative	Africa
Liriomyza spp.	Leaf miner	Vegetative	North Africa, China
Lixus algirus L.	Stem borer	Vegetative	North Africa, West Asia
Autographa gamma L.	Silver y moth	Vegetative and podding	Europe
Helicoverpa punctigera (Walleng.)	Native budworm	Vegetative and podding	Australia
Helicoverpa armigera (Hübner)	Budworm	Vegetative and podding	Australia, Eurasia, Africa
Chrysodeixis spp.	Loopers	Vegetative and podding	Australia
Apion vorax Herbst.	Weevil	Vegetative and podding	Europe

Sources: Bardner (1983), Van Emden et al. (1988), Wood et al. (2000), Blackman and Eastop (2000, 2007), Biddle and Cattlin (2007), Miles et al. (2007), personal experience of the authors.

important and damaging insect pest of faba beans worldwide, causing damage by direct feeding on the phloem and as vectors of plant diseases, particularly viruses (Cammell and Way, 1983). Fourteen species of aphid have been recorded as colonizing faba beans (Blackman and Eastop, 2000, 2007) and three are most widely recognized as important (Table 1). Because aphids and the 50-plus diseases they vector can be so damaging, their control often dominates faba bean pest management programs.

Bardner (1983) identified over 50 (excluding aphids) and Van Emden et al. (1988) 21 species of insect as being important pests of faba bean. In a later survey in the rather atypical environment of southern Florida Nuessly et al. (2004) found 61 species of insect from 31 families (7 orders) feeding directly on plants, of which 4 were recorded feeding on the stems, 1 on the roots, 15 on the leaves, 4 on flowers and 13 on pods. Nine were pollen or nectar feeders and some fed on more than one part of the plant. A further 39 species were recorded as predators and parasites of this complex. Only 6 of the species identified by Van Emden et al. (1988) were included in the Nuessly et al. (2004) survey. Comparing the species listed in these papers it can be seen that on a regional basis, insect pest complexes differ in their species composition rather than the types or groups of pests.

2.2. Agronomic management techniques

Cultural techniques that include site selection, crop rotation, cultivar and seed selection, preferential sowing dates, row spacing and plant density, weed control and more recently stubble retention are all used to reduce insect pest populations (Way and Heathcote, 1966; Bardner, 1983; McEwen and Yeoman, 1989; Berlandier and Bwye, 1998; Jones, 2001). A field's geophysical attributes can influence its pest status. Sloping sites and border hedgerows that reduce wind speed promote aphid landing and affect aphid distribution (Cammell and Way, 1983). Crops grown in stony calcareous soils are more likely to be affected by field thrips (*Thrips angusticeps* Uzel), and slugs and snails in clay soils (Biddle and Cattlin, 2007).

Crop rotation, volunteer plant and weed management practices reduce the availability of alternate hosts and prevent the build up of pests, particularly aphids and thrips, over successive seasons. Some aphids, e.g., *A. fabae*, have a tendency to colonize fields from the margins. Thus choosing fields with a low perimeter to area ratio, i.e., large as opposed to small fields in effect reduces aphid colonization and thus virus infection.

Cultivars are primarily selected for quality, yield and resistance to disease but while 36 breeding lines have been classified as resistant to aphid feeding there are no commercially available cultivars with useful resistance to any insect pests (Prüter and Zebitz, 1991; Makkouk et al., 1998). Various cultivars respond differently to plant density, with significant interactions between row spacing and the use of either aphicides or broad-spectrum insecticides to control insect pests and insect-transmitted diseases affecting yield (McEwen and Yeoman, 1989). Some tall cultivars, such as Minden, were suited to lower chemical input systems while the shorter cv. Alfred required more inputs to maximize yield (McEwen and Yeoman, 1989).

Sowing date can have a significant effect on pest populations, particularly aphid infestation and their rate of increase (Way, 1967). In temperate climates, crops sown too early in winter or too late in spring are generally exposed to higher aphid infestations and earlier virus infection than those sown at optimal times. Young seedlings are particularly susceptible to damage by aphid feeding. In sub-tropical winter cropping systems, sowing early maximizes potential yield but again exposes the seedlings to late aphid flights and early virus infection. Sowing late can result in lower yield, but also significantly increases the crops exposure to insect pests during the podding stage, e.g., spring emerging *Helicoverpa* species.

Aphids tend to select plants surrounded by bare earth. Higher plant densities, where the canopy closes early, incur lower aphid populations (Al-Jallad et al., 2007). Increasing plant density from 22 plants/m^2 to 33 plants/m^2 was found to decrease virus incidence by 10–20% in coastal Syria (Al-Jallad et al., 2007). Al-Jallad et al. (2007) also demonstrated that planting cereal borders around faba bean fields reduced the spread of non-persistently transmitted viruses but not that of persistently transmitted viruses.

The use of straw and mustard (*Sinapis alba* L.) mulches can reduce aphid populations by up to 80% and 75%, respectively, and are particularly effective during the early colonization period when plants are small (Heimbach, 2001). Aphid colonization of lupins and wireworm infestation of sunflowers are also reduced when planted directly into cereal stubble (Robertson and Kettle, 1993; Berlandier and Bwye, 1998; Bwye et al., 1999) and while this effect has not been directly shown in faba bean it is recommended practice in Australia (Schwinghamer et al., 2003). The use of press wheels during sowing to firm the soil around the seed has been shown to reduce damage and seed loss from soil pests such as wireworms and weevils (Radford and Allsopp, 1987). In Australia, where minimum tillage is general practice as it preserves soil moisture, a technique of shallow soil disturbance (cultivation to a depth of 10 cm) known as 'pupae busting' is often used to reduce the population of *Helicoverpa* species. *H. armigera* is the key pest of cotton and has multiple insecticide resistance, so pupae busting is the recommended practice after harvest in cotton where other susceptible crops, including faba bean, are in the rotation (Anon, 2005; Rossiter et al., 2007).

