Integrated Pest Management Reviews **3**, 127–154 (1998)

Integrated pest management in forage alfalfa

CHARLES G. SUMMERS*
Department of Entomology, University of California, Davis, CA, 95616 USA

Alfalfa, *Medicago sativa* L., is among the most prized of forages, and is grown worldwide as a feed for all classes of livestock. It is one of man's oldest crops, and its cultivation probably predates recorded history. In addition to its versatility as a feed, alfalfa is well known for its ability to improve soil structure and, as a legume, is an effective source of biological nitrogen. As a perennial crop, alfalfa has a lifespan approaching 5 years, but in some areas of the world fields may remain productive for considerably longer. Such a long stand life affords ample time for the establishment and development of a diverse community structure by an abundance of organisms. In spite of system perturbations caused by frequent harvests and occasional pesticide applications, an alfalfa field provides a temporal stability which is uncommon among field crops. As a result of this stability, alfalfa supports an immense diversity of flora and fauna which, at times, exceeds that of riparian ecosystems. While most of alfalfa's inhabitants have little or no impact on it as a crop, a few are capable of causing extensive damage. Arthropods, plant pathogens, weeds, vertebrates, and plant parasitic nematodes can all cause significant yield and/or quality reductions and frequently contribute to shortening the productive life of the stand. This paper reviews the major strategies which have been developed to manage many of these alfalfa pests including: host plant resistance; cultural controls, such as harvest strategies, irrigation management, sanitation, planting schedules, and crop rotation; mechanical and physical controls; chemical control; and biological controls. Multiple pest interactions, e.g. insect-insect; insect-disease; insect-weed, and their management are discussed. Potential conflicts arising from the use of strategies which may reduce one pest but exacerbate others are also examined. A cross index of management strategies and their role in managing multiple pests is provided. Computer models, both ecological and economic, and their role in alfalfa pest management are discussed. Selected information sources on alfalfa and alfalfa IPM available over the Internet are listed. Alfalfa's role in the agricultural landscape, as it relates to pests, natural enemies, and pest management in other cropping systems as well as its role in crop rotation, is considered.

Keywords: alfalfa; alfalfa IPM review; diseases; forage; insects; integrated pest management; IPM; lucerne; *Medicago sativa*; nematodes; pest control; vertebrates; weeds.

Introduction

Alfalfa or lucerne, *Medicago sativa* L., is often called 'Queen of the Forages.' It is highly prized as a superior feed for dairy and beef cattle (*Bos* spp.) since it is quickly digested, relatively high in protein, high in cell solutes, and low in cell wall and neutral detergent fibers (Conrad and Klopfenstein, 1988). It is also an excellent source of calcium, magnesium, phosphorus, caratene and vitamin D. The protein is of excellent quality, a characteristic especially important to dairy and beef cattle as well as other livestock including: swine (*Sus* spp.), poultry (*Gallus* spp.), sheep (*Ovis* spp.), and horses (*Equus* spp.) (van Keuren and Matches, 1988). It has even become popular for human consumption in the form of 'alfalfa sprouts.' Alfalfa can be fed fresh as pasture or greenchop or preserved as hay, silage, or dehydrated meal, pellets, or cubes. In addition to its versatility as a feed, alfalfa is well known for its ability to improve soil structure as a legume is an effective source of biological nitrogen.

Alfalfa is recognized as the oldest plant grown solely for forage and it was likely cultivated prior to recorded history (Michaud *et al.*, 1988). Common alfalfa probably originated in or around Asia Minor, Transcaucasia, Iran, and Turkministan (Whyte *et al.*, 1953; Bolton, 1962; Wilsie,

*Mailing address for correspondence and reprint request: University of California, Kearney Agricultural Center, 9240 S. Riverbend Avenue, Parlier CA 93648, USA. E-mail address: <chasum@uckac.edu>.

The literature review for this manuscript was completed in January 1997. Some additional references, as suggested by the reviewers, were added in December 1997.

The mention of a trademark of proprietary product is solely to identify materials or to illustrate a concept and does not constitute a guarantee or warranty of that product by the author, Chapman & Hall, or the University of California, and does not imply its approval to the exclusion of other products that may also be suitable.

1962; McWilliam, 1968). Bolton *et al.* (1972) and Michaud *et al.* (1988) present a fascinating chronicle of alfalfa's geographical movement, distribution, and production throughout the world. Their account also references climatic conditions, crop utilization, cultivar selection, and pest problems encountered in each of the major worldwide growing regions. Michaud *et al.* (1988) estimated that in the early 1980s approximately 32 million hectares of alfalfa were being grown worldwide with 70% coming from the USA, USSR, and Argentina and 17% from France, Italy, Canada, and China.

Alfalfa is an extremely adaptable plant and can be grown under a wide range of soil and climatic conditions. Plant breeders have taken advantage of the rich genetic diversity within the genus *Medicago* to create numerous cultivars with increased winter hardiness, enhanced yield potential across a wide range of climatic and edaphic factors, tolerance to unfavorable soil conditions such as drought and mineral toxicity, and improved multiple-pest resistance. Estimates for the number of cultivars grown worldwide are not available but Miller and Melton (1983) listed more than 400 cultivars or brand names being offered in the US and Canadian markets as of 1983. As many as 40 new cultivars currently receive registration annually in North America (L. Teuber, personal communication).

An alfalfa field is, perhaps, unlike any other natural or man-made ecosystem. While sometimes grown in mixed culture with various grass species, alfalfa is most often grown in pure stands. With the use of appropriate weed control strategies, this results in an expansive monoculture. Alfalfa's dense canopy and crown structure afords a wide variety of habitats and niches for exploitation by a diverse array of organisms (Brown and Fick, 1986). An alfalfa field had a productive lifespan of approximately 5 years, but in some areas of the world, fields may remain in production for as long as 20 years. Such longevity provides a temporal stability which is uncommon among most agricultural crops and, ample time is available for the establishment and development of a diverse community structure by colonizing organisms. Alfalfa is also unique in that it is harvested (cut) and the foliage removed every 25 to 45 days during the growing season. Harvesting drastically alters the field microclimate within a few hours. Removal of the existing dense foliage exposes the alfalfa ecosystems inhabitants to markedly increased temperature, vapour pressure deficit and soil heat flux, and reduced relative humidity (Pinter *et al.*, 1975). Harvesting leads to the death of vast numbers of alfalfa's arthropod inhabitants and the forced emigration of many others (van den Bosch and Stern, 1969; Summers, 1976).

Alfalfa supports an incredible diversity of organisms, most of which have little or no impact on the plant itself. Van den Bosch and Stern (1969) estimated that approximately 1000 species of arthropods are associated with alfalfa in California's Central Valley while Pimentel and Wheeler (1973) collected 591 arthropod species from alfalfa in Upstate New York. Many are incidental visitors, others are predators or parasitoids, and relatively few are significant pests. Similar estimates on the number of microorganisms, such as fungi, bacteria, and nematodes associated with alfalfa are not available. It may be safely assumed however, that these also number in the hundreds, with most probably living as saprophytes. As is the case with arthropods, relatively few of these organisms are serious pests. Weeds probably fall into a similar situation with many species little more than an occasional nuisance. They do differ from the previously discussed organisms in that they are primary producers rather than consumers (Norris, 1982). While the majority of organisms associated with alfalfa cause little or no injury, those which are pests can cause considerable economic losses. In the US alone, arthropods cause an estimated $260 million and diseases and nematodes $400 million in losses annually (Manglitz and Ratcliffe, 1988; Leath *et al.*, 1988).

Pest management can trace its origins to alfalfa. In 1946, the first supervised control entomologist was hired in California to monitor alfalfa fields and make recommendations regarding the management of the alfalfa caterpillar, *Colias eurytheme* Boisduval (Hagen *et al.*, 1971). Numerous strategies have since been developed to better manage the majority of pest species injurious to alfalfa including: plant pathogens, nematodes, weeds, and vertebrates. This paper reviews the current status of these pest management strategies in forage alfalfa, integrating biological control, cultural manipulations, chemical control, and host plant resistance. I have attempted to limit the review to those strategies that are proven, through research and application, to be effective for the specific pest species discussed. In some cases, the discussion of certain pests, e.g. virus diseases, is limited because no effective management strategies are available. Because registrations for chemicals change frequently, I have tried to avoid reference to specific pesticides. Those which are mentioned are given only as examples to illustrate a point. While this review covers primarily pest management in North America, I have attempted to include examples from other major alfalfa growing areas throughout the world. The present review is limited to forage pests although occasional mention is made of pests of the seed crop.

I believe this to be the first comprehensive review of alfalfa IPM that considers management of all of the major classes of pests: nematodes, diseases, insects and other invertebrates, vertebrates, weeds and their integration, as well as the management of multiple pests and multiple pest interactions. This review is dedicated to the memory of Dr Kenneth S. Hagen, Division of Biological Control, University of California, Berkeley, in honour of his outstanding contributions both practical and scholarly to the art and science of alfalfa insect pest management.

Strategies for IPM in alfalfa and their application

Host plant resistance

Host plant resistance has beeen exploited in numerous situations to manage insects, diseases and nematodes. It may serve as the principal control method or can be integrated with chemical, biological, or cultural control strategies. Alfalfa is a cross-pollinated plant with rapid inbreeding depression and a complex inheritance of characteristics due to its autotetraploid nature of inheritance (Nielson and Lehman, 1980; Busbice *et al.*, 1972). An alfalfa cultivar is composed of a heterogeneous population of plants improved for one or more specific characteristics, e.g. pest resistance, which can be retained through subsequent generations of seed multiplications (Elgin *et al.*, 1988). Pest resistance is thus characterized according to the frequency of resistant plants in the population and is usually expressed as a percentage of those plants. Populations with $<5\%$ resistant plants are classified as susceptible, 6–14% as having low resistance, 15–30% moderate resistance, 31–50% resistant and $>50\%$ as having high resistance (Certified Alfalfa Seed Council, 1995). Some percentage of susceptible plants is present within all resistant cultivars regardless of their resistance rating and under heavy pest pressure even highly resistant cultivars may experience injury and yield or quality reduction.

Biological control

Biological control can be described as a limitation in the abundance of pest organisms by other organisms (natural enemies) and, in the context of crop production, reducing or maintaining pest species below the economic threshold. Biological control agents include predators, parasitoids, bacteria, fungi, and viruses. Biological control may be accomplished by means of indigenous species, by natural enemies imported and released for the control of introduced exotic pests, or by periodic inundative releases of natural enemies to control a specific pest. The latter strategy is seldom employed in alfalfa because it is not cost effective. Often, the goal is the conservation of indigenous natural enemies through the judicious use of pesticides and by cultural manipulation. Presently, biological control, as a management strategy in alfalfa, is mainly confined to the management of arthropod pests.

Cultural control

Cultural manipulations used for the management of alfalfa pests include modification of harvesting practices, such as delayed or early harvest; habitat modification through strip-cutting or border-cutting; removal of hay for greenchop, ensilage, or dehydration rather than field curing for baling; and grazing by livestock. Harvesting can also be used to enhance or conserve natural enemy species and to reduce humidity and moisture conditions in the canopy which in turn limits disease development. Harvesting disease- or weed-free fields before harvesting infected/infested fields can limit the movement of inoculum and weed seeds. Sanitation is important in reducing the incidence and spread of nematodes, weeds, and pathogens. Cleaning soil and plant debris from machinery between fields reduces weed, pathogen, and nematode movement. Irrigation management is important in reducing the spread of several soil borne pathogens, reducing the competitiveness of certain weeds, and the density reducing of some arthropod pests. Crop rotation mitigates the impact of some nematode species and reduces the incidence of numerous diseases, some vertebrate pests, and weeds. Planting disease and weed free seed can reduce and/or delay the incidence and severity of several pest problems.

Chemical control

While one of the goals of IPM is a reduction in the use of pesticides, they still play an integral role in managing many alfalfa pests. In some situations, stand establishment would be impossible without the appropriate herbicides and stand longevity can be shortened by as much as a year without the use of herbicides in established stands. Several vertebrates can be successfully managed by applications of poison baits. Insect pests, even those for which resistant cultivars are available or natural enemies are well established, must occasionally be suppressed with insecticides. The negative impacts of insecticides, e.g. disruption of natural enemy populations, development of insecticide resistance, and outbreaks of secondary pests, can be moderated by their judicious use including: adherence to economic threshold levels, use of selective insecticides when available, and the timing and method of application and rate.

Physical and mechanical control

These strategies are used mainly against vertebrate pests and include exclusion tactics such as fencing, both above and below ground, trapping out of established individuals, shooting, and the use of scare devices.

Management strategies for specific pests

NEMATODES

Host plant resistance

Plant parasitic nematodes may attack either the foliage or root system. Their microscopic size and cryptic nature often leads to severe injury before their presence is recognized. The use of resistant cultivars provides the most practical means of managing nematodes in alfalfa. The alfalfa stem nematode, *Ditylenchus dipsaci* (Kühn) Filipjev, is the most important nematode pest of alfalfa, It causes losses worldwide and was the first nematode species for which resistance was developed. 'Lahontan' was released specifically for the management of this pest (Smith, 1958) and currently over 150 alfalfa cultivars with resistance to *D. dipsaci* are available (Certified Alfalfa Seed Council, 1995). The northern root-knot nematode, *Meloidogyne hapla* Chitwood, and southern root-knot nematode, *M. incognita* (Kofiod & White) Chitwood, have also been the objective of extensive selection and breeding programs in recent years. Several cultivars with resistance to both species are available, but races of *M. hapla* have been reported which break that resistance (McKenry, 1987; Griffin and McKenry, 1989). Other root-knot species of lesser importance include Javanese root-knot nematode, *M. javanica* (Treub.), peanut root-knot nematode, *M. arenaria* Chitwood, and the Columbia root-knot nematode, *M. chitwoodi* Golden, O'Bannon, Santo & Finley. Resistance to *M. chitwoodi* and *M. javanica* is available in several alfalfa germplasm sources (Reynolds, 1955; Reynolds and O'Bannon, 1960; Peaden *et al.* 1995). Before alfalfa is planted into root-knot nematode infested soils, proper identification of the nematode species present is imperative. Cultivars resistant to northern root-knot nematode may not contain resistance to southern root-knot nematode and vice versa (Certified Alfalfa Seed Council, 1995).

Numerous other species of parasitic nematodes including: *Tylenchorhynchus* app., *Xiphinema* spp., *Paratrichodorus* spp. and *Criconemella* spp. can also damage alfalfa, although in most cases, the extent of their injury has not been quantified. Resistant cultivars have not currently been identified. One of the most important nematode pests is the root-lesion nematode, *Pratylenchus penetrans* (Cobb) Filipjev & Schuumans Stekhoven, (Thompson and Willis, 1970; Nelson *et al.*, 1983; Nelson *et al.*, 1985; Christie and Townshend, 1992; Thies *et al.*, 1992). While cultivars with resistance to *P. penetrans* are not available, some promising germplasm has been released (Barnes *et al.*, 1990).

Biological control

Currently, there are no augmentatively released biological agents attacking alfalfa nematodes that provide economic levels of control in the field. In a laboratory study, Townshend *et al.* (1989) found fewer *M. hapla* galls on 'Saranac' alfalfa roots grown from seed inoculated with the fungus *Meria coniospora* Drechsler before sowing, than on roots of alfalfa plants grown from uninoculated seed. Efforts are continuously ongoing to identify effective biological control agents of nematodes and to develop successful methods of their introduction into the field.

Chemical control

Chemical control, through soil fumigation or the use of other nematicides, is generally not cost effective in alfalfa production (Summers *et al.*, 1981; Townshend *et al.*, 1989; Carlson and Westerdahl, 1995). In some situations, the use of nematicides has been shown to aid in stand establishment and improve yields. Thies *et al.* (1992) found that carbofuran, applied pre-plant, increased alfalfa stand establishment rates by 21% and reduced populations of *P. penetrans* by 37% during the stand establishment period. Thompson and Willis (1970) reported that carbofuran reduced *P. penetrans* populations in alfalfa roots for up to 69 weeks after application resulting in increased yields during the seedling-year. Nematicides may be economical for use in other crops planted in a rotation sequence with alfalfa.

Cultural control

Various cultural manipulations can be employed to reduce the population density and hence the injury that results from infestations by plant parasitic nematodes. Willis and Thompson (1979) found that fallowing for one growing season significantly reduced *P. penetrans* populations and increased subsequent alfalfa yields. Heavily infested fields can also be planted to a non-host crop for 2 to 3 years before rotating back to alfalfa. As noted in the discussion of host plant resistance, proper nematode identification is extremely important in determining the selection of a non-host rotational crop. Good weed control is also imperative since many weed species can be excellent alternate hosts for nematodes, effectively serving as a bridge between susceptible crops. Sanitation is important in avoiding the contamination of non-infested fields. Nematodes can be carried from infested to clean fields in plant debris, on soil or machinery, and in irrigation water (Summers *et al.*, 1981). Dry soil reduces the within field movement of *D. dipsaci* and delaying irrigation following cutting slows its invasion into new crown buds (Griffin, 1987). A summary of strategies currently available for use in the management of nematodes is presented in Table 1.

DISEASES

Host plant resistance

Diseases attack the leaves and stems, the crown and roots, and the vascular system. Planting disease-resistant cultivars is the most effective means of managing most diseases and minimizing the losses they cause in alfalfa (Leath *et al.*, 1988). Foliar diseases affecting leaves and stems are common in alfalfa, frequently causing significant yield reductions (Summers and McClellan, 1975a and b; Broscious and Kirby, 1988; Rizvi and Nutter, 1993). Pathogens causing foliar and stem diseases may also invade the crown and root systems inciting diseases in these organs that may ultimately kill the plant (Leath *et al.*, 1988; Summers and Gilchrist, 1991).

Several foliar/stem diseases can be successfully managed using resistant varieties. Anthracnose, caused by

Table 1. Summary of strategies for the management of major nematode pests of forage alfalfa[a]

Pest[b]	Cultivar resistance	Biological control	Cultural control	Chemical control
Stem nematode	Yes	No	Delay irrigation, sanitation	None
Root-knot nematodes				
NRKN	Yes	No	Avoid heavily infested fields, sanitation	None
SRKN	Yes	No	Avoid heavily infested fields, sanitation	None
Lesion-nematode	No	No	Fallow, rotation	Limited[c]

[a]This table is only a summary overview. See text for full explanation of strategies and their proper application.
[b]See text for scientific names. NRKN, northern root-knot nematode; SRKN, southern root-knot nematode.
[c]Carbofuran has been shown to be effective during stand establishment.

Colletotrichum trifolii (Bain. & Essary), is a major disease throughout much of the world (Leath *et al.*, 1988). It occurs most commonly on the stems where large lesions cause stem girdling. *C. trifolii* can also invade the crown frequently killing the plant. Growing cultivars with moderate to high levels of resistance has resulted in increased dry matter yields and stand persistance (Elgin *et al.*, 1981). Downy mildew, caused by *Peronospora trifoliorum* dBy., and rust, caused by *Uromyces striatus* Schroet. var. *medicaginis* (Pass.) Arth., can cause extensive defoliation in established stands. Downy mildew may also kill seedlings resulting in complete stand failures (Leath *et al.*, 1988). Cultivars resistant to both pathogens are available and should be grown in areas where these diseases are problems (Leath *et al.*, 1988; Elgin *et al.*, 1988). Rizvi and Nutter (1993) suggested using mixtures of alfalfa germplasm in which cultivars were selected on the basis of their resistance to one or more foliar pathogens present in a complex. They cite this approach as being most useful in systems in which resistance to multiple foliar pathogens in one background is not available, yet some cultivars have resistance to individual diseases.

Several other pathogens cause foliar diseases which result in extensive defoliation. Cultivars with acceptable levels of resistance to these diseases are not generally available, but germplasm containing resistance to common leaf spot [*Pseudopeziza medicaginis* (Lig.) Sacc.] (Kehr *et al.*, 1984; Thyr *et al.*, 1984a; Thyr *et al.*, 1984b); summer black stem and leaf spot [*Cercospora medicaginis* Ell. & Ev.] (Kehr *et al.*, 1984); spring black stem and leaf spot [*Phoma medicaginis* Malbr. & Roum. var. *medicaginis* boerema] (Hill *et al.*, 1989); and stemphylium leaf spot [*Stemphylium botryosum* Wallr.] (Teuber *et al.*, 1982) has been released. *Stagonospora meliloti* (Lasch) Petr., the causal pathogen of Stagonospora leaf spot, frequently invades the alfalfa crown where it causes more damage than it does as a foliar pathogen (Summers and Gilchrist, 1991). While resistant cultivars are not available, resistant germplasm has been developed (Erwin *et al.*, 1987). In the course of developing new cultivars, some selection for resistance to foliar diseases, albeit unintentional, has apparently taken place. When newer cultivars are grown adjacent to older cultivars such as ‘Ranger’ and ‘Buffalo’, differences in disease susceptibility are readily apparent (Leath *et al.*, 1988).

Among the root diseases, perhaps the most serious in Phytophthora root rot caused by *Phtophthora megasperma* f. sp. *medicaginis* Kuan & Erwin. This disease occurs worldwide (Leath *et al.*, 1988). Resistance, in moderate to high levels, is available in a large number of cultivars (Certified Alfalfa Seed Council, 1995) and resistant varieties should be grown wherever this disease is a problem. Water management, discussed below, is also key to preventing or reducing the incidence of Phytophthora root rot since even highly resistant cultivars may become diseased if inoculum is abundant and the soil remains wet for an extended period of time (Leath *et al.*, 1988). Aphanomyces root rot, caused by *Aphanomyces euteiches* Drechs., causes a blight of seedling and root rot of mature plants (Richard *et al.*, 1991; Wiersma *et al.*, 1995; Munkvold and Caralton, 1995). Resistance to this disease is widely available in dormant cultivars (Certified Alfalfa Seed Council, 1995) but, like Phytophthora root rot, the disease may flourish in poorly drained soils even if resistant varieties are grown (Richard *et al.*, 1991; Wiersma *et al.*, 1995). Resistance to Aphanomyces root rot is lacking among non-dormant varieties (Certified Alfalfa Seed council, 1995).

Diseases of the vascular system are among the most important in alfalfa. Bacterial wilt, caused by *Clavibacter michiganense* subsp. *insidiosum* (McCullich) Davis *et al.*, was once the most serious disease of alfalfa worldwide. Its discovery in the US marked the beginning of breeding for disease resistance in alfalfa and currently most cultivars contain moderate to high levels of resistance (Elgin *et al.*, 1988). Two other vascular diseases for which extensive resistance is available are Verticillium wilt, caused by *Verticillium alboatrum* Reinke et Berth, and Fusarium wilt, caused by *Fusarium oxysporum* Schl. f. sp. *Medicaginis* (Weimer) Syn. & Hans. Several other *Fusarium* spp. including *F. solani* (Mart.) Appel & Wr., *F. oxysporum* Schl., *F. roseum* Lk. ex Fr. emend. Sny. & Hans., and *F. tricinctum* (Corda) Saccardo. also cause root and crown diseases, many exhibiting symptoms of Fusarium wilt. Diseases caused by these latter organisms, for which resistance is not available (Wilcoxson *et al.*, 1977; Elgin *et al.*, 1988; Miller-Garvin and Viands, 1994), should not be confused with Fusarium wilt. Planting Fusarium wilt resistant cultivars in soils infested with these latter organisms will not prevent their development. As noted elsewhere in this review, the identity of the causal agent of any malady is paramount in its management. Genes conferring to this *Fusarium* spp. complex are known to exist (Wilcoxson *et al.* 1977; Miller-Garvin and Viands, 1994; Salter *et al.*, 1994) and will eventually be incorporated into useful cultivars.

Biological control

The role of biolgical control agents of alfalfa pathogens is unclear. While numerous competitive and/or antagonistic organisms have been reported for both soil and foliar pathogens of other crops (Papavizas and Lumsden, 1980; Lindow, 1985) few are known from the alfalfa ecosystem. Barnes *et al.* (1981) found the nematode *Aphelenchus avenae* Bastian effective in controlling *F. solani* and *Rhizoctonia solani* Kuhn in alfalfa under laboratory conditions, but its effectiveness in the field has not been evaluated. Casida and Lukezic (1992) obtained control of common leaf spot, Stemphylium leaf spot, and Phoma leaf spot on alfalfa in the laboratory using the bacterium *Pseudomonas* Strain 679–2. They also reported some control of common leaf spot under field conditions with the same bacterium. There are currently, however, no known effective biological control agents of alfalfa pathogens which can be routinely utilized under field conditions.

Chemical control

Fungicides, while effective in controlling many alfalfa diseases (Summers and McClellan, 1975a and b; Broscious and Kirby, 1988) are generally not cost effective and few are registered for use (Stuteville and Erwin, 1990). Registered fungicides are generally used only as seed treatments or occasionally as preplant soil applications to prevent or reduce seedling damping off caused by *P. megasperma* or *Pythium* spp. (Grau, 1990; Bergstrom, 1991).

Cultural control

Cultural manipulations such as early or delayed harvest, water management, sanitation, and crop rotation may be employed to manage disease and limit losses. Together with resistant cultivars, cultural manipulations are the mainstay of reducing disease impact. The importance of good water management was noted earlier as a means of reducing the incidence and spread of Phytophthora root rot and Aphanomyces root rot. Both diseases are favoured by saturated soil conditions. Fields should be deep-tilled to improve water percolation and leveled to eliminate low spots. Providing adequate drainage to eliminate standing water also helps to prevent water logged soils and reduces the incidence of Phytophthora and Aphanomyces root rots. The incidence of crown wart, caused by *Urophlyctis alfalfae* (Pat. & Lagerh.) Magnus, can also be mitigated by avoiding excessive irrigation (Erwin, 1990a). Scald, a serious disease of physiological origin, can cause severe stand losses in hot, irrigated regions of the southwestern US. This disease is frequently associated with *R. solani* although a causal relationship is unclear (Leath *et al.*, 1988). The incidence and severity of scald can be reduced by avoiding excessive irrigation and promoting good soil drainage (Leath *et al.*, 1988). Reducing plant stress, by avoiding the application of too much or too little water, may also reduce the incidence of crown and root rot diseases associated with *Fusarium* spp. (Leath *et al.*, 1988).

The timing, frequency, and scheduling of harvest all play an important role in disease management. A timely harvest may reduce yield and quality losses caused by foliar diseases, and may reduce the spread of inoculum (Leath *et al.*, 1988; Leath *et al.*, in press). Early cutting is recommended to reduce leaf loss from common leaf spot, Stemphylium leaf spot, leaf rust, spring and summer black stem and leaf spot, and Leptosphaerulina leaf spot, caused by *Leptosphaerulina briosiana* (Pollacci) J.H. Graham and Luttrell (Leath, 1990; Leath *et al.*, 1988). The incidence and spread of Sclerotinia crown and stem rot [caused by *Sclerotinia trifoliorum* Eriks. and *S. sclerotiorum* (Lib.) dBy.], a disease which thrives under cool moist conditions can be curtailed by early spring mowing. This opens the canopy, admits more sunlight, and produces drier conditions and higher temperatures (Leath *et al.*, in press). Mowing younger stands before old stands reduces the spread of anthracnose, bacterial wilt, and Verticillium wilt (Erwin, 1990b; Leath *et al.*, 1988). Harvesting can also exacerbate some disease problems. Inoculum may be spread in the sap covering cutter bars and the higher incidence of mechanical injury to the crown enhances the opportunity of infection by crown and root rotting pathogens (Leath *et al.*, in press; Rodriguez *et al.*, 1990).

Rotation of 3 to 4 years between legume crops, deep plowing to bury sclerotia, and planting clean seed all help to decrease the incidence of Sclerotinia crown and stem rot (Leath *et al.*, 1988). Rotation to a non host crop, maintaining land free of weed hosts, and planting seed free of infected debris also reduces the inoculum potential of Verticillium wilt (Leath and Pennypacker, 1990; Leath *et al.*, 1988). A summary of strategies useful in the management of alfalfa diseases may be found in Table 2.

INSECTS

Host plant resistance

When available, host plant resistance is the major component of insect management. The greatest success in developing insect resistant alfalfa cultivars has been with the aphids; pea aphid, *Acyrthosiphon pisum* (Harris), blue alfalfa aphid, *A. kondoi* Shinji, and spotted alfalfa aphid, *Therioaphis maculata* Buckton (Nielson and Lehman, 1980; Manglitz and Ratcliffe, 1988; Sorensen *et al.*, 1988). While the mechanisms of resistance to these aphids have not been fully elucidated, multiple factors are evidently involved since antibiosis, nonpreference, and tolerance have all been documented as occurring (Sorensen *et al.*, 1988). The mechanisms of resistance are of practical importance since antibiosis may exert selection pressure on aphid populations that results in the evolution of biotypes capable of circumventing the resistance found in the original cultivar (Horber, 1980). Environmental factors may also influence resistance levels. Temperatures < 15 °C have been reported to reduce resistance to all three aphid species (McMurtry, 1962; Isaak *et al.*, 1963 and 1965; Summers, 1988). The reduction or loss of resistance is particularly important when dealing with pea aphid and blue alfalfa aphid since both are cool-season species, usually reaching pest status in the spring and/or fall. Extended periods of cooler than normal temperatures may decrease resistance and result in several aphid outbreaks on otherwise resistant varieties. The spotted alfalfa aphid is normally a mid-summer pest and is less likely to encounter periods of sustained temperatures cool enough to modify resistance.