2.3. Chemical and biological control methods

IPM in faba beans continues to depend heavily on broad-spectrum insecticides, which due to their low cost are often used prophylactically, particularly to control aphids, to avoid the need and expense of pest monitoring. However strategies to minimize the use of broad-spectrum insecticides are widely used and when required they are where possible substituted with more selective chemicals or bio-pesticides. Economic thresholds are central to IPM programs, assisting growers to decide when a control measure is warranted, thus avoiding unnecessary spraying and allowing the conservation of pollinators, predators and parasites. The dependence of faba bean on bees for pollination necessitates particular care in the choice of chemical and timing of insecticide treatments. The economic threshold of *Aphis fabae* in some cultivars was reported as 5% of plants infested (Way et al., 1977) but modern cultivars may be more tolerant (Parker and Biddle, 1998). In Australia, economic thresholds have been established for aphids (10% of plants heavily infested), green vegetable bug (1–2 m^{-2}) *Helicoverpa* spp. (2–4 larvae/m^2 or 1 m^{-2} for human consumption), thrips (4–6 flower^{-1}) and earth mites >50/100 cm^2 quadrat (Hopkins, 2000; Panagiotopoulos et al., 2002; Hertel and Roberts, 2007). Traps utilizing insect sex and aggregation pheromones and feed baits, i.e., poultry mash to attract snails and seed baits for wireworms, are used to monitor pest presence (McDonald, 1995; Biddle and Cattlin, 2007). Decision support models for forecasting aphid flights have been developed but are not in commercial use (Knight and Cammell, 1994). The suction sampling network in the United Kingdom monitors aphid flights and the results are available on the internet (Rothamsted Insect Survey: Aphid Bulletin). This information can be used to assist growers to make control decisions.

Broad-spectrum insecticides, e.g., carbamates and pyrethroids, continue to be used to control faba bean pests, pirimicarb is an effective aphicide and pyrethroids are used to control pests such as cutworms and silvery moth (Biddle and Cattlin, 2007; Anon, 2008). However in line with the worldwide move towards IPM, a new generation of more selective chemicals, e.g., indoxacarb and spinosad, and a range of biocontrol agents have been developed. These new, more selective insecticides are less harmful to beneficial insects and help in preventing secondary pest outbreaks (Wilson et al., 2007). In Australia, indoxacarb, spinosad and biocontrol agents, utilizing polyhedral inclusion bodies of *H. armigera* nucleo-polyhedrovirus, control *Helicoverpa* spp. while conserving beneficial insects. *Bacillus thuringiensis* ssp. *kurstaki* is used in faba beans to control lepidopteran larvae, including *Helicoverpa* spp., *Spodoptera* armyworms, diamondback moth *Plutella xylostella* L., and *Chrysodeixis* loopers (Anon, 2008).

The relatively new insecticide imidacloprid has considerable potential in faba bean IPM programs. Its use is still the subject of research but it is effective against aphids, wireworms, thrips and broad bean weevil *Bruchus rufimanus* Boh (Kaniuczak and Matosz, 1998). Controlling aphids with imidacloprid effectively reduces infection from bean leaf roll virus, faba bean necrotic yellows virus and soybean dwarf virus (Narkiewicz-Jodko and Rogowska, 1999; Makkouk and Kumari, 2001; Al-Jallad et al., 2007). Applied as a foliar spray during podding, imidacloprid significantly reduced leaf miner *Liriomyza huidobrensis* (Blanchard) populations but also suppressed its parasitoid *Diglyphus isaea* (Walker) (Chen et al., 2003).

Most faba bean growers use cultural techniques, e.g., altering sowing date or plant density, based on personal experience. Nevertheless, IPM in faba bean is still overly reliant on broad-spectrum insecticides. Many of the cultural techniques have been studied and used in isolation and although found to be effective, rarely have they been used in combination to demonstrate their collective potential. Together with modern selective insecticides and bioinsecticides, numerous options exist to improve IPM in faba beans and with the potential to reduce insecticides are worthy of research.

3. Broomrapes

3.1. The organisms

Faba bean can be parasitized mainly by three different species of broomrapes, namely crenate broomrape (*Orobanche crenata* Forsk.), fetid broomrape (*O. foetida* Poir.) and Egyptian broomrape (*Phelipanche aegyptiaca* (Pers.) Pomel (syn. *O. aegyptiaca* Pers.)) (Rubiales et al., 2006; Joel et al., 2007).

O. crenata has been known to threaten legume crops since antiquity. It is of economic importance in the Mediterranean Basin and Middle East in faba bean, but also in other grain and forage legumes (lentil, pea, vetches, grasspea) and members of Asteraceae, such as safflower, and Apiaceae, such as carrot. It is characterized by large erect plants, branching only from their underground tubercle. The spikes may reach the high of up to 1 m, bearing many flowers of diverse pigmentation, from yellow, through white to pink and violet. *O. foetida* is known as a weed of faba bean only in Tunisia, but the species is common in native habitats in other North African countries and Spain and France. The plant has unbranched stems that bear red or purple flowers that release an unpleasant smell. *P. aegyptiaca* parasitizes faba bean, chickpea and lentil and also many other crops belonging to various families, including Asteraceae, Brassicaceae, Cucurbitaceae, Fabaceae, and Solanaceae. It is widely distributed in eastern parts of the Mediterranean, in the Middle East and in parts of Asia.