Most cultivars appear to maintain their resistance when introduced into geographic locations far removed from their origin. Several US cultivars resistant to *T. maculata* retained their resistance when introduced into Australia (Hamilton *et al.*, 1978; Lloyd *et al.*, 1980a). Similar observations have been made with cultivars introduced into Australia (Lloyd *et al.*, 1980b) and New Zealand (Farrell and Stufkens, 1981) for the management of *A. kondoi*. However, the cultivars ‘Apex’ and ‘Team’, resistant to *A. pisum* in the US, were susceptible to pea aphid biotypes found in France (Auclair, 1989). Of several cultivars evaluated, only ‘CUF 101’ retained its resistance to a red

Table 2. Summary of strategies for the management of major diseases of forage alfalfa[a]

Disease[b]	Cultivar resistance	Biological control	Cultural control	Chemical control
Vascular diseases				
BW	Yes	No	Cutting schedule,	No
VW	Yes	No	Cutting schedule, rotation, clean seed	No
FW	Yes	No	Water management	No
Root & crown diseases				
PRR	Yes	No	Water management, improved drainage	No
SCR	No	No	Clean equipment	No
FRR	No	No	Water management	No
APH	Yes	No	Water management, improved drainage	No
Damping off (DO)	No	No	–	Seed treatment
Anthracnose	Yes	No		No
SCSR	No	No	Rotation, clean seed, deep plowing, early cut	No
Foliar & stem diseases				
CLS	No	No	Early cut	No[c]
SLS	No	No	Early cut	No[c]
DM	Yes	No	Early cut	No
Rust	Yes	No	Early cut	No
Anthracnose	No	No	Cutting schedule, early cut	No
Spring & summer				
Blackstem	No		Early cut	No
Lepto leaf spot	No	No	Early cut	No

[a]This table is only a summary overview. See text for full explanation of strategies and their proper application.
[b]See text for causal organisms and scientific names. BW, Bacterial wilt; VW, Verticillium wilt; FW, Fasarium wilt; PRR, Phytophthora root rot; SCR, Stagonospora crown rot; FRR, Fusarium root rot; APH, Aphanomyces root rot; DO, damping off caused primarily by *Phytophthora* spp. and *Pythium* spp.; SCSR, Sclerotinia crown and stem rot; CLS, common leafspot; SLS, Stemphyllium leafspot; DM, Downy mildew.
[c]Registered fungicide are available but are generally considered cost prohibitive.

form of *A. pisum* that was introduced from Europe into the US (Kugler and Ratcliffe, 1983).

Several cultivars, including ‘Team’, ‘Arc’, ‘Liberty’, and ‘Weevilchek’, with resistance to the alfalfa weevil, *Hypera postica* (Gyllenhal), have been released in the US over the past 25 years (Sorensen *et al.*, 1988). ‘Team’ and ‘Weevilchek’ also supported significantly lower populations of the Egyptian alfalfa weevil, *H. brunneipennis* (Boheman), had a lower whole plant and single stem damage rating, and a higher tolerance rating to this insect than did the susceptible ‘Moapa 69’ (Summers and Lehman, 1976). ‘Team’ and ‘Weevilchek’ are winter dormant cultivars, however, and are not well adapted to areas where *H. brunneipennis* occurs. The non-dormant germplasm UC 73, with tolerance to *H. brunneipennis* equal to that of ‘Team’ and ‘Weevilchek’, has been released (Summers and Lehman, 1976; Lehman *et al.*, 1992).

Glandular-haired alfalfa germplasm containing resistance to potato leafhopper, *Empoasca fabae* (Harris), has been released in the US (Sorensen *et al.*, 1985 and 1986a and 1994) and eight glandular-haired cultivars, with resistance to *E. fabae*, were released for sale during 1997 (W. Johnson, personal communication). All have some level of enhanced resistance and are adapted to the midwest and the northest where *E. fabae* problems are the most severe (Johnson, 1997).

Other alfalfa pests for which limited resistance is available include: meadow spittlebug, *Philaenus spumarius* L.; potato capsid, *Calocoris norvegicus* (Gmelin) and grasshoppers (Nielson and Lehman, 1980). Moellenbeck *et al.* (1993) found several commercial cultivars that contained useful resistance to the threecornered alfalfa hopper, *Spissistilus festinus* (Say). Byers *et al.* (1996) reported plant introductions with potential resistance to clover root curculio, *Sitona hispidulus* (F.). Germplasm with resistance to the lygus bugs, *Lygus hesperus* (Knight) and *L. lineolaris* (Palisot de Beauvois), and the alfalfa seed chalcid, *Bruchophagus roddi* (Gussakovsky), are also available although levels are currently inadequate to provide effective control (Nielson and Lehman, 1980; Sorensen *et al.*, 1988). Cultivars with resistance to silverleaf whitefly, *Bemisia argentifolii* Bellows & Perring, are under development and expected to be available by the year 2000 (Teuber *et al.*, 1997).

Biological control

An alfalfa field contains a fauna rich in parasitoids and predators. The parasitoids *Trioxys complanatus* Quilis, *Praon exsoletum* (Nees) and *Aphelinus asychis* Walker were introduced into California following the arrival of the spotted alfalfa aphid and, together with resistant cultivars, played a significant role in reducing populations to below economic levels (Stern *et al.*, 1959; van den Bosch *et al.*, 1964; Carver, 1989). *Trioxys complanatus* was introduced into Australia following the detection of *T. maculata* there in 1977 and SAA is no longer considered a major pest there due in part to its activity (Hughes *et al.*, 1987). *Aphidius smithi* Sharma & Subba Rao and *A. ervi* Haliday are highly effective parasitoids of *A. pisum* and *A. kondoi* in the US. *A. ervi* has also been introduced into Argentina, New Zealand, and Australia (Carver, 1989) where it has become well established. Currently, *A. ervi* appears to be displacing *A. smithi* in North America (Mackauer and Kambhampati, 1986), but both are effective parasitoids. Biological control has greatly limited the impact of the alfalfa weevil (*H. postica*) in much of north America (Kingsley *et al.*, 1993; Yeargan, 1985). The larval parasitoids, *Bathyplectes curculionis* (Thomson) and *B. anurus* (Thomson), and the adult parasitoid, *Microctonus aethiopoides* (Loan), have been shown to cause significant alfalfa weevil mortality and have contributed to maintaining this insect at sub-economic injury levels across much of the eastern US and Canada (Kingsley *et al.*, 1993). In addition to the parasitoids, an effective indigenous fungal pathogen, *Zoopthora phytonomi* (Authur), contributes to alfalfa weevil larval population reduction throughout much of its range (Kingsley *et al.*, 1993). *Zoopthora phytonomi* is considered to be the principal regulator of weevil populations in eastern Canada (Harcourt and Guppy, 1991). Occasional larval outbreaks can be traced to climatic conditions unfavourable to *Z. phytonomi* epizootics (Harcourt and Guppy, 1991). In certain areas, the fungus *Beauveria bassiana* (Balsamo) is also active on the adults, contributing to weevil control (Manglitz and Ratcliffe, 1988).

Despite the introduction of 10 species of parasitic Hymenoptera in California for control of the Egyptian alfalfa weevil, biological control of this pest has not been realized (Pitcairn and Gutierrez, 1989). Failure has been attributed to insufficient numbers released, poorly adapted climatic strains, and the lack of alternate hosts (Pitcairn and Gutierrez, 1989).

The alfalfa blotch leafminer, *Agromyza frontella* (Rondani), once a serious pest of alfalfa in much of the Northeastern US is now predominantly kept under control by three introduced parasitoids, *Dacnusa dryas* (Nixon), *Chrysocharis panctifacies* Delucchi, and *Miscogaster hortensis* Walker (Drea and Hendrickson, 1986). Certain native parasitoids of other *Agromyza* spp. have provided some additional control (Hendrickson and Plummer, 1983).

The larvae of several Lepidoptera regularly feed on alfalfa. The alfalfa caterpillar, *C. eurytheme*, is found throughout North America, but causes the greatest amount of injury in the southwest. *Colias eurytheme* is most often kept in check by the larval parasitoid, *Cotesia* (= *Apanteles*) *medicaginis* Muesebeck, and the egg parasitoid, *Trichogramma semifumatum* (Perkins). *Cotesia* destroys the caterpillar in its early instars and very little alfalfa is eaten. During hot weather, *C. medicaginis* can control the alfalfa caterpillar within the cutting cycle (Hagen, 1990). *Cotesia medicaginis* activity, an its effectiveness in regulating alfalfa caterpillar populations, is closely associated with the cutting cycle and alfalfa regrowth (Hagen *et al.*, 1971). Harvesting schedules and strip-cutting (see next section on harvest strategies) may be manipulated to enhance the activity of *C. medicaginis*.

In the western US, outbreaks of beet armyworm, *Spodoptera exigua* (Hübner), and western yellowstriped armyworm, *S. praefica* (Grote), are primarily prevented by the activity of a large number of native predators and parasitoids (Hagen *et al.*, 1971; Hagen, 1990). The predator complex includes *Chrysoperla* spp., *Geocoris* spp., *Nabis* spp., and *Collops* spp. adults (Hagen, 1990). The two most common parasitoids are *Hyposoter exiguae* (Viereck) and *Cotesia marginiventris* (Cresson) (Miller and Ehler, 1978). The alfalfa looper, *Autographa californica* (Speyer), in the western US and the green cloverworm, *Plathypena scabra* (F.), in the eastern US are both limited by a complex of parasitoids and diseases and they rarely reach pest status (Davis and Knowlton, 1976; Lentz and Pedigo, 1975).

Diseases, most notably those caused by polyhedrosis viruses and the bacterium *Bacillus thuringiensis* Berliner (B.t.), are important components in regulating larval densities of many Lepidoptera species in alfalfa. Naturally occurring epizootics of *B. thuringiensis* and viruses frequently maintain larval densities well below economic threshold values. Commercial preparations of *B. thuringiensis* are also available for the control of alfalfa caterpillar and armyworms. These can be applied like insecticides and are as effective as the latter, but without the associated disruption of predators and parasitoids.

Prevalence of the aphidophagous fungus, *Erynia neoaphidis* Remaudière & Hennebert, is closely linked in a density-dependent manner to pea aphid populations (Gutierrez *et al.*, 1984a). Under favourable conditions of temperature, rainfall and humidity, *E. neoaphidis* epidemics can effectively regulate pea aphid populations, rapidly reducing them below the economic threshold levels (Pickering and Gutierrez, 1991). Biotypes of the pea aphid, resistant to *E. neoaphidis*, have been found in Australia (Hughes and Bryce, 1984). This fungus apparently has little or no impact on the blue alfalfa aphid (Pickering and Gutierrez, 1991).

Forage alfalfa typically harbours large numbers of generalist predators including, but not limited to: *Nabis* spp., *Orius* spp., *Chrysopa* spp., *Chrysoperla* spp., *Geocoris* spp., several species of Coccinellidae and spiders, plus numerous other general feeders. Of the 591 species recovered in their survey of the arthropod fauna of alfalfa, Pimentel and Wheeler (1973) found that 216 were predators and 63 were parasitoids. Although predator species outnumber parasitoids by 3 to 1 (Pimentel and Wheeler, 1973), far less is known about prey (pest) regulation by predators since their impact is considerably more difficult to assess than is that of pathogens and parasitoids (Hagen and van den Bosch, 1968). Coccinellids have long been known for their ability to regulate aphid numbers in alfalfa and have been show to maintain spotted alfalfa aphid and pea aphid populations well below economic threshold levels (Dickson *et al.*, 1955; Smith and Hagen, 1956; Smith and Hagen, 1959; Neuenschwander *et al.*, 1975). Economic thresholds for spotted alfalfa aphid and pea aphid in California consider the ratio of Coccinellids per sweep to the number of aphids per stem in determining the need for chemical control measures (Summers *et al.*, 1981; Summers *et al.*, 1994).

Neuenschwander *et al.* (1975) showed that polyphagous predators such as Chrysopidae and Hemiptera became important in aphid control only when the dominant coccinellids were inactive because of diapause or in cases where insufficient numbers of aphids necessary for reproduction prompted the beetles to leave the fields. In Canada, Frazer *et al.* (1981) concluded that while early season populations of pea aphids can be limited by coccinellid predation alone, populations occurring later in the year are most often regulated by the combined action of several predators including spiders, *Orius* spp., *Heterosoma* sp., and *Anystis* sp. Benedict and Cothran (1980), in studies of predation by *Nabis alternatus* Parshley and *N. americoferus* Carayon in northern California alfalfa fields, found that in addition to feeding on pea aphids, *N. alternatus* and *N. americoferus* consumed large numbers of *C. eurytheme* and *S. praefica* eggs and early instar larvae. The authors concluded however, that *Nabis* spp. are probably not capable of maintaining these Lepidopterans below economic threshold levels without assistance from other [unspecified] natural enemy species.

Chemical control

Insecticides are an integral component in the management of alfalfa insect pests, and in some situations, the only viable option available to prevent economic losses. The negative impacts of insecticides, e.g. disruption of natural enemy populations, development of insecticide resistance, and outbreaks of secondary pests can be moderated by their judicious use including: adherence to economic threshold levels, use of selective insecticides when available, timing and method of application, and application rate. The use of commercial preparations of *B. thuringiensis* for alfalfa caterpillar control was discussed earler in this review. This material is highly selective for Lepidoptera larvae and has only minimal adverse impacts on most natural enemies. Earlier formulations of B.t.s were not particularly effective against the larvae of several armyworm species, but recently newer materials containing different crystal proteins e.g. *B. thuringiensis* subsp. *aizawai* (Shelton *et al.*, 1993), appear to have increased efficacy against these pests (P. A. Grau, personal communication). *Bacillus thuringiensis*, including *B. thuringiensis* subsp. *aizawai* is most effective on early instar larvae and its efficacy decreases as larvae reach the third and fourth instar.

In general, alfalfa aphids can easily be controlled with a wide variety of insecticides (Summers, 1975). Use of a selective material, e.g. primicarb which is highly selective for aphids, aids in the conservation of predators and parasitoids (Summers *et al.*, 1975; Syrett and Penman, 1980).

Timing, application rate, and placement of insecticides can reduce their negative impact on natural enemies. Summers and Cothran (1972a; 1972b) found that Egyptian alfalfa weevil could be effectively controlled in most years by a single early winter application of carbofuran timed to coincide with the return of adults to the alfalfa from their summer aestival sites but before oviposition had occurred. Spraying at this time had little or no impact on populations of *Nabis* spp., *Orius* spp., *A. smithi*, *Chrysopa* spp., and Coccinellidae (Summers and Cothran, 1972b). Davis (1970) also found that early season treatments with carbofuran had no effect on *B. curculionis*, a larval parasitoid of alfalfa weevil. Roberts *et al.* (1987) found that spraying a 12 to 21 m swath around the perimeter of an alfalfa field in the fall, immediately after all adults had returned from summer aestivation, was effective in controlling *H. postica*. In the northeastern US, the alfalfa weevil and potato leafhopper frequently occur simultaneously in late spring and early summer (Hower and Davis, 1984). Insecticides applied for leafhopper control often disrupt *M. aethiopoides*, an important parasitoid of the adult alfalfa weevil. Hower and Davis (1984) determined that the pupal stage of *M. aethiopoides* Loan was less susceptible to insecticides than the adult and developed a control strategy for leafhoppers using lower insecticide rates below those recommended by the manufacturer. These lower rates, while providing adequate leafhopper suppression, minimized *M. aethiopoides* mortality.

Cultural control

Harvesting, including grazing, has been used alone and in combination with other strategies to manage numerous arthropod pests. An earlier than usual first crop harvest was recommended as early as 1918 in Utah to reduce losses from alfalfa weevil (Hagan, 1918). Casagrande and Stehr (1973) observed 100, 73 and 53% mortality of alfalfa weevil larvae in Michigan alfalfa fields harvested prior to, at, and after the larval peak, respectively. Many larvae were killed by desiccation or starvation and the eggs, which are normally laid in the stems, were removed along with the forage. Timing is crucial however, since cutting before oviposition peaked resulted in injury to the second crop regrowth by larvae hatching from the eggs that remained in the stubble below cutter bar height. Similar results were obtained in New York (Koehler and Gyrisco, 1959) and Alberta (Harper *et al.*, 1990). Schoner and Norris (1975) noted that larvae of *H. brunneipennis*, that were not mechanically killed by harvesting, were concentrated in the swather windrow and made their way to the underside where they were protected from excessive heat and drying. Larval feeding under the windrow severely weakened the alfalfa regrowth causing injury which persisted in the form of yield losses through the fifth cutting (Schoner and Norris, 1975). Alfalfa weakened by larval feeding under the windrows also conferred a competitive advantage to summer grasses due to slower regrowth. Spraying under the windrow in advance of the alfalfa being laid on the ground (from a spray boom attached beneath the crimper) resulted in a 54% yield increase in the following cutting (Schoner and Norris, 1975). Buntin and Bouton (1996) found that the combination of an early application of an insecticide followed by continuous spring grazing provided satisfactory control of alfalfa weevil larvae.

Flaming with liquid propane has been used successfully to control *H. postica* in various parts of the US (Hanson and Simpson, 1969; Scheibner, 1969; Harris *et al.*, 1971; Hower, 1975). This tactic also has the added advantage of killing many weeds (Hanson and Simpson, 1969). Although effective, this technique was generally abandoned in the 1970s when the price of petroleum products rose beyond the cost effectiveness of the method.

An early first harvest, made at bud stage rather than the normal 10% bloom, has significantly reduced losses caused by alfalfa blotch leafminer (Spencer, 1974; Bermer, 1976; Alicandro and Peters, 1983). As with alfalfa weevil larvae, exposure to hot dry conditions significantly increases larval mortality, therefore, the hay must be removed from the field as soon as possible to eliminate shelter afforded under the windrows (Mellors and Helgensen, 1978; Alicandro and Peters, 1983; Therrien and McNeil, 1985). If alfalfa cannot be cut prior to 10% bloom, immediate removal for ensilage or greenchop rather than leaving it in the field to dry for hay, will minimize leafminer development (Alicandro and Peters, 1983).

Beet armyworm and western yellowstriped armyworm can be effectively controlled by early cutting if economic thresholds are reached late in the alfalfa growing cycle (Summers *et al.*, 1981). Harvesting results in the death of early instar larvae by heat and desiccation and triggers the emigration of late instar larvae out of the cut field. Surrounding susceptible crops such as sugarbeets, cotton, or tomatoes may require protection, to prevent the migrating larvae from damaging the adjacent crop.

Changes in harvest schedule have been used successfully in managing aphids and potato leafhopper in forage alfalfa. In Canada, Harper *et al.* (1990) recommended cutting at 10% bloom rather than waiting until 100% bloom, the conventional time to harvest, as a control for pea aphid. Immediate removal of the hay for dehydration or ensilage resulted in a more rapid rebound of pea aphid populations than when hay was field cured for baling. In Czechoslovakia, Stary (1970) noted that maximum pea aphid control was obtained when harvesting was delayed, if possible, until aphid populations were in decline. Cutting before the population peak resulted in a rapid resurgence of aphids on the regrowth. In Australia, Bishop *et al.* (1980) observed that harvesting and grazing reduced both blue alfalfa aphid and spotted alfalfa aphid numbers and damage initially, but damaging infestations were frequently found on the regrowth following forage removal. It is uneconomical to use insecticides on dry land lucerne in south Australia and so grazing is recommended for aphid control (Allen, 1978; Bishop *et al.*, 1980). Both a delayed (Garber and Sprague, 1933 and 1935; Searls 1934, 1935) and an early (Pienkowski and Medler, 1962; Summers and Newton, 1986) harvest have been recommended for control of the potato leafhopper in alfalfa. In the former circumstance, eggs are removed with the hay and high insect mortality results from exposure to hot, dry conditions. In the latter situation, the alfalfa is removed before serious injury occcurs. Cuperus *et al.* (1983) however, found that most damage occurs early in the regrowth cycle and failure to control leafhoppers at this time may lead to significant yield and quality losses. A more recent study (Hutchins and Pedigo, 1989) determined that late in the growth cycle, alfalfa can compensate for earlier leafhopper injury and hence cutting too early may negate any compensatory response that the crop might make late in the growth cycle.

Stubble height can significantly effect pest and natural enemy survival following harvest. Simonet and Pienkowski (1979) found that 7–10 days post-harvest, nymphal populations of potato leafhopper were reduced by approximately 95% in alfalfa cut with a 2 to 5 cm stubble height. In taller stubble, particularly that containing leafy material or lodged uncut stems, nymphal survival was significantly higher. Hagen *et al.* (1971) observed that pea aphids survived in the longer stubble left adjacent to irrigation levees but its parasitoid, *A. smithi* and many generalist predators did not. Alfalfa weevil eggs remaining in the stubble below cutter bar height was discussed earlier in this review as a possible reason for failure of cutting to control this pest.

Harvesting can be manipulated to markedly alter the habitat of an alfalfa field which, in turn, effects the population dynamics of the resident arthropod fauna. One of the most well known habitat modifications is strip-cutting, originally conceived as a strategy to keep *Lygus* spp. from emigrating from a cut forage field to nearby cotton (Stern *et al.*, 1964 and 1967; van den Bosch and Stern, 1969). It was soon discovered however, that under strip-cutting, more natural enemies were retained in the alfalfa field than in a solid cut field and the densities of aphids and lepidopterous larvae were significantly lower (Schlinger and Dietrick, 1960; van den Bosch *et al.*, 1964; van den Bosch and Stern, 1969). Alfalfa caterpillar control by *C. medicaginis,* is dependent on synchronization of the parasitoid population with that of the caterpillar. Such synchronization can be achieved with strip-cutting (Schlinger and Dietrick, 1960; van den Bosch and Stern, 1969). Schlinger and Dietrick (1960) found that larvae of the western yellowstriped armyworm and beet army worm failed to reach maturity in strip-cut fields and did not cause economic damage. In solid cut fields however, insecticides were often required to control these pests (Schlinger and Dietrick, 1960). Summers (1976) proposed a modification to strip-cutting (border cutting) in which alfalfa on every other irrigation levee (or border, hence the name) is removed at alternate cuttings. This strategy is not dependent on the existence of irrigation levees and simply leaving alternating strips of uncut alfalfa accross the field works equally well. Border cut fields retained almost three times the number of generalist predators and parasitoids as did solid-cut fields and had significantly lower pea aphid populations (Summers, 1976). In southern Alberta, Harper *et al.* (1990) found that several pest species, particularly alfalfa weevil and pea aphid, rebounded more quickly in fields where alfalfa was removed immediately for dehydration than in fields where hay was cured for baling.

A summary of strategies employed for the management of insect pests is presented in Table 3.

OTHER INVERTEBRATES

Several species of non-insect invertebrates may occasionally damage alfalfa. Slugs can cause considerable injury to seedling stands, particularly in conservation tillage systems (Gregory and Musick, 1976; Grant *et al.*, 1982). Some control of slugs has been obtained using a broadcast application of ammonium sulfate, but this material must come in contact with the slugs in order to be effective (Long, 1997). Sowbugs, *Porcellio* spp., and pillbugs, *Armadillidum* spp. also occasionally injure seedling fields. Their incidence can be significantly reduced or eliminated by thorough incorporation of all organic trash and plant residue from any previous crop before planting alfalfa (Summers and Godfrey, 1997). Insecticidal baits are also effective in controlling these pests (Long, 1997; Summers and Godfrey, 1997). While most prevalent in the seed crop, populations of spider mites, *Tetranychus* spp., may occasionally build up to levels capable of causing damage in alfalfa hay. This condition generally occurs during periods of plant water stress and can usually be alleviated by an irrigation (Summers and Godfrey, 1997). If irrigation is not an option and injury is severe, sulfur may be used to suppress the mite population (Summers and Godfrey, 1997).

VERTEBRATES

General considerations

Vertebrates damage alfalfa by direct feeding and, in the case of gophers and ground squirrels, an elaborate system

Table 3. Summary of strategies for the management of major insect pests of forage alfalfa[a]

Pest[b]	Cultivar resistance	Biological control	Cultural control	Chemical control[c]
Aphids	Yes	Predators, parasites, fungus	Early cut, delayed cut, grazing, strip & border cutting	Selective chemicals, reduced rates
Weevils				
AW	Limited	Parasites, fungus	Early cut, green chop, flaming, weed control, grazing	Perimeter spray
EAW	No	No	Early cut, weed control	Winter spray, spray under windrow
CRC	No	No	None	None
Lepidoptera	No	Parasites, bacteria, viruses	Early cut, strip cutting	B.t.s.
ABL	No	Parasites	Early cut	
PLH	No	No	Early cut, late cut, clean cut & short stubble, oat intercrop	Reduced rates to protect AW parasites

[a]This table is only a summary overview. See text for full explanation of strategies and their proper application. Some strategies may appear to be in conflict, e.g. both early and late cutting listed for the same pest(s). both have been shown to work and the choice depends on other factors occurring at the time. See text for full explanation.
[b]See text for scientific names. AW, alfalfa weevil; EAW, Egyptian alfalfa weevil; CRC, clover root curculio; ABL, alfalfa blotch leafminer; PLH, potato leaf hopper.
[c]Only chemical alternatives of the special use of insecticides are listed. Unless otherwise noted, chemical pesticides are readily available for control of the listed pest.

of underground burrows can seriously impact irrigation, disrupt harvesting, and lead to equipment damage (Orloff *et al.*, 1995). As with any other pests, proper identification is essential in devising an effective management strategy. For example, in California two species of ground squirrels, the California ground squirrel, *Spermophilus beecheyi*, and the Belding ground squirrel, *S. beldingi*, are injurious to alfalfa. The former species prefers to live on field edges, along fence rows and roadsides, and damage occurs mainly on field perimeters. The latter species however, rapidly invades and colonizes alfalfa fields, creating extensive burrow systems within fields, and consuming large quantities of plant material (Orloff *et al.*, 1995; Whisson, 1997). A knowledge of animal behaviour is especially important in vertebrate pest management. Some vertebrates are active only at night and their identity must be determined by footprints, scat, the presence of burrows or mounds, or the type of damage. Feeding habits and food preferences may change depending on the time of year and thus certain baits may be totally ineffective if used during the wrong season.

Many vertebrates, e.g. deer, *Odocoileus* spp.; migrating waterfowl; and rabbits, *Sylvilagus* spp., and hares, *Lepus* spp., are classified as game animals in some locations and methods used in their control are strictly regulated by State and Federal fish and game laws. When dealing with game animals, local authorities should be consulted before any contol measures are taken. The presence of any organism on the endangered species list may dramatically affect the type and method of control measures that can legally be used. Current regulations also dictate the means and frequency of carcass removal and disposal, particularly if poison baits are used, to minimize the dangers to non-target species.

While the majority of vertebrate pests of alfalfa are mammals, birds can occasionally effect major damage. Canada geese, *Branta canadensis*, may cause severe defoliation of established or seedling stands, particularly during the winter. Starlings, *Sturnus vulgaris* L., and blackbirds, *Agelaius* spp., occasionally injure seedling stands. Most techniques used for vertebrate control such as trapping, baiting, and burrow fumigation are labour intensive and although no thereshold levels have been established for vertebrate pests, control measures should generally be initiated before pest populations become extensive (Marsh, 1991).

Mechanical and physical control

Wire fences can be used to exclude deer, but they are expensive and not always effective (Whisson, 1997). Fences should be at least 2–2.5 meters high to prevent the animals from jumping over them. Wire or plastic mesh fences, ca. 1 meter high, can also be used to exclude rabbits and hares although they are generally effective only in cases of repeated, severe damage (Marsh, 1991). Care must be taken to secure the fence at the soil line or the animals will readily crawl underneath. Fencing around new alfalfa fields may also serve to reduce invasion by Belding ground squirrels (Whisson, 1997). Wire mesh, buried to 1 meter deep in the soil, has been shown to successfully exclude gophers from alfalfa but this approach is also very expensive (Tickes, 1989).

Trapping can be used to remove pocket gophers, *Thomomys* spp., and ground squirrels from alfalfa fields. Trapping is most effective during early invasion periods when populations are relatively low. As the number of individuals increase, the cost of trapping, both in terms of the number of traps required and the amount of time necessary to maintain the traps, increases dramatically and ultimately, trapping becomes not cost effective. To minimize exposure to non-target species, traps should be placed only in active burrows (USEPA, 1996). Baiting with walnuts, almonds, oats, barley, or melon rinds may increase the effectiveness of traps for ground squirrel control. Such baiting should be with non-poison baits only. (The use and limitations of poison baits is discussed under the section on chemical control). It is recommended that traps be baited, but not set, for the first few days to accustom the squirrels to feeding at the bait stations. Shooting ground squirrels can be used to augment a trapping program and may be helpful in limited situations. It is most effective when combined with other control measures and should be conducted in a systematic fashion, i.e. in 1 to 2 hectare grids. Rabbits and hares may also be shot during hunting season and at other times during the year provided that local game statutes are observed. Depredation permits to shoot deer out of season may be issued by game authorities although shooting is unlikely to solve the problem.