A healthy broomrape plant can produce 200,000 seeds and in exceptional cases, half a million. These seeds remain latent in the soil until they recognize the presence of a host root, and germinate. The seedling adheres to the host root surface, penetrating through the cortex, endodermis and central cylinder with mechanical pressure and enzyme activity. Over the subsequent weeks, the parasite develops a tubercle on the host root surface, eventually producing one (*O. crenata* or *O. foetida*) or various (*P. aegyptiaca*) flowering shoots that emerge from the soil and produce seeds. The minute seeds are easily transferred by cultivation, and also by water, wind, animals, and especially by vehicles and farming machines (Joel et al., 2007).

There is no single technology to control broomrape (Pérez-de-Luque et al., 2010). The effectiveness of conventional control methods is limited due to numerous factors, in particular the complex nature of the parasites, their tiny and long-lived seeds, and the difficulty of diagnosis before the crop is irreversibly damaged. The intimate connection between host and parasite hinders efficient control by herbicides. Managing these weedy root parasites requires an integrated approach, employing containment and sanitation, direct and indirect measures to prevent the damage caused by the parasites, and finally eradicating the parasite seedbank in soil.

3.2. Agronomic management techniques

Breeding for broomrape resistance in faba bean is difficult, but significant successes have been achieved (Cubero and Moreno, 1999; Rubiales et al., 2006). The first significant finding of resistance was the selection of the *O. crenata*-resistant line F402 (Nassib et al., 1982). Resistance against *O. foetida* has been identified in faba bean germplasm in Tunisia (Abbes et al., 2007). Combining resistance to both *O. crenata* and *O. foetida* has proved possible, by selecting for *O. foetida* resistance in germplasm resistant to *O. crenata*. Resistance identified so far seems to be of complex inheritance (Cubero and Moreno, 1999; Rubiales et al., 2006; Torres et al., 2010).

Target site herbicide resistance might be a promising solution for controlling broomrape, that is being explored in some crops (Gressel, 2009), particularly now with non-transgenic imidazolinone target-site resistant sunflowers which are now being released in Europe (Tan et al., 2004).

Prevention is of great importance. On a local level, the sources of infestation can be reduced by controlling the use of contaminated seed lots, farmyard manure from broomrape-fed cattle (Jacobsohn et al., 1987), or simply by destroying heavily infested crops. Seedbank demise can be efficiently achieved by fumigation or solarization, but this is not economically feasible in relatively low-value and low-input crops like faba bean. Some biological control agents have shown promise in managing broomrape, but the technology is not ready yet for commercial application (Amsellem et al., 2001).

Early plantings of faba bean are often more severely infected so delayed sowing is arguably the best-documented traditional method for *O. crenata* control in Mediterranean countries, even though it is at the cost of some yield potential. Shifting sowing from October to November, December or January reduces numbers and dry weight of attached and emerged broomrapes, both *O. crenata* and *O. foetida* (Pérez-de-Luque et al., 2004; Grenz et al., 2005b). However, faba bean has a long growth period and delaying sowing date implies shortening grain filling, which is detrimental for yield particularly under Mediterranean conditions. The highest yields can be expected from intermediate sowing dates, the optimum period varying according to weather, cultivar and infestation density.

Manual weeding is useful just to avoid spreading of the seeds and further increases of the seed bank at the beginning of the infestation in field, but it is not economic in industrialized agriculture.

Crop rotation is of limited value due to the long viability of the seeds and the broad host range. In southern Australia, effective methods for control of branched broomrape (*O. ramosa* L.) combine rotation with non-host cereals and use of imidazolinone herbicide-resistant host oilseed rape (*Brassica napus* L.) (Matthews, 2002). There is also promise in a number of strategies, such as suicidal germination by application of germination stimulants or by the use of trap or catch crops, that have not yet proved economical. An alternative might be intercropping, as widely recommended used for Striga control on maize and sorghum in Africa (Oswald et al., 2002). Intercrops with cereals or with fenugreek can reduce *O. crenata* infection on faba bean, with allelopathy being a major component of the reduction (Fernández-Aparicio et al., 2007, 2008).

3.3. Chemical and biological control methods

Broomrape on faba bean can be effectively controlled by glyphosate (Mesa-García and García Torres, 1982). Broomrape underground development stages should be monitored because control is not effective when the attachments become too large. On the other hand, when the herbicide is applied too early, not enough attachments are controlled. Broomrape control normally requires lower foliar herbicide application rates than those applied for control of autotrophic weeds. Three sequential foliar applications of the herbicides imazapic or imazamethapyr can also effectively control *O. crenata* in faba bean. Seed treatments with imidazolinones have proven to be effective at controlling *O. crenata* in faba bean (Jurado-Expósito et al., 1997), with the considerable advantage of low cost of application as the herbicide is incorporated as a seed coating. This replaces a pre-emergence treatment, saves mechanical application costs, reduces the herbicide rate required by 2–3-fold, and is thus more environmentally friendly. Nevertheless, where environmental conditions are especially favourable for broomrape attack, the treatment must be supplemented to obtain good control of the parasite.

Numerous microorganisms that might be useful for biocontrol of broomrape species have been isolated and reported in the past, but none has been used widely (Amsellem et al., 2001; Boari and Vurro, 2004). However, the technology is not ready yet for commercial application. Further research on the development of an appropriate formulation that allows storage, handling and a successful application of the fungal propagules is required (Müller-Stöver and Sauerborn, 2007).