Lights, 'scarecrows', and noise making devices sometimes discourage deer and birds but the results have generally been erratic and their long term effectiveness is questionable.

Biological control

Owls, hawks, foxes, and coyotes prey on many vertebrate pests found in alfalfa fields. Some growers place nesting boxes and perches around alfalfa fields to encourage habitation by various raptors. While thse predators remove a portion of the vertebrate pest population, they fail to provide adequate economic control in most situations, particularly when pest densities are high (Whisson, 1997).

Myxoma virus was introduced into Australia in the 1950s for rabbit control (Fenner and Ratcliffe, 1965), and while rabbits have developed some resistance to the virus it still exerts a strong controlling influence on rabbits in mesic regions (Williams, 1996). In October 1995, rabbit calicivirus was introduced into Australia and has caused very high mortality of rabbits in some parts of the arid and semi-arid interior although its long-term impact remains to be determined (Williams, 1996).

Chemical control

Gophers, ground squirrels, and meadow mice, *Microtus* spp., can all be effectively controlled by the use of poison and/or anticoagulant baits. In many locations where endangered species are known to occur, poison grain can no longer be broadcast on the ground and must be confined to bait stations or placed in burrows. Even the design of bait stations must be such that the poison bait is inaccessible to non-target organisms, especially those on the endangered species list. Poison grain and/or anticoagulant baits can be placed in gopher burrows using hand-baiting and the one-time use of a mechanical bait applicator can control gophers over large areas (Orloff *et al.*, 1995). Tickes (1989) however, found that many baits are ineffective in controlling gophers due to poor bait acceptance. He found that as long as alfalfa is available, gophers prefer that over all grain baits evaluated. Baits to control ground squirrels must be placed in a bait station which has been designed to prevent entry by non-target organisms. Baits are generally effective only in the late spring or fall when seeds are the preferred food of the ground squirrel (Whisson, 1997). Anticoagulant baits can also be used for rabbit and hare control and pre-baiting with non-treated bait is usually necessary (Whisson, 1997).

Fumigation is frequently used for ground squirrel control. Fumigation is most effective when the animals are active as hibernating individuals plug their burrows behind them and are not exposed to the introduced fumigants. Fumigation is most effective under conditions of high soil moisture (Marsh, 1991; Orloff *et al.*, 1995 Whisson, 1997).

Perimeter repellents are sometimes used for deer control, but they appear to have only limited effectiveness.

Cultural control

Deep tillage can be used to disrupt or destroy ground squirrel burrows prior to planting alfalfa and when combined with other control measures may delay squirrel colonization. Flood irigation, while not eliminating pocket gophers, can significantly decrease their numbers and may reduce the potential for large populations to rebuild (Whisson, 1997). Loeb (1990) however, reported that irrigation in alfalfa can increase pocket gopher fecundity by extending the breeding season and increasing litter frequency and size. Rotating alfalfa with cereal crops greatly reduces the gopher problem when alfalfa is replanted (Marsh, 1991; Whisson, 1997). Case (1989) recommends planting alfalfa cultivars with a fibrous root system rather than a main tap root and argues that the former plant type can sustain higher levels of gopher feeding without being killed. Controlling weeds and cultivating along fence rows, roadsides, and ditch banks adjacent to alfalfa fields can help reduce meadow mouse populations by reducing the number of invading individuals. Reducing the amount of vegetative cover by either mowing or grazing, especially during the winter months, will also aid in reducing meadow mouse populations. Management strategies for the major vertebrate pests of alfalfa are summarized in Table 4.

Table 4. Summary of strategies for the management of major vertebrate pests of forage alfalfa[a]

Pest	Mechanical control	Chemical control	Cultural control
Deer	Fencing, Repellent, Frightening	No	No
Gophers	Trapping	Baits, Fumigation	Rotation, Irrigation
Ground squirrels	Shooting	Baits, Fumigation	Deep tillage
Rabbits & Hares	Fencing, Shooting	Baits	No
Mice or Voles	None	Baits	Vegetative cover control

[a]This table is only a summary overview. See text for full explanation of strategies and their proper application.

WEEDS

General considerations

Weeds differ from other alfalfa pests in that they are primary producers rather than consumers (Norris, 1982; Peters and Linscott, 1988). As such, they compete directly with the alfalfa for sunlight, soil nutrients, and water. In addition to causing yield losses, they contribute to indirect losses in a variety of ways. Weeds lower the quality of alfalfa since most are considerably lower in total digestible nutrients and protein than is alfalfa (Cords, 1973; Norris and Schoner, 1975; Temme *et al.*, 1979). Weeds such as curly dock, *Rumex crispus* L., and horseweed, *Conyza canadensis* (L.) Cronq. have coarse stems that livestock reject (Peters and Linscott, 1988). Fiddleneck, *Amsinkia intermedia* (Fischer & C. Meyer) Ganders, and common groundsel, *Senecio vulgaris* L., are poisonous to livestock and their presence results in the hay being severely discounted in price, or totally unmarketable (Summers *et al.*, 1981; Molyneus and Ralphs, 1992). When eaten, awns of some grass species such as foxtail barley, *Hordeum jabatum* L., and weedy bromegrasses, *Bromus* spp., may injure the mouths of animals (Fleming and Peterson, 1919; Muenscher, 1949). Bristles on the inflorescence of yellow foxtail, *Setaria glauca* (L.) Beauv., causes severe ulceration in the mouths of livestock and the pain freqeuntly prevents them from eating (R. Norris, personal communication). Heavy infestations of annual bluegrass, *Poa annua* L., clog the cutter bar and may make cutting impossible (Summers *et al.*, 1981). It is often difficult to establish alfalfa on land that has been infested with quackgrass, *Agropyron repens* (L.) Beauv., due to the production of toxins or growth inhibiting (allopathic) substances (Kommedahl *et al.*, 1959) by this grass.

Chemical control

Weeds are most successfully managed using a combination of cultural strategies and herbicides. Effective weed control should begin in the crops preceeding alfalfa to prevent a large weed seed band from building up in the soil. Crop rotation schedules can also be used to help reduce weed populations in seedling alfalfa. Some weeds are more easily controlled in other crops than they are in alfalfa, e.g. relatively inexpensive phenoxy herbicides will control most broadleaf weeds in small grains thus reducing weed infestations in alfalfa stands that follow (Schmierer and Orloff, 1995).

Two very important aspects of weed management are proper identification and good records of the pests present, including their general abundance. Herbicides do not affect all weed species equally. Failure to properly identify the offending species may result in unsatisfactory control. Knowledge of the weed species commonly found on specific properties aids in the selection of the correct herbicide, particularly pre-emergence materials, and the appropriate application rate.

Stand establishment is a critical period since alfalfa seedlings grow relatively slowly and early weed invasions may result in complete stand failures (Peters and Linscott, 1988). It is important to select an appropriately adapted cultivar for the area and to plant weed-free, certified seed (Peters and Linscott, 1988; Schmierer and Orloff, 1995). The seed bed should be carefully prepared and existing weeds controlled by tillage and/or herbicides. Adequate soil fertility is important in promoting alfalfa seedling vigor (Peters and Linscott, 1988). Time of planting is also critical to good weed management in seedling stands. Planting time is dependent on location and weed populations but, in general, fall seedings are preferred in southern areas and spring seedings in northern regions (Peters and Linscott, 1988). Pre-emergence herbicides can be applied and incorporated prior to planting, particularly if alfalfa is to established as a pure stand. Post-emergence herbicides are available for use following germination if weeds become a problem at that time. Particular caution must be exercised in using post-emergence materials, particularly those used to control broadleaf species. Most herbicide labels recommend that alfalfa be beyond a certain growth stage, which may vary between herbicides, before the material is used. If applied to alfalfa that is too young, severe injury can occur. The growth stage of the target weed species is also important since young weeds are generally more susceptible to herbicides than are older weeds. Late application, relative to the growth stage of the target weed(s), is the most common reason for post-emergence herbicide failure (Schmierer and Orloff, 1995). Additional considerations for effective control include: application rate, temperature, percentage of organic matter in the soil, soil texture, and the amount of rainfall or irrigation water applied. As with all pesticides, the most prudent course is to read and follow the label directions.

Weed control in established stands is no less important than in seedling stands. The best management strategy is to keep the alfalfa healthy and maintain a dense, vigorously growing stand. Shading from a dense canopy prevents weed seedlings from becoming established (Crafts and Robbins, 1962; Dawson, 1966a). Alfalfa plants weakened by disease, insects, or the action of harvesting machinery may be unable to out-compete weeds for nutrients, water, and light (Sheesley *et al.*, 1974; Summers and Newton, 1989; Summers and Gilchrist, 1991).

Weed management in established stands begins with effective weed control during stand establishment. Practices that remove perennial and biennial weeds from seedling alfalfa will prevent these plants from becoming established in mature stands (Peters and Linscott, 1988). Winter and summer annual weeds invading established stands can be controlled by a variety of herbicides. These include both pre- and post-emergence materials. As with the use of herbicides on seedling stands, proper weed identification, the timing of application relative to weed growth stage, and the application rate are essential to maximizing weed control and minimizing injury to the alfalfa. A number of new selective post-emergence grass killing herbicides have recently been registered for use on alfalfa. These materials do an excellent job of reducing or eliminating perennial and annual grasses in alfalfa without injury to the alfalfa itself (Ahrens and Harvey, 1983).

As noted earlier, alfalfa is susceptible to herbicide injury if applications are made at the wrong growth stage or at excessively high rates. Efforts are underway to develop alfalfa cultivars which contain high degrees of resistance or tolerance to herbicides (D'Halluin *et al.*, 1990). Germplasm with resistance to terbacil, a broad spectrum herbicide with activity on many weeds and grasses, is currently available (Caddel *et al.*, 1992).

Cultural control

Cutting interval and irrigation timing have been used to successfully manage weeds in established stands. In general, the best control of weeds by harvesting results when harvesting disrupts seed production of annuals or the regrowth potential of perennials (Leath *et al*, in press). Dallisgrass, *Paspalum dilatatum* Pior, barnyardgrass, *Echinochloa crus-galli* (L.) Beauv., and windmillgrass, *Chloris truncata* R. Br., invaded alfalfa in Australia more rapidly at 25 to 28 day cutting intervals than at 35 to 48 day intervals (Lodge, 1986). Norris and Ayres (1991) found in Calfornia that yellow foxtail could be effectively controlled by increasing the harvest interval from 25 to 31 or 37 days and delaying irrigation by 7 to 14 day after cutting. Reduced alfalfa quality compromised the economic return for hay cut on a 37 day schedule, however. Perennial weeds such as Canada thistle, *Cirsium arvense* (L.) Scop., johnsongrass, *Sorghum halepense* (L.) Pers., and field bindweed, *Convolvulus arvensis* L., can be controlled by harvesting at a time that disrupts their regrowth potential (Leath *et a.*, in press). Grazing by sheep can also be effective in reducing weeds (Bell and Guerrero, 1992).

While dodder, *Cuscuta* spp., is usually more important in the seed alfalfa crop, it can cause significant losses in forage alfalfa as well (Cudney *et al.*, 1992). Prevention is the best control and only alfalfa seed certified to be dodder free should be planted (Erwin *et al.*, 1990). In alfalfa grown for forage, the negative impact of dodder can be reduced by an early cutting (Cudney *et al.*, 1992; Peters and Linscott, 1988). Cudney *et al.* (1992) also recommended burning infested areas with a propane burner at the end of each season to prevent the development of seed since it may remain viable for as long as 10 to 20 years (Hutchison and Ashton, 1979; Erwin *et al.*, 1990). A combination of pre- and post-emergence herbicides may also be used to reduce the incidence of dodder (Dawson, 1989; Cudney *et al.*, 1992). In alfalfa seed fields, dodder control less than 100% is unsatisfactory (Dawson, 1966b) since dodder seed is similar in size to alfalfa seed and is difficult and expensive to remove (Rincker *et al.*, 1988).

Alfalfa stands may also be established with a companion crop, formerly called a nurse crop. The companion crop is usually a small grain such as oats (*Avena sativa* L.). The use of a companion crop essentially substitutes a less competitive (relative to competition with alfalfa) plant population (oats) for a more competitive plant population (weeds) (Peters and Linscott, 1988; Schmierer and Orloff, 1995; Schmierer *et al.*, 1995). Lanini *et al.* (1991) reported a reduction of 30 to 50% in the weed biomass of second year alfalfa that had been established with an oat companion crop as compared to alfalfa established as a pure stand. Companion crops offer other benefits such as adding stability where blowing soil is a problem, the breaking of crusting soil, and the return of forage, grain, and straw while the alfalfa is becoming established (Peters and Linscott, 1988; Lanini *et al.*, 1991; Schmierer *et al.*, 1995). Prather *et al.* (1993) found that companion crops in aging alfalfa stands also suppressed weeds and increased total herbage yields. The use of companion crops is not without risk, however. The short-term benefits of stand establishment with a companion crop can be nullified if the alfalfa stand and vigor suffer from excessive competition (Schmierer *et al.*, 1995). The use of a companion crop such as oats requires a different herbicide strategy, one that avoids herbicides active on grasses, contrasted to that employed in establishing pure alfalfa stands. Alfalfa may also be established by no tillage or limited tillage. This approach also requires a modification of the herbicide programme from that used in conventional establishment.

Multiple pest interactions

Clearly, an alfalfa field is a dynamic ecosystem in which a multitude of interactions occur. In general, most pest management strategies are devised for a single pest and often fail to take into account these interactions. A notable exception is the development and release of multiple pest resistance in alfalfa cultivars, many of which contain effective levels of resistance to insects, plant pathogens, and nematodes (Sorensen *et al.*, 1983; Sorensen *et al.*, 1986b; Sorensen *et al.*, 1989a and b; Sorensen *et al.*, 1992). It is important that in addition to quantifying the injury and losses attributable to individual pest stress, that losses due to pest interactions also be quantified. Tactics must be developed which optimize the management of all interacting pests and that do not exchange one set of problems for another. Only then can truly integrated pest management strategies be developed which maximize returns for both producer and consumer.

Pest interactions may significantly alter economic threshold levels or result in a synergistic or additive effect of the various species involved. Wilson *et al.* (1979) studied the full season impact of alfalfa weevil, meadow spittlebug, and potato leafhopper in alfalfa. Alfalfa growth, yield, and rate of maturity were decreased in all cuttings following infestation of the first cutting by the alfalfa weevil and meadow spittlebug. Potato leafhopper infestations reduced yield in the third cutting with a carryover effect into the fourth harvest. Generally, the effects of the three pests were additive. In a three year study, Summers (1989) found that injury caused by Egyptian alfalfa weevil feeding before the first cutting affected yields for an additional two to three cuttings. There was also a significant interaction between Egyptian alfalfa weevil and pea aphid and blue alfalfa aphid damage that influenced yields for one to two cuttings after that in which the injury occurred. Neither Wilson *et al.* (1979) nor Summers (1989) found any of the insects in their respective studies to contribute to a reduction in stand density. Summers and Gilchrist (1991) found total forage yield over a five year period was reduced 18 and 22% by insects and diseases respectively, while the combined effect of these pests reduced yield by 36%. The stress of insects and diseases shortened productive stand life by one and two years respectively, compared to plots maintained insect and disease free (Summers and Gilchrist, 1991).

Feeding by alfalfa weevil and Egyptian alfalfa weevil larvae resulted in significantly lower forage production and increased weed invasion in Oklahoma (AW) (Dowdy *et al.*, 1993), California (EAW) (Summers and Newton, 1989), and Kentucky (AW) (Godfrey and Yeargan, 1987). Norris and Schoner (1975) and Schoner and Norris (1975) found that controlling the Egyptian alfalfa weevil in California resulted in a decrease in the growth of yellow foxtail later in the season. In California, Norris *et al.* (1984) showed that damage caused to first cutting alfalfa by Egyptian alfalfa weevil larvae was greater in the presence of high populations of winter annual weeds, albeit at lower weevil densities, than in weed free alfalfa. They suggested that economic threshold levels for weevil larvae should be adjusted to reflect weed densities. A similar interaction was observed by Berberet *et al.* (1987) with the alfalfa weevil and weedy alfalfa in Oklahoma. In an economic analysis of alfalfa integrated pest management practices, Ward *et al.* (1990) concluded that alfalfa production was optimized by planting insect and disease resistant cultivars, winter grazing of fall alfalfa growth, and the combined use of insecticides and herbicides. They found that insect control alone increased returns more than did weed control alone. Buntin and Pedigo (1986) found that weed density, biomass, and percentage by weight at harvest, increased linearly with increasing stubble defoliation by the variegated cutworm, *Peridroma saucia* (Hübner). Peterson *et al.* (1995) have determined injury equivalents (injury by one species in terms of another species) for the interactions of adult clover leaf weevil, *H. punctata* (F.), larval variegated cutworm, and larval and adult alfalfa weevils (*H. postica*).

Godfrey and Yeargan (1987 and 1989) found a significant interaction between alfalfa weevil, clover root curculio, and a complex of soil-borne fungi in reducing alfalfa yield and stand density. Clover root curculio has been implicated in increasing the incidence of bacterial wilt (Hill *et al.*, 1971) and *Fusarium* wilt (Hill *et al.*, 1969; Leath and Hower, 1993). Root-knot nematodes (McGuire *et al.*, 1958) and stem nematode (Griffin, 1990 and Griffin, 1992) are also known to increase the severity of injury caused by *Fusarium* wilt.

Lamp *et al.* (1984), and Oloumi-Sadeghi *et al.* (1989) found that the population density of potato leafhopper was reduced, and damage to alfalfa lessened, when grass weeds were present. Oloumi-Sadeghi *et al.* (1989) suggested that leafhopper control in alfalfa was more important than grass weed control during the summer. Lamp (1991) suggested that an oat-alfalfa inter-crop during the establishment year may reduce the need for responsive tactics for leafhopper management on spring-planted alfalfa when compared to alfalfa establishment as a pure stand.

Pest interactions can also influence the degree of resistance exhibited by alfalfa cultivars. Northern and southern root-knot nematodes have been found to reduce the level of resistance to *P. megasperma* in several cultivars (Welty *et al.*, 1980). The incidence and severity of bacterial wilt has been shown to be increased by northern root-knot nematode in both a wilt resistant and susceptible variety (Norton, 1969; Hunt *et al.*, 1971; Erwin 1990b) and the stem nematode is known to decrease the level of resistance to bacterial wilt (Hawn and Hanna, 1966). Bacterial wilt can also be transmitted by stem nematode (Hawn, 1963).

Strategies designed to manage one pest may exacerbate others. In California, *Empoasca* leafhoppers, alfalfa caterpillar, armyworms, and yellow foxtail frequently occur simultaneously from July through Septembr. While early harvest is recommended for control of the insect pest (Summers *et al.*, 1981), this strategy may increase the incidence and severity of yellow foxtail (Norris and Ayres, 1991). Grazing can be effective for the control of certain weeds but, it can also increase the rate of spread and the incidence of disease within a field (Leath *et al.*, in press) and the movement of livestock between fields can spread nematodes, weeds, and pathogens. As noted previously, *Z. phytonomi* and *B. anurus* frequently interact to control populations of alfalfa weevil larvae. *Zoophthora phytonomi* may occasionally cause high mortality of *B. anurus* in Kentucky although the two have coexisted there for over 10 years with no apparent long-term reduction of *B. anurus* populations (Parr *et al.*, 1993). As noted earlier, spraying for potato leafhopper control may adversely affect biological control of the alfalfa weevil unless insecticide dosage rates are properly adjusted to minimize injury to the parasitoids (Hower and Davis, 1984).

Table 5 provides an overview of the integration of

Table 5. Cross reference of strategies used to manage the major pests associated with forage alfalfa and to reduce their impact on yield and quality[a]

	Pests[b] partially or completely managed by selected strategy			
Strategy	Nematode	Disease	Insect	Weed
Host resistance	SN, NRKN, SRKN	BW, VW, FW, An, PRR, APH, DM, R	PA, SAA, BAA, AW	–
Early cutting	–	CLS, SLS, DM, R, SCSR, LLS, SSBS	PA, SAA, BAA, AW, EAW, BAW, WYSA, ABL, PLH, AC	D
Delayed cuttting	–	–	PA, PLH	YFT, BG, DG
Cutting schedule	SN	An, BW, VW	–	–
Stubble height	–	SCSR	PA, PLH	–
Strip cutting	–	–	SAA, PA, BAA, AC, WYSA, BAW	–
Border cutting	–	–	PA, SAA, BAA	–
Green chopping	–	CLS, SLS, DM, R, SCSR, LLS, SSBS	AW	–
Grazing	–	–	AW, BAA	Many
Irrigation	SN	PRR, FW, FRR, APH, CW, S	–	YFT
Intercropping	–	–	PLH	Many
Crop rotation	RLN	VW, SCSR	–	N
Sanitation	SN, NRKN, SRKN	SCR, VW	–	D
Clean seed	–	VW, SCSR	–	D
Predators	–	–	PA, SAA, BAA, WYSA, BAW	–
Parasites	–	–	PA, SAA, BAA, AC, WYSA, BAW, ABL, AW	–
Disease	–	–	PA, SAA, BAA, AW, AC, BAW, WYSA	–
Flaming	–	–	AW	D
Weed control	–	–	AW, EAW	–
Pesticides				
Conventional	–	DO	Most	Most
Biorational	–	–	AC, WYSA, BAW	–

[a]This table is only a summary overview. See text for full explanation of strategies and their proper application. Some strategies may appear to be in conflict, e.g. both early and late cutting listed for the same pest(s). Both have been shown to work and the choice depends on other factors occurring at the time. See text for full explanation.

[b]See text for scientific names and causal organisms. SN, stem nematode; NRKN, northern root-knot nematode; SRKN, southern root-knot nematode; RLN, root-lesion nematode; BW, Bacterial wilt; VW, Verticillium wilt; FW, Fusarium wilt; PRR, Phytophthora root rot; CW, crown wart; FRR, Fusarium root rot; APH, Aphanomyces root rot; DO, damping off caused primarily by *Phytophthora* spp. and *Pythium* spp.; SCSR, Sclerotinia crown and stem rot; CLS, common leafspot; SLS, Stemphyllium leafspot; DM, downy mildew; SSBS, spring and summer blackstem; LLS, Lepto leafspot; S, scald; SCR, Stagonospora crown rot, AW, alfalfa weevil; EAW, Egyptian alfalfa weevil; CRC, ABL, alfalfa blotch leafminer; PLH, potato leaf hopper; YFT, yellow foxtail; D, dodder; BG, barnyard grass; DG, dallisgrass; N, nutsedge.

strategies available for the management of nematodes, diseases, insects, and weeds. The table is cross-indexed in such a manner that each major pest managed by a given strategy is listed adjacent to that strategy.

Systems analysis and computer models

Getz and Gutierrez (1982) defined systems analysis as the 'application of those techniques (both qualitative and quantitative) that enhance our understanding of the interactions between components of the crop-pest system and their relationship to the environment ... and management practices.' They further suggested that current research on the application of systems analysis to problems in agricultrual pest management fall into three basic modelling approaches: (a) the simulation approach—used to explore the structure and functioning of the system; (b) the analytical approach—used to develop qualitative principles in ecology and resource management theories; (c) the operations research approach—designed to address specific management problems. In recent years, a number of computer models of all three types have been developed to describe the alfalfa production system and several of its components, most notably insects and their natural enemies.

The first alfalfa models available for pest management applications were those linking Egyptian alfalfa weevil (Gutierrez *et al.*, 1976) and the alfalfa weevil (Fick, 1975; Ruesink, 1976) to alfalfa growth and development. These early models proved highly successful in predicting field events and more importantly, they provided a means of evaluating alternative management strategies for weevil control. This modelling effort was intensified under the Consortium for Integrated Pest Management Project (CIPM) from 1979 to 1985 (Frisbie and Adkisson, 1986). These efforts resulted in more robust models and an expansion of the modelling effort to improve the alfalfa production model (Fick, 1981; Denison and Loomis, 1989). In addition, nearly a dozen additional pest species and numerous natural enemies, together with their interactions were added to the system (Brown and Fick, 1986). Shoemaker and Onstad (1983) developed a stochastic dynamic programming model for optimization of alfalfa weevil control which integrated biological control, cultural control through early harvest, and chemical control tactics. The completion of a model describing the dynamics of *E. neoaphidis* epizootics (Brown and Norden, 1982; Brown, 1984) resulted in a significant revision of the alfalfa weevil control recommendations in the northeastern US (Brown and Fick, 1986).

Gutierrez and Baumgaertner (1984) developed a multitrophic model to examine the theoretical properties of alfalfa, pea aphid, blue alfalfa aphid, the parasitoid *A. smithi*, and two predators, *Hippodemia convergens* Guérin-Méneville and *C. carnea* Stephens. Using this model, Gutierrez *et al.* (1984a) simulated the observed year-long dynamics of these pest and natural enemy species in the field using observed initial numbers and observed weather patterns and found the model results compared favourably with actual field counts. Caution is advised however, against extrapolating theoretical results to the field where subtle behaviour differences may sometimes yield results contrary to model predictions (Gutierrez *et al.*, 1984b). These models have proven to be extremely valuable however, in examining the complex interactions occurring across multiple trophic levels.

Onstad *et al.* (1984) devised a model for potato leafhopper which coupled an alfalfa growth model, a population dynamics model of *E. fabae*, and an economic analysis of crop loss and management action. This model was used to determine the dynamic economic thresholds for controlling leafhoppers as immigrants into each cutting of alfalfa throughout the season. Flinn *et al.* (1986) improved on the *E. fabae* dynamics model by adding information on the age structure of the immigrant potato leafhoppers and the survivorship of leafhopper eggs and nymphs under field conditions. Both models (Onstad *et al.*, 1984; Flinn *et al.*, 1986) support the tactic of early harvest for leafhopper control.

Sawyer and Fick (1987) modified a physiological model of alfalfa growth, ALSIM (Level 2) (Fick, 1981) to incorporate eight hypothesized mechanisms of injury by alfalfa blotch leafminer.

In addition to these ecological models, economic models which link herbivore damage, control costs and strategies, and other on farm considerations to the economics of production and usage, are also available (McGukin, 1983; Regev *et al.*, 1976; Onstad and Shoemaker, 1984; Onstad *et al.*, 1984).

Modeling of other alfalfa pests has lagged far behind that for insects. The reasons for this are unclear. Extensive modeling of disease processes and epidemics in many other cropping systems has been ongoing for a number of years.

Alfalfa in the agricultural landscape

A review of alfalfa pest management would be incomplete without a brief discussion of alfalfa's role in the agricultural landscape. As noted in the introduction, alfalfa ecosystem is a complex environment and the home of an amazingly large number of organisms, most of which cause little or no damage. The late, eminent biological control authority Dr. Robert van den Bosch of The University of California at Berkeley frequently referred to the alfalfa field as 'a field insectary' which, except during times of perturbations, continuously produces large numbers of generalist predators and parasitoids. This was clearly demonstrated in California during the height of the chemical campaign against the spotted alfalfa aphid in the mid-1950s which eliminated vast numbers of natural enemies from the alfalfa ecosystem.

Unprecedented numbers of leafminers, *Liriomyza* spp.; spider mites, *Tetranychus* spp.; pea aphid, *A. pisum*; beet armyworm, *S. exigua*; and the omnivorous leafroller, *Platynota sultana* Walsingham, were observed in alfalfa during that period (van den Bosch and Stern, 1962). *Platynota sultana* moved from alfalfa to cotton where, for the first time, it caused serious damage to that crop in southern California (Atkins *et al.*, 1957a and 1957b). Natural enemy species which develop in alfalfa not only reduce pest populations within that ecosystem, but emigrate to surrounding agroecosystems where they help to regulate numerous pests (Toscano, 1976; Knipling, 1979; Flint and Roberts, 1988). Perhaps the most well documented of these relationships is between alfalfa and cotton. The role of alfalfa as a source of lygus bugs for adjacent cotton and the use strip cutting to manage lygus was discussed previously. Stern (1969) and Godfrey and Leigh (1994) noted that adults of several natural enemy species migrate from alfalfa to the adjacent cotton (in alfalfa-cotton interplanted fields) where they attack eggs and small larvae of bollworm, *Helicoverpa zea* (Boddie), cabbage looper, *Trichoplusia ni* (Hübner), and beet armyworm, *S. exigua*. DeLoach (1970) found populations of *Orius insidiosus* (Say), *H. convergens*, and *Coleomegilla maculata* (DeGeer), were more abundant in cotton interplanted with alfalfa, corn, *Zea mays* L., and oats, than in solid planted cotton. Corbett *et al.* (1991) suggested the interplanting of alfalfa into cotton as a source of *Metaseiulus occidentalis* (Nesbitt) for controlling spider mites in the cotton. In Australia, alfalfa strips are interplanted into cotton and beneficial insects are then encouraged to move from the alfalfa into the cotton with the strategic use of food sprays (Mensah, 1996).