The fly *Phytomyza orobanchia* is widely distributed in the broomrape infected zone, eating a substantial number of seeds (Rubiales et al., 2001). This natural infestation is, however, insufficient in areas with heavy broomrape infestations. This effect can be increased by massive propagation and inundative release of this insect (Klein et al., 1999).

A combined competition and seedbank model has been used to simulate short- and long-term effects of control measures and confirmed the superiority of integrated strategies (Grenz et al., 2005a). Yet no model has had significant impact on production practice, most likely because of lack of communication of results and easy-to-use models for farmers. Prospects for practical application seem better for phenological models that predict host and parasite development based on temperatures. Such a model has recently been implemented for *O. minor* infecting red clover (Eizenberg et al., 2005) and could be developed for faba bean.

4. Diseases caused by fungi

4.1. The organisms

Faba bean is susceptible to several pathogenic fungi (Table 2). Ascochyta blight, rust, chocolate spot, downy mildew and cercospora leaf spot all attack few other host species, whereas stem rot, root rot, wilt and alternaria leaf spot all have broad host ranges and are thus beyond the scope of this review.

Chocolate spot is one of the most destructive diseases affecting faba bean. The pathogen responsible is the necrotrophic fungus *Botrytis fabae* Sard., which is present in nearly all faba bean cultivation areas. The first symptoms are discrete dark-brown spots surrounded by an orange-brown ring on leaves, flowers and stems. When temperatures are mild (15–22 °C) and relative humidity is high (>80%), the limited-lesion stage may be followed by an aggressive phase in which necrosis spreads rapidly, defoliating and then killing the plant, sometimes within as little as 2 days (Harrison, 1988). The most important damage usually occurs when plants are flowering, since that is when the environmental conditions are often more conducive to disease development, decaying flower petals are available for growth of the fungus and yield reductions may be serious due to spread of the pathogen from the flowers into the developing pods. Spores of *B. fabae* are produced by conidiophores that are visible with the naked eye in senescent leaves of diseased plants. The conidia are commonly airborne, allowing the disease to spread easily. New tissue is then infected, later giving rise to more conidiophores and

Table 2
The main pathogenic fungi and nematodes on faba bean, with the number of citations in the Commonwealth Agricultural Bureau Abstracts (1973–2009 week 17) as a measure for the international importance of the pathogen.

Species	Common name	Risk factors	Citations in CAB abstracts of faba bean with the pathogen
Botrytis fabae Sard. and *B. cinerea* (de Bary) Whetzel	Chocolate spot	Mild, humid conditions (20°, 95% RH).	497
Ascochyta fabae Speg.	Ascochyta blight	Splash-dispersed in 15° weather on winter and Mediterranean-type beans.	244
Uromyces viciae-fabae (Pers.) J. Schröt.	Rust	Warm, humid conditions (25°, 80% RH).	211
Peronospora viciae f. sp. *fabae* (Berk.) Caspary	Downy mildew	Cool, humid conditions.	29
Cercospora zonata G. Winter	Cercospora leaf spot	Cool, humid conditions.	24
Fusarium oxysporum Schltdl	Wilt	Wide host range.	253
Rhizoctonia solani J.G. Kühn	Root rot	Wide host range.	97
Alternaria alternata (Fr.) Keissl. and *A. tenuissima* (Kunze) Wiltshire	Alternaria leaf spot	Wide host range.	79
Sclerotinia sclerotiorum (Lib.) de Bary and *S. trifoliorum* Erikss. (	Stem rot	Wide host range.	49
Ditylenchus dipsaci (Kühn) Filipjev species complex	Stem nematode	Cosmopolitan in temperate regions. Host specialization exists.	100
Meloidogyne incognita (Kofoid & White) Chitwood and *M. javanica* (Treub) Chitwood	Root-knot nematode	Hot, dry, tropical and subtropical regions. Wide host range.	60
Pratylenchus neglectus (Rensch) Filipjev & Schuurmans, *P. thornei* Sher & Allen, *P. penetrans* (Cobb) Filipjev & Schuurmans Stekhoven and *P. pinguicaudatus* Corbett	Root-lesion nematode	Mediterranean and cool-temperate climates. Wide host range.	41

starting another cycle of infection. The fungus survives between seasons as mycelium or sclerotia in crop debris, and conidiophores grow when temperature and humidity are again favourable. Other host plant species are common vetch (*Vicia sativa* L.), narbon bean (*V. narbonensis* L.), and lentil (*Lens culinaris* Medik.). Infection of faba bean seeds by *B. fabae* is rarely considered important in setting off the disease. *Botrytis cinerea* (de Bary) Whetzel sometimes contributes to chocolate spot disease.

Ascochyta blight is caused by *Ascochyta fabae* Speg. (teleomorph *Didymella fabae* Jellis and Punithalingam). The disease is most prevalent where faba beans are grown through the winter, in either Mediterranean-type or mild oceanic climates, and spreads most rapidly in the early spring, before the plant starts flowering. Lesions on leaves are round and those on stems elongated, both usually grey in colour and presenting distinctive rings of black pynidia. The septate pycnidiospores are elongated and slightly curved, 3–6 μm $\times$ 10–26 μm (Kohpina et al., 1999), and splash-dispersed. There is a high variability among populations of *A. fabae*. Some reports suggest the existence of races (Hanounik and Robertson, 1989; Rashid et al., 1991) what is an important consideration in breeding programmes for disease resistance and in developing disease management systems, making necessary the search for additional sources of resistance. Sexual reproduction allows new virulence combination and as a consequence the pathogen may respond overtime to selection exerted by the introduction of host resistance genes. The teleomorph, *D. fabae*, may play an important role in the disease cycle by increasing survival of the fungus on infested crop residues, producing ascospores that can be wind-dispersed over significant distances, and generating increased genetic diversity in the pathogen which could adversely affect resistance breeding programs or chemical control strategies (Kaiser et al., 1997). It was discovered on overwintering faba bean straw in 1991 in the United Kingdom (Jellis and Punithalingam, 1991) and since then described in many other countries (Kaiser, 1997; Rubiales and Trapero, 2002).

Faba bean rust, caused by *Uromyces viciae-fabae* (Pers.) J. Schröt., is a disease of worldwide distribution. It is a major disease in the Middle East, North Africa and parts of Australia. The same species also causes rust on common vetch and lentil. *U. viciae-fabae* is autoecious, completing its life cycle on host plants. Based on differences in host specialization, spore dimensions, and shape and dimensions of the substomal vesicle, a classification into "host-specialized isolates" (*viciae-fabae*, *viciae-sativae* and *lentis-culinaris*) has been proposed (Emeran et al., 2005). A race structure for faba bean isolates has been demonstrated twice. Conner and Bernier (1982) described different races based on the differences of colony size induced by *U. viciae-fabae* isolates on a set of nine faba bean lines in North America. Emeran et al. (2001) classified 23 isolates of *U. viciae-fabae* into 16 races according to the Infection Type (IT), based on the presence or absence of necrosis on six faba bean lines, as the discriminatory criterion for resistance and susceptibility.

All above-ground parts of faba bean are susceptible to rust infection. The epidemic usually starts in low-lying parts of the field and spreads to other areas, and it normally begins late in the season, when pod filling has started, so yield components are little affected by the infection, and losses usually range from 5 to 20%. However, epidemics that start early in the season can be severe and yield losses as high as 70% have been reported (Liang, 1986; Rashid and Bernier, 1991). Oval, brown-colored uredial pustules up to 1 mm in diameter develop on both surfaces of leaflets, branches, stems and pods. The echinulated uredospores, 22–28 μm $\times$ 19–22 μm, have 3–4 germination pores and are borne in single pedicels. The dark brown to black, elongated telia form late in the season below the epidermis, then are erumpent on leaves, but remain covered by the epidermis on stems for an extended period. Globose to sub-globose unicellular teliospores, 25–40 μm $\times$ 18–26 μm, have a single germination pore and are borne singly on pedicels. The teliospores are resistant to adverse conditions and are the primary surviving structure between crop seasons. In production areas where prolonged hot and dry summers prevail, infected crop debris and teliospores left in the field or carried in seeds serve as primary inoculum. Teliospores readily germinate at 17–22 °C without dormancy and remain viable for up to 2 years in a resting state. In cooler production regions, the uredospore may also be an important means of survival between crop seasons. Primary inoculum also comes from other hosts, such as vetch. Secondary spread is by means of aeciospores and uredospores, both of which readily germinate on plant surfaces under humid conditions and are dispersed by wind. Cloudy weather with high humidity and 17–22 °C favours development of the disease.

The most damaging epidemics of downy mildew of faba bean, caused by *Peronospora viciae* f. sp. *fabae* (Berk.) Caspary, occur in northwestern Europe, though the disease has been reported in most regions where faba bean is grown. Primary infection arises from soil-borne oospores that germinate to infect the hypocotyls and upper part of the root (van der Gaag and Frinking, 1997a), leading to systemic colonization of plants. Humid conditions promote sporulation, and give rise to cycles of secondary infection via conidia. Downy mildew may also survive between crops on volunteer seedlings, and where winter- and spring-sown crops are commonly found together, there is greater opportunity for disease survival and transmission.

Cercospora leaf spot, caused by *Cercospora zonata* Winter, has received attention in Australia, China and Poland. It infects vetch, narbon bean and possibly lentil as well as faba bean (Kimber et al., 2007). Lesions on leaves are zoned and brown to grey, and may be distinguished from Ascochyta blight by the lack of its typical black pynidia, and from chocolate spot by the presence of the zonation. In moist conditions, clusters of conidiophores give the lesion a furry appearance. Cercospora favours the same growing conditions as Ascochyta (Hawthorne et al., 2004) and is thus more prevalent in the vegetative phase of the crop cycle.

4.2. Agronomic management techniques

The use of host plant resistance is the best means of disease control, given that management practices are not always effective enough and fungicides are costly (both in economic and environmental terms).

Faba bean collections have been screened for response to chocolate spot and evaluation methods improved (Hanounik and Robertson, 1988; Rhaïem et al., 2002; Bouhassan et al., 2003, 2004). The International Centre for Agriculture Research in Dry Areas (ICARDA) has incorporated resistance into local germplasm, so new cultivars have been introduced in Australia, Egypt and Ethiopia, among other countries. Nevertheless, resistance is incomplete, and new sources of resistance are needed. Most of the resistant material originates from Colombia and Ecuador (Tivoli et al., 2006) rather than from regions where faba beans have been in cultivation for thousands of years.

Both major and minor genes conferring resistance to Ascochyta blight have been identified (Kohpina et al., 2000) and some genes have been mapped to regions on chromosomes (Román et al., 2003; Avila et al., 2004). Numerous cultivars with moderate to strong resistance to the disease are available in many countries.