Schaber *et al.* (1990) found that the minute pirate bug, *Orius tristicolor* white, and the damsel bug, *N. alternatus*, readily moved from harvested alfalfa forage fields into adjacent alfalfa seed fields. Unfortunately, several pest species, including *Lygus* spp., the alfalfa plant bug, *Adelphocoris lineolatus* (Goeze) and the pea aphid, *A. pisum*, also moved from the forage to the seed fields.

Groden *et al.* (1990) provided some evidence that the ladybird beetle, *Coleomegilla maculata* DeGeer, a predator of Colorado potato beetle, *Leptinotarsa decemlineata* (Say), larvae can build up in alfalfa during the early spring and subsequently move into potatoes, *Solanum tuberosum* L., when the alfalfa is cut. Lentz and Pedigo (1975) observed a mid-season increase in parasitism of the green cloverworm in soybeans, *Glycine max* (L.) Merrill, by several species of parasites and noted that this increase may have been due in part to a shift of adult parasites from cut alfalfa into soybeans where the green cloverworm was generally more abundant.

Alfalfa can be planted in rotation with cotton to reduce the levels of the cotton nematode, *M. incognita* (University of California, 1984). In a one year rotational trial, cotton planted after alfalfa had a *M. incognita* population 61% below that of cotton following cotton and yielded 45% more lint (P. B. Goodell, personal communication). Keeping alfalfa stands for 2–3 years generally reduces nematode populations to sufficiently low levels to permit growing cotton for one season without the need for soil treatment. Chen *et al.* (1995) found that two years of an alfalfa rotation, followed by planting potatoes, resulted in lower *P. penetrans* population densities and significantly higher tuber yields in the potato crop planted in the third year than in plots continuously cropped to potatoes for three years. In California, population levels of the sugar-beet cyst nematode, *Heterodera schachtii* Schmidt, can be significantly reduced by growing alfalfa for 3–4 years between beet crops (Kodira and Westerdahl, 1996).

Weed populations can also be reduced by rotation with alfalfa. Keeley *et al.* (1979) found that two years of cropping with alfalfa, which received a single yearly application of EPTC in the irrigation water, reduced the number of viable yellow nutsedge, *Cyperus esculentus* L., tubers by 96%.

Alfalfa dwarf is a disease caused by a gram-negative fasitidious, xylem-limited bacterium, *Xyella fastidosa* Wells *et al.*, (Davis *et al*,, 1978; Leath *et al.*, 1988; Goodwin and Purcell, 1992). This same organism also causes almond leaf scorch disease, leaf scorch diseases in several landscape trees (Schrald and Lei, 1991), and Pierce's disease, a lethal disorder of grape, *Vitis vinifera* L. Pierce's disease can be so devasting to grapes, that during severe epidemics, vineyards may require major replanting (Hewitt *et al.*, 1946; Davis *et al.*, 1978; Goodwin and Purcell, 1992). Alfalfa dwarf causes little or no economic damage in alfalfa (Summers *et al.*, 1981), but the presence of infected alfalfa plants provides a significant reservoir of inoculum for adjacent grape vineyards (Goodwin and Purcell, 1992; Purcell, 1981). The situation is further exacerbated by the presence of several grass weeds in alfalfa including bermudagrass, *Cyodon dactylon* (L.) Pers., and watergrass (barnyard grass), *Echinochloa crus galli*, (L.) Beauv., both of which are hosts of the bacterium as well as the sharpshooter leafhopper vectors (Goodwin and Purcell, 1992; Purcell, 1981).

Alfalfa is a host of numerous plant viruses. Most varieties appear equally susceptible as Rahman and Peaden (1993) found no differences in the incidence of numerous viruses among different alfalfa cultivars. Brunt, *et al.* (1996) list 33 viruses known to infect *M. sativa*. Some of the more economically important viruses infecting alfalfa include: alfalfa mosaic virus (AMB), pea streak virus (PSV), pea enation mosaic virus (PEMV), pea leafroll virus (PeLRV), and tobacco streak virus (TSV), cucumber mosaic virus (CMV), beet curly top virus (BCTV), watermelon mosaic virus-2 (WMV-2). A significant number of these viruses are transmitted by aphids (Kennedy *et al.*, 1962) that are frequently associated with alfalfa. In addition to causing yield and quality loss in alfalfa, many of these viruses are causal agents of diseases in other important crops including other legumes, tomato, sugarbeets, and cucumbers (Rahman and Peaden, 1993).

Alfalfa IPM on the world wide web

The technology of the Internet brings to the office or home of anyone with a computer and modem the latest information on the management of virtually any alfalfa pest. Most land grant universities in the US, agricultural universities worldwide, and governmental agencies such as USDA and CSIRO, currently have web sites. Much of the information is available free of charge. Information is available on agronomic, culture, cultivar selection, and pest management. This information is invaluable to researchers, extension agents, pest control advisors, and growers alike. A partial list of important Uniform Resource Locations (URLs) is given in Table 6. After reviewing many sites, I have tried to list those which provide the most complete information or include multiple links to other useful locations. Some, like ‘Alfagenes’, contain multiple searchable data bases. Others, such as the ‘Internet IPM Resources on Forage Crops,’ which provides 30 plus Internet addresses, are lists of available sites to which the reader may go for specific information on insect, disease, vertebrate, or weed management. This list is only a sampling of the resources available. It would be impossible to list every location containing alfalfa IPM information and new sites are being added almost daily. Additional information is available by employing any of the various Internet search engines. As with any resource, the user is cautioned to be aware of the sources of information and to judge their credibility accordingly.

Conclusions

As should be apparent from this review, a plethora of strategies are available for the management of the pests associated with alfalfa. Alfalfa is an ideal candidate for IPM. It can sustain a certain degree of injury and not sacrifice significant yield or quality. It is not saddled with ‘artificial’ cosmetic injury standards that are common in many horticultural crops. It should be equally apparent, however, that the alfalfa ecosystem is extremely complex with multiple pest and natural enemy interactions occurring at many levels.

In 1987, the last year for which complete statistics are available, it was estimated that only 4.7% of the total alfalfa acreage in the United States was under IPM (National Research Council, 1989). This is an alarming statistic, particularly given the multitude of strategies available to manage alfalfa pests. Unlike many other crops, alfalfa is largely managed ‘on farm’ with the grower often making all cultural and pest control decisions.

While we appear to have done a good job in educating pest control advisors and field scouts, we have perhaps done a less than admiral job in training growers to make the same sound pest management judgments. Also, much of the alfalfa produced in the US is consumed ‘on farm’, particularly dairies, where factors such as cutting for feed availability and/or forage quality may be of greater significance than is accelerating or delaying a harvest or modifying an irrigation schedule for pest management purposes.

Truly integrated pest management requires knowledgeable individuals who can make judgements and formulate decisions based on an extensive knowledge base. These individuals must be proficient not only in the disciplines of entomology, plant pathology, nematology, weed science, wildlife management, and agronomy, but must have a thorough understanding of the underlying ecological principals which govern the population dynamics of pest and natural enemy species as well as a knowledge of the overall economics of alfalfa production and utilization.

Acknowledgments

I am grateful to my colleagues who significantly improved this manuscript with their thoughtful and constructive comments on earlier drafts and provided additional literature references: L.D. Godfrey, S.C. Mueller, C.A. Frate, M.L. Flint, K.S. Hagen, T.S. Prather, R.F. Norris,

Table 6. Partial list[a] of Uniform Resource Locators (URLs) containing information on alfalfa and alfalfa IPM

Uniform Resource Locator	Name
<http://www.ipm.ucdavis.edu/>	Integrated Pest Management Project, UC Davis
<http://www.forages.css.orst.edu>	Forage Information System
<http://www.ippc.orst.edu/cicp/crops/forage.htm>	Internet IPM Resources on Forage Crops
<http://probe.nalusda.gov.8000/plant/aboutalfagenes.html>	Alfagenes
<http://www.agnic.nal.usda.gov/agdb/erdcalfr.html>	Agricultural Network
<http://ianrwww.unl.edu/ianr/pat/impserf.htm>	IPM Information
<http://hammock.ifas.ufl.edu/>	Florida Agricultural Information Retrieval System
<http://www.aginfo.com.label/label.html>	Pesticide Label and MSDS Management System
<gttp://www.alfalfa.org/index1.html>	Certified Alfalfa Seed Council

[a]Selected on the basis of completeness of information supplied and the links provided to other sites.

B.C. Pass, M.V. McKenry, P.B. Goodell, D.H. Putnam, A.C. Crabb, and J.C.Parr. I thank Dan Gonzales, Pete Goodell, and Ken Hagen for many valuable discussions regarding both the philosophy and practicality of pest management. Any errors of omission or commission, however, remain mine. I greatly appreciate the assistance, patience, and council of Dr. David Dent during the preparation of this manuscript. I thank Kathy Evans for editorial assistance and Lois Strole for her valuable assistance in the preparation of the final draft.

References

Ahrens, T.M. and Harvey, R.G. (1983) Established alfalfa-quackgrass control study. *Research Report North Central Weed Control Conference* **40**, 22–8.

Alicandro, A.J. and Peters, T.M. (1983) Survival of alfalfa blotch leafminer, *Agromyza frontella* (Diptera: Agromyzidae), in field-curing of alfalfa. *Canadian Entomologist* **115**, 89–91.

Allen, P. (1978) Control of aphids in dryland lucerne on sandy soils. *Department of Agriculture & Fisheries South Australia* Fact Sheet No. **51/78**.

Atkins, E.L., Frost, M.H., Anderson, L.D. and Deal, A.S. (1957a) The omnivorous leaf roller, *Platynota sultana* Wlshm., on cotton in California: nomenclature, life history and bionomics (Lepidoptera: Torticidae). *Annals Entomological Society America* **50**, 251–9.

Atkins, E.L., Frost, M.H., Deal, A.S. and Reynolds, H.T. (1957b) The omnivorous leaf roller, *Platynota sultana* Wlshm., on cotton in Southern California: damage and control. *J. Economic Entomology* **50**, 59–64.

Auclair, J.L. (1989) Host plant resistance. In A.K. Minks and P. Harrewijn (eds) *World crop pests-Aphids their virology, natural enemies and conrol*, pp. 225–65. Elsevier, Amsterdam.

Barnes, D.K., Thies, J.A., Rabae, D.L., Nelson, D.L. and Smith, D.M. (1990) Registration of two alfalfa germplasms with field resistance to the root-lesion nematode. *Crop Science* **30**, 751–2.

Barnes, G.L., Russell, C.C., Foster, W.D. and McNew, R.W. (1981) *Aphelenchus avenae*, a potential biological control agent for root rot fungi. *Plant Disease* **65**, 423–4.

Bell, C.E. and Guerrero, J.N. (1992) Sheep grazing for weed control in seedling alfalfa. *Research Progress Report Western Society Weed Science* **7**, 5–6.

Benedict, J.H. and Cothran, W.R. (1980) Damsel bugs useful as predators but need help. *California Agriculture* **34(8–9)**, 11–2.

Berberet, R.C., Stritzke, J.F. and Dowdy, A.K. (1987) Interactions of alfalfa weevil (Coleoptera: Curculionidae) and weeds in reducing yield and stand of alfalfa. *J. Economic Entomology* **80**, 1306–13.

Bergstrom, G.C. (1991) Fungicide benefits assessment field crops-north. *National Agricultural Pesticide Impact Assessment Program* Ohio State University, Columbus, OH.

Bermer, C. (1976) Life history and pest management of the alfalfa blotch leafminer, *Agromyza frontella* (Rondani) (Diptera: Agromyzidae). MS Thesis, Cornell University, Ithaca, NY.

Bishop, A.L., Greenup, L.R. and Holtkamp, R.H. (1980) Management of *Acyrthosiphon kondoi* Shinji, blue-green aphid and *Therioaphis trifolii* (Monell) f. *maculata*, spotted alfalfa aphid, by grazing and cutting lucerne. *Australian J. Experimental Agriculture and Animal Husbandry* **20**, 710–16.

Bolton, J.L. (1962) Alfalfa botany, cultivation and utilization. *World Crops Books*. Leonard Hill. London.

Bolton, J.L., Goplen, B.P. and Baenziger, H. (1972) World distribution and historical developments. In C.H. Hanson (ed) *Alfalfa science and technology*, pp. 1–34. American Society Agronomy, Madison, WI.

Broscious, S.C. and Kirby, H.W. (1988) Economic evaluation of fungicides for control of alfalfa foliar diseases. *Phytopathology* **78**, 934–9.

Brown, G.C. (1984) Stability in an epizoological model with age-dependent immunity and seasonal host reproduction. *Bulletin Mathematical Biology* **46**, 139–53.

Brown, G.C. and Fick, G.W. (1986) Modeling the ecological components of alfalfa production. In R.E. Frisbie and P.L. Adkisson (eds) *Integrated pest management of major agricultural systems*, pp. 174–91. Texas Agricultural Experiment Station Publication **MP–1616**. College Station, TX.

Brown, G.C. and Nordin, G.L. (1982) An epizootic model of an insect-fungal pathogen system. *Bulletin Mathematical Biology* **44**, 731–40.

Brunt, A.A., Crabtree, K., Dallwitz, M.J., Gibbs, A.J., Watson, L. and Zurcher, E.J. (1996) Plant viruses online: *Descriptions of lists from the VIDE database. Version:* 16th January 1997. URL <http://biology.anu.edu.au/Groups/MES/vide/>.

Buntin, G.D. and Bouton, J.H. (1996) Alfalfa weevil (Coleoptera: Curculionidae) management in alfalfa by spring grazing with cattle. *J. Economic Entomology* **89**, 1631–7.

Buntin, G.K. and Pedigo, L.P. (1986) Enhancement of annual weed populations in alfalfa after stubble defoliation by variegated cutworm (Lepidoptera: Noctuidae). *J. Economic Entomology* **79**, 1507–12.

Busbice, T.H., Hill Jr, R.R. and Carnahan, H.L. (1972) Genetics and breeding procedures. In C.H. Hanson (ed) *Alfalfa science and technology*, pp. 283–318. American Society Agronomy, Madison, WI.

Byers, R.A., Kendall, W.A., Peaden, R.N. and Viands, D.W. (1996) Field and laboratory selection of *Medicago* plant introductions for resistance to the clover root curculio. *J. Economic Entomology* **89**, 1033–9.