Incomplete resistance to rust is common (Rashid and Bernier, 1984, 1991; Khalil et al., 1985; Polignano et al., 1990; Sillero et al., 2000; Herath et al., 2001), and hypersensitive resistance has also been identified (Sillero et al., 2000). However, the necrotic reaction occurs late, resulting in a reduction of the infection type rather than complete resistance. Both types of incomplete resistance are associated with an increased latent period, a reduction in colony size and a decreased infection frequency. They differ only in the presence or absence of macroscopically visible necrosis (Sillero et al., 2000). Valuable levels of resistance to downy mildew have been identified (Thomas and Kenyon, 2004) and the UK cultivar Betty is considered to be resistant. Resistance to Cercospora leaf spot has become a breeding objective in southern Australia (Egan et al., 2006).

Crop rotation is a critical part of control of all of the major diseases and the rotation period needs to take into account the other host species. Crop stubble, residues and volunteer seedlings have been implicated as sources of infection for all of these diseases. The minimum interval is considered to be 4 years for chocolate spot, Ascochyta blight, rust and Cercospora leaf spot (Hawthorne et al., 2004; Richardson, 2008). Longer periods may be required for powdery mildew, as oospores may survive at significant levels for at least 10 years (Biddle, 2001) and this delay would probably not be practical in most bean growing areas. Extraction methods for determining oospore numbers in soil have been developed (van der Gaag and Frinking, 1997b) and indexing fields to predict risk from soil-borne infection remains a possibility, but considerable research effort would be needed to develop sampling regimes, and to determine risk thresholds. Isolation from other fields that may carry stubble or volunteer seedlings is also desirable and a distance of 500 m (Hawthorne et al., 2004) is appropriate.

The use of clean, unblemished and preferably certified seed is vital for minimizing the spread of Ascochyta blight as the pathogen can be carried under the seed coat (Davidson and Kimber, 2007). There is less solid evidence for seed transmission of *Botrytis fabae*, *Uromyces viciae-fabae* or *Cercospora zonata* other than by associated plant material carried on the outside of the seed. The sudden appearance of downy mildew infection in fields where there has been no history of bean growing has lead to suggestions that oospores may be carried in small particles of infected plant debris adhering to seed, and thus be responsible for introducing disease into the soil. Seed washing tests have been devised for other downy mildew pathogens and these might also be developed for bean seed. Positive results would mean that the seed lot should either be treated or not sown.

Reducing relative humidity next to the plant surface is an effective way to hinder the infection process. In order to do this, it is crucial to facilitate aeration throughout the crop, which can be achieved by lowering sowing rate (hence decreasing plant density, although this reduces potential yield in a disease-free situation) and good weed control. Intercropping faba bean with cereals has been proposed as a means to lessen the incidence of chocolate spot (Fernández-Aparicio and Rubiales, 2007; Sahile et al., 2008) and rust (Fernández-Aparicio et al., 2006). This practice combines two of the aspects mentioned above: on the one hand, the cereal acts as a barrier to the spread of inoculum, since it is not a host for the pathogen; and it also favours aeration and prevents the formation of a dense faba bean canopy that might enhance disease damage. Intercropping is discussed further by Jensen et al. (2010).

In addition to their requirements for high humidity and damp leaf surfaces, each of these diseases has an optimum temperature range. Ascochyta and Cercospora favour relatively cool temperatures (5–15 °C, Hawthorne et al., 2004) and Ascochyta blight is effectively dispersed by rain splash (Davidson and Kimber, 2007). Chocolate spot and rust favour warmer temperatures, 15–25 °C and above 20°, respectively and the aggressive phase of chocolate spot has already been described above. Biddle et al. (2003) reported that downy mildew disease was most likely to develop rapidly at temperatures below 10 °C in the 7 days before onset of flowering, if leaves had been wet for periods longer than 12 h. An in-season bean downy mildew monitoring service has been established in the UK (www.cropmonitor.co.uk). The monitoring is based on untreated observation crops in areas prone to disease, and is aimed at providing growers with early warning of disease development so that sprays on susceptible crops can be timed effectively. A comprehensive guide indicating thresholds for spraying against Ascochyta blight, chocolate spot and rust has been produced in Western Australia (MacLeod and Galloway, 2006). Further collection of weather and disease data should enable a comprehensive forecasting scheme to be devised for all of the main diseases of faba bean with relatively little effort.

Finally, any factor that diminishes plant vigour promotes the development of the disease. Therefore, nutrient deficiencies such as phosphorus or potassium should be avoided, the same as with high weed infestation; equally a good soil drainage has to be maintained, thus preventing water logging. Frost damage also increases susceptibility to chocolate spot (Harrison, 1988), so sowing date should be chosen accordingly.

4.3. Chemical and biological control methods

Fungicides are available that control the diseases of faba bean, but a particular product may not be registered for use in a given country because the crop is too minor, or the disease is too rare, or both. Legume seed treatment of course has to be compatible with rhizobium inoculant. Seed treatment with P-Pickel T® (Thiram and Thiabendazole) is recommended in Australia against *Pythium* and *Fusarium* in faba bean (Hawthorne et al., 2004) and also acts against *Ascochyta* and *Botrytis* in other grain legumes. Effective products are also available in Europe against downy mildew of pea, such as Wakil XL (cymoxanil, fludioxonil and metalaxyl-M), but they are seldom used on faba bean, which is generally sown without any seed treatment.

Disease control with fungicide is therefore focused on foliar sprays. Fungicides are regularly employed to prevent further progress of chocolate spot disease in fields around the world, and have been tested in different studies (Bainbridge et al., 1985; Mohamed et al., 1996; Sahile et al., 2008). Many compounds have been reported as helpful in controlling chocolate spot: benzimidazoles (benomyl, carbendazim), dicarboximides (procymidone, iprodione, vinclozolin), dithiocarbamates (mancozeb), aromatics (chlorothalonil), conazoles (tebuconazole, cyproconazole, metconazole) and strobilurins (azoxystrobin, pyraclastrobin). Chlorothalonil and mancozeb are also recommended for controlling Ascochyta blight (Davidson and Kimber, 2007), and chlorothalonil and carbendazim control Cercospora leaf spot although neither is registered (Hawthorne et al., 2004). Mancozeb, chlorothalonil, copper and triadimefon with propineb have been recommended against rust.

Biddle et al. (2003) used a range of spray sequences with a metalaxyl and chlorothalonil fungicide (Folio) to determine optimum timings for application against downy mildew. The greatest losses in yield occurred when the disease became established at early flowering, and first sprays are targeted at this growth stage, with a subsequent application at mid- to late flowering often being used commercially if favourable disease conditions persist. A single spray applied 7 days after the start of flowering produced a yield response of 0.5 t ha^{-1}. Metalaxyl-M is highly effective against downy mildew and, though costly, is frequently necessary on susceptible cultivars.

Nevertheless, fungicides present the disadvantages of high cost and environmental repercussions, so their use should be restricted to those circumstances where they are indispensable and always in combination with other measures of integrated management. The date of the first application and the number of the subsequent ones will depend on regional experience. Weather conditions are critical in the development of each disease, so forecasts have to be taken into account when planning sprays. A decision-making scheme ought to be followed, involving the symptoms observed in the field, the weather forecast and the potential crop yield; a good example is described by MacLeod and Galloway (2006). The number of applications should be the minimum possible to combine disease control with a return on investment: this is both environmentally friendly and economically wise. Growers must also respect the withholding period between spraying and harvest for each chemical.

The development of resistance by the pathogen is one of the most important criteria considered when choosing the right fungicide for each situation. These resistances have already been reported to some products, such as benzimidazoles and dicarboximides (Anonymous, 2006). In order to avoid them, appropriate mixtures and alternations of active materials from different groups ought to be utilized and only the correct doses employed.

Research on alternatives to traditional fungicides has found that the essential oil of basil (*Ocimum basilicum*) possesses antifungal properties against *B. fabae*, both *in vitro* and *in vivo* on infected plants (Oxenham et al., 2005). Compounds extracted from three species of cyanobacteria inhibited the growth of several fungi, including *B. fabae*, *in vitro* (Abo-Shady et al., 2007) but field results have not yet been reported. Vicine, one of the two pyrimidine glycosides synthesized by faba bean, was effective against *B. cinerea in vitro* at a low concentration of 500 ng mL^{-1} and several other pathogenic fungi at higher concentrations (Pavlik et al., 2002). Biological control may also be used in the future; so far, studies with some microorganisms antagonistic to the pathogen have shown interesting results (Jackson et al., 1997; Sharga, 1997). Nevertheless, it is always a long way from the laboratory to the field, and it often happens that those options performing well in controlled experiments end up failing under agricultural conditions (Sharga, 1997).

Applications of salicylic, benzoic, citric and oxalic acids, and ribavirin enhanced the resistance of plants infected with *B. fabae* (Hassan et al., 2006). As these chemicals are all considered inducers of resistance, the development of preventive treatments was proposed. The induction of resistance to *B. fabae* by dual inoculation with *Rhizobium leguminosarum* and vesicular-arbuscular mycorrhizal fungi has also been proposed (Rabie, 1998), but it is still too early to know if any of these strategies will ultimately make it to the agricultural market.

5. Nematode pests

5.1. The organisms

The most widely reported nematodes affecting faba bean are in the genera *Ditylenchus*, *Meloidogyne* and *Pratylenchus* (Table 2).

The stem nematode, *Ditylenchus dipsaci* (Kühn) Filipjev, species complex includes about 30 taxa affecting more than 500 host species. Faba bean is affected by two of these, formerly called the oat race and the giant race. Revisions of taxonomy based on DNA sequences indicate that the oat race should retain the specific epithet, while the giant race is a separate species, still un-named at the time of writing ("species B", Subbotin et al., 2005; Kerkoud et al., 2007).

While the faba bean is occasionally attacked by *D. dipsaci*, the former "giant race" is much more commonly reported (Esquibet et al., 2003; Kerkoud et al., 2007). Symptoms include swelling and distortion of the stem along with discolouration of plant parts. The nematodes may get under the coat of the developing seed, killing the seed or at least reducing its vigour and causing staining. Cultivars resistant to the "giant race" have been identified at ICARDA and in France, but the best resistance in French line 29H has been overcome by a particularly virulent genotype of the nematode in a region of Morocco (Abbad Andaloussi, 2001).

The root-knot nematodes, *Meloidogyne* spp., have a broad host range in hot, dry, tropical and subtropical regions such as much of India, Iraq and Egypt. The sessile females cause the development of large multinuclear syncytia in the roots of the host plants by breaking down cell walls.

Root-lesion nematodes, *Pratylenchus* species, attack and consume cortical parenchyma cells of the roots of many species, and each *Pratylenchus* species has a wide host range. The damage to the roots directly weakens the plant and its uptake of nutrients and water, and furthermore it leads to secondary infections by bacteria and fungi. Affected plants are stunted, yellowed and wilted, and the damaged roots are short, black and rotten.

5.2. Agronomic management techniques

Chemical treatment of the seeds stained by stem nematode infestation seldom destroys the population, so clean (certified) seed is the best form of prevention. Similarly, transfer of infected straw and plant debris is to be avoided and some nematodes in infected seeds can even survive passage through a monogastric or ruminant mammal (Palmisano et al., 1971). Thus incineration is still considered the most effective method of destroying infected material.

Where the giant race of *Ditylenchus* is present, a 3–8-year interval between successive faba bean crops is recommended (Caubel et al., 1999). As the species of both genera are being redefined (De Luca et al., 2004; Subbotin et al., 2005), the host range of each parasite species will be clarified, and it will become possible to design appropriate rotation strategies. Cowpea (*Vigna unguiculata* (L.) Walp.), mungbean (*Vigna radiata* (L.) Wilcz.), narbon bean (*Vicia narbonensis* L.), soybean (*Glycine max* (L.) Merr.), sunflower (*Helianthus annuus* L.) and triticale (X Triticosecale Wittmack) are considered to be resistant to *P. neglectus* while canaryseed (*Phalaris canariensis* L.), cotton (*Gossypium hirsutum* L.), fenugreek (*Trigonella foenum-graecum* L.), lentil (*Lens culinaris* Medik.), pigeon pea (*Cajanus cajan* (L.) Millsp.) and sorghum (*Sorghum bicolor* L.) are resistant to *P. thornei* and blue lupin (*Lupinus angustifolius* L.), pea (*Pisum sativum* L.), lablab (*Lablab purpureus* (L.) Sweet), linseed (*Linum usitatissimum* L.), rye (*Secale cereale* L.), and safflower (*Carthamus tinctorius* L.) are resistant to both (Thompson et al., 2008; Vanstone et al., 2008).

Resistance to *Meloidogyne javanica* (Treub) Chitwood has been identified in the Egyptian cultivar Romy (Shafshak et al., 1985), but no resistance to *M. incognita* (Kofoid & White) Chitwood has been reported.

The first released cultivar of faba bean in Australia, Fiord, acquired a reputation as a "cleaner" crop, substantially reducing *Pratylenchus* populations (V.A. Vanstone, pers. comm.). In a long-term rotation study, *P. neglectus* (Rensch) Filipjev & Schuurmans Stekhoven numbers on wheat roots were 8-fold lower after a Fiord faba bean crop than after a grass pasture (Yunusa and Rashid, 2007). Faba bean is considered to be resistant to *P. neglectus* and moderately resistant to *P. thornei* Sher & Allen (Thompson et al., 2008). Work in the Mediterranean basin, however, has shown the faba bean to be a host for *P. neglectus*, *P. thornei*, *P. penetrans* (Cobb) Filipjev & Schuurmans Stekhoven and *P. pinguicaudatus* Corbett, and that resistance to each of these species was identified in some North African faba bean germplasm (Di Vito et al., 2002). Genetic diversity is wide, with *P. penetrans* possibly representing a species complex, whereas *P. neglectus* appears to be a true species (De Luca et al., 2004).

5.3. Chemical and biological control methods

Chemical control of nematodes is difficult. The powerful insecticide Aldicarb was considered effective against *Pratylenchus*, *Meloidogyne* and *Ditylenchus* species, but it has been banned within the European Union and in some other regions. The nematicide

Oxamyl is considered effective against root-knot nematodes. Solarization was found effective against several species including *P. thornei* when the temperature under the plastic cover reached 55 °C (Sauerborn et al., 1990). Reduced tillage is associated with increased populations of *Pratylenchus* species (Thompson et al., 2008; Vanstone et al., 2008). The fungi *Paecilomyces lilacinus* (Thom) Samson and *Monacrosporium lysipagum* (Drechsler) Subram along with several *Streptomyces* spp. have been tested as biological control against various nematodes. *M. lysipagum* showed some activity against *P. neglectus* and *D. dipsaci* (Khan et al., 2006) while *Streptomyces* isolates quantitatively reduced *P. penetrans* numbers in potted alfalfa plants (Samac and Kinkel, 2001). Treating faba bean seeds with *Streptomyces avermitilis* (Burg et al.) Kim and Goodfellow and *Serratia marcescens* Bizio (trade name Nemaless) significantly reduced the population of *M. incognita* (El-Nagdi and Youssef, 2004).

6. Conclusions

Each country or region has its own cross-section of arthropod, nematode, fungus and broomrape pests on its faba bean crops so a generalized IPM strategy is unlikely to be realized. Sowing of uncontaminated or treated seed is necessary to prevent the spread of broomrapes, nematodes and several fungi, and for almost all pests it is important to isolate the crop from sources of trash or volunteer seedlings by several years within the field or by several hundred metres between fields. Chemical controls are available for most arthropods and fungi (e.g., Rothamsted Insect Survey, 2008), while attention must be paid to the need for bees to pollinate the crop and the need to prevent the development of resistance in the target organisms. Forecasting methods help in the management of arthropod pest populations, but few models are available for faba bean pests, and this is an area of continuing need. Thresholds have been defined for the incidences of many pests (see, e.g., Hawthorne et al., 2004), and the economic threshold depends on many issues outside the range of this paper, such as the cost of the chemical, the yield per hectare and the value of the harvest per tonne. Biological control methods are under investigation, but few have yet reached the market. Genetic resistance is available for all of the major fungi, nematodes and broomrapes, and cultivars with single resistances are on the market in many countries. Combining resistances is the objective of continuing research and development by plant breeders, along with biotechnological intervention both to identify endogenous genes and to introduce transgenes.

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