Caddel, J.L., Stritzke, J.F., Anderson, M.P. and Bensch, C. (1992) Alfalfa germplasm with resistance to terbacil. *American Forage and Grassland Council* **1**, 162–5.

Carlson, H.L. and Westerdahl, B.B. (1995) Nematodes. In S.B. Orloff and H.L. Carlson (eds) *Intermountain alfalfa management*, pp. 73–6. University of California Publication No. **3366**. Oakland, CA.

Carver, M. (1989) Biological control of aphids. In A.K. Minks and P. Harrewijn (eds) *World crop pests – Aphids their virology, natural enemies and control*, pp. 141–65. Elsevier, Amsterdam.

Casagrande, F.A. and Stehr, F.W. (1973) Evaluating the effects of harvesting alfalfa on alfalfa weevil (Coleoptera: Curculionidae) and parasite populations in Michigan. *Canadian Entomologist* **105**, 1119–28.

Case, R.M. (1989) Managing damage to alfalfa caused by plains pocket gophers. *Proceedings Ninth Great Plains Wildlife Damage Control Workshop* **9**, 160–1.

Casida, L.E. and Lukezic, F.L. (1992) Control of leaf spot diseases of alfalfa and tomato with applications of the bacterial predator *Pseudomonas* Strain 679–2. *Plant Disease* **76**, 1217–20.

Certified Alfalfa Seed Council. (1995) *Fall dormancy & pest resistance ratings for alfalfa varieties*. 1995/96 edition. Davis, CA.

Chen, J., Bird, G.W. and Mather, R.L. (1995) Impact of multi-year cropping regimes on *Solanum tuberosum* tuber yields in the presence of *Pratylenchus penetrans* and *Verticillium dahliae*. *J. Nematology* **27**, 654–60.

Christie, B.R. and Townshend, J.L. (1992) Selection for resistance to the root-lesion nematode in alfalfa. *Canadian J. Plant Science* **72**, 593–8.

Conrad, H.R. and Klopfenstein, T.J. (1988) Role in livestock feeding-greenchop, silage, hay, and dehy. In A.A. Hanson, D.K. Barnes, and R.R. Hill (eds) *Alfalfa and alfalfa improvement*, pp. 539–51. American Society Agronomy. Madison, WI.

Corbett, A., Leigh, T.F. and Wilson, L.T. (1991) Interplanting alfalfa as a source of *Metaseiulus occidentalis* (Acari: Phytoseiidae) for managing spider mites in cotton. *Biological Control* **1**, 188–96.

Cords, H.P. (1973) Weeds and alfalfa hay quality. *Weed Science* **21**, 400–1.

Crafts, A.S. and Robbins, W.W. (1962) *Weed control*. McGraw-Hill. New York.

Cudney, D.W., Orloff, S.B. and Reints, J.S. (1992) An integrated weed management procedure for the control of dodder (*Cuscuta indecora*) in alfalfa (*Medicago sativa*). *Weed Technology* **6**, 603–6.

Cuperus, G.W., Radcliffe, E.B., Barnes, D.K. and Marten, G.C. (1983) Economic injury levels and economic thresholds for potato leafhopper (Homoptera: Cicadellidae) on alfalfa in Minnesota. *J. Economic Entomology* **76**, 1341–9.

D'Halluin, K.D., Botterman, J. and De Greef, W. (1990) Engineering of herbicide-resistant alfalfa and evaluation under field conditions. *Crop Science* **30**, 866–71.

Davis, D.W. (1970) Insecticidal control of the alfalfa weevil in northern Utah and some resulting effects on the weevil parasite *Bathyplectes curculionis*. *J. Economic Entomology* **63**, 119–25.

Davis, D.W. and Knowlton, G.F. (1976) Foliage pests of alfalfa. In D.W. Davis (ed) Insects and nematodes associated with alfalfa in Utah, pp. 3–12. *Utah Agricultural Experiment Station Bulletin* No. **494**. Logan, UT.

Davis, J.J., Purcell, A.H. and Thomson, S.V. (1978) Pierce's disease of grapevines: Isolation of the causal bacterium. *Science* **199**, 75–7.

Dawson, J.H. (1966a) Response of field dodder to shade. *Weeds* **14**, 4–5.

Dawson, J.H. (1966b) Factors affecting dodder control with granular CIPC. *Weeds* **14**, 255–9.

Dawson, J.H. (1989) Established forage alfalfa (*Medicago sativa*) tolerates glyphosate and SC-0224 applied to control dodder (*Cuscuta* spp.). *Weed Technology* **3**, 560–5.

DeLoach, C.J. (1970) The effect of habitat diversity on predation. *Proceedings Tall Timbers Conference on Ecological Animal Control by Habitat Management* No. **2**, pp. 223–41. Tall Timbers Research Station. Tallahassee, Florida.

Denison, R.F. and Loomis, R.S. (1989) An integrative physiological model of alfalfa growth and development. *University of California Publication* No. **1926.** University of California, Oakland, CA.

Dickson, R.C., Laird, E.F. and Pesho, G.R. (1955) The spotted alfalfa aphid (yellow clover aphid) on alfalfa. *Hilgardia* **24**, 93–118.

Dowdy, A.K., Berberet, R.C., Stritzke, J.F., Caddel, J.L. and McNew, R.W. (1993) Interaction of alfalfa weevil (Coleoptera: Curculionidae), weeds, and fall harvest options as determinants of alfalfa productivity. *J. Economic Entomol*. **86**, 1241–9.

Drea, J.J. and Hendrickson, R.M. (1986) Analysis of a successful classical biological control project: the alfalfa blotch leafminer (Diptera: Agromyzidae) in the Northeastern United States. *Environmental Entomology* **15**, 448–55.

Elgin, J.H., Barnes, D.K., Busbice, T.H., Buss, G.R. Clark, N.A., Cleveland, R.W., Ditterline, R.L., Evans, D.W., Fransen, S.C., Horrodks, R.D., Hunt, O.J., Kehr, W.R., Lowe, C.C., Miller, D.A., Offutt, M.S., Pickett, R.C., Sorensen, E.L., Taliaferro, M., Tesar, M.B., and Van Keuren, R.W. (1981) Anthracnose resistance rescues alfalfa yields. *Crop Science* **21**, 457–60.

Elgin, J.H., Welty, R.E. and Gilchrist, D.G. (1988) Breeding for disease and nematode resistance. In A.A. Hanson, D.K. Barnes and R.R. Hill (eds) *Alfalfa and alfalfa improvement*, pp. 827–58. American Society Agronomy, Madison, WI.

Erwin, D.C. (1990a) Crown wart. In D.L. Stuteville and D.C. Erwin (eds) *Compendium of alfalfa diseases*. 2nd ed., pp. 24. American Phytopathological Society Press, St. Paul, MN.

Erwin, D.C. (1990b) Bacterial wilt. In D.L. Stuteville and D.C. Erwin (eds) *Compendium of alfalfa diseases*. 2nd ed., pp. 5–6. American Phytopathological Society Press, St. Paul, MN.

Erwin, D.C., Khan, R.A. and Lehman, W.F. (1987) Registration of UC 129 alfalfa germplasm with moderate resistance to stagonospora leaf spot and root rot. *Crop Science* **27**, 820.

Erwin, D.C., Ashton, F.M. and Fischer, B.B. (1990) Dodder. In D.L. Stuteville and D.C. Erwin (eds) *Compendium of alfalfa diseases*. 2nd ed., pp. 57–8. American Phytopathological Society Press, St. Paul, MN.

Farrell, J.A. and Stufkens, M.W. (1981) Field evaluation of lucerne cultivars for resistance to blue-green lucerne aphid and pea aphid (*Acyrthosiphon* spp.) in New Zealand. *New Zealand J. Agricultural Research* **24**, 217–20.

Fenner, F. and Ratcliffe, F.N. (1965) *Myxomatosis*. Cambridge University Press, London.

Fick, G.W. (1975) ALSIM 1 (LEVEL 1). User's manual. *Agronomy Mineo* **75–20**. Department of Agronomy, Cornell University, Ithaca, NY.

Fick, G.W. (1981) ALSIM (LEVEL 2). User's manual. *Agronomy Mineo* **81–35.** Department of Agronomy, Cornell University, Ithaca, NY.

Fleming, C.E. and Peterson, N.F. (1919) Don't feed fox-tail hay to lambing ewes. *Nevada Agricultural Experiment Station Bulletin* **97**.

Flinn, F.W., Taylor, F.A.J. and Hower, A.A. (1986) Predictive model for the population dynamics of potato leafhopper, *Empoasca fabae* (Homoptera: Cicadellidae), on alfalfa. *Environmental Entomology* **15**, 898–904.

Flint, M.L. and Roberts, P.A. (1988) Using crop diversity to manage pest problems: some California examples. *American J. Alternative Agriculture* **3**, 163–7.

Frazer, B.D., Gilbert, N., Nealis, V. and Raworth, D.A. (1981) Control of aphid density by a complex of predators. *Canadian Entomologist* **113**, 1035–41.

Frisbie, R.E. and Adkisson, P.L. (eds) (1986) Integrated pest management on major agricultural systems. *Texas Agricultural Experiment Station* MP–**1616**. College Station, TX.

Garber, L.F. and Sprague, V.G. (1933) Alfalfa yellows. *Science* **78**, 385–6.

Garber, L.F. and Sprague, V.G. (1935) Cutting treatments of alfalfa in relation to infestations of leafhopper. *Ecology* **16**, 48–59.

Getz, W.M. and Gutierrez, A.P. (1982) A perspective on systems analysis in crop production and insect pest management. *Annual Review Entomology* **27**, 447–66.

Godfrey, L.D. and Leigh, T.F. (1994) Alfalfa harvest strategy effect on lygus bug (Hemiptera: Miridae) and insect predator population density: implications for use as a trap crop in cotton. *Environmental Entomology* **23**, 1106–18.

Godfrey, L.D. and Yeargan, K.V. (1987) Effects and interactions of early season pests on alfalfa yields in Kentucky. *J. Economic Entomology* **80**, 248–56.

Godfrey, L.D. and Yeargan, K.V. (1989) Effect of clover root curculio, alfalfa weevil (Coleoptera: Curculionidae), and soil-borne fungi on alfalfa stand density and longevity in Kentucky. *J. Economic Entomology* **82**, 1749–56.

Goodwin, P. and Purcell, A.H. (1992) Pierce's disease. *Grape pest management*. 2nd ed. Publication No. **3343**, pp. 76–84. Division of Agricultural and Natural Resources. University of California, Oakland CA.

Grant, J.F., Yeargan, K.V., Pass, B.C. and Parr, J.C. (1982) Invertebrate organisms asociated with alfalfa seedling loss in complete-tillage and no-tillage plantings. *J. Economic Entomology* **75**, 822–6.

Grau, C.R. (1990) Pythium seed rot, damping-off and root rot. In D.L. Stuteville and D.C. Erwin (eds) *Compendium of alfalfa diseases*. 2nd ed., pp. 11–2. American Phytopathological Society Press, St. Paul, MN.

Gregory, W.W. and Musick, G.J. (1976) Insect management in reduced tillage systems. *Bulletin Entomological Society America* **22**, 302–4.

Griffin, G.D. (1987) The importance of environmental factors and cultural practices on parasitism of alfalfa by *Ditylenchus dipsaci*. *J. Nematology* **19**, 267–76.

Griffin, G.D. (1990) Pathological relationship of *Ditylenchus dipsaci* and *Fusarium oxysporum* f. sp. *medicaginis* on alfalfa. *J. Nematology* **22**, 333–6.

Griffin, G.D. (1992) Stem nematode-Fusarium wilt complex in alfalfa as related to irrigation management at harvest time. *J. Nematology* **24**, 315–20.

Griffin, G.D. and McKenry, M.V. (1989) Susceptibility of Nevada Synthetic XX germplasm to a California race of *Meloidogyne hapla*. *J. Nematology* **21**, 292–293.

Groden, E., Drummone, F.A., Casagrande, R.A. and Haynes, D.L. (1990) *Coleomagilla maculata* (Coleoptera: Coccinellidae): its predation upon the Colorado potato beetle (Coleoptera: Chrysomelidae) and its incidence in potatoes and surrounding crops. *J. Economic Entomology* **83**, 1306–15.

Gutierrez, A.P. and Baumgaertner, J.U. (1984) Multitrophic models of predator prey energetic. II. A realistic model of plant-herbivore-parasitoid-predator interactions. *Canadian Entomologist* **116**, 933–49.

Gutierrez, A.P., Christensen, J.B., Merritt, C.M., Loew, W.B., Summers, C.G. and Cothran, W.R. (1976) Alfalfa and the Egyptian alfalfa weevil (Coleoptera: Curculionidae). *Canadian Entomologist* **108**, 635–48.

Gutierrez, A.P., Baumgaertner, J.U. and Summers, C.G. (1984a) Multitrophic models of predator-prey energetic. III. A case study in an alfalfa ecosystem. *Canadian Entomologist* **116**, 950–63.

Gutierrez, A.P., Baumgaertner, J.U. and Summers, C.G. (1984b) Multitrophic models of predator-prey energetics. *Canadian Entomologist* **116**, 923–4.

Hagan, H.F. (1918) The alfalfa weevil, *Phytomomus posticus* F. *Utah Agricultural Experiment Station Circular* No. **31**. Logan, UT.

Hagen, K.S. (1990) Biological control of insect pests in alfalfa hay. *Proceedings 20th California Alfalfa Symposium*, pp. 74–83. University of California Cooperative Extension Service, Davis, CA.

Hagen, K.S. and van den Bosch, R. (1968) Impact of pathogens, parasites, and predators on aphids. *Annual Review Entomology* **13**, 325–84.

Hagen, K.S., van den Bosch, R. and Dahlsten, D.L. (1971) The importance of naturally-occurring biological control in the western United States. In C.B. Huffaker (ed) *Biological control*, pp. 253–93. Plenum, New York.

Hamilton, B.A., Greenup, L.R. and Lodge, G.M. (1978) Seedling mortality of lucerne varieties in field plots subjected to spotted alfalfa aphid. *J. Australian Institute Agricultural Science* March 1978: 54–6.

Hanson, R.W. and Simpson, R.G. (1969) Agricultural flaming for insect and weed control in Colorado. *Colorado Agricultural Experiment Station Bulletin* No. **538S**.

Harcourt, D.G. and Guppy, J.C. (1991) Numerical analysis of an outbreak of the alfalfa weevil (Coleoptera: Curculionidae) in eastern Ontario. *Environmental Entomology* **20**, 217–23.

Harper, A.M., Schaber, B.D., Story, T.P. and Entz, T. (1990) Effect of swathing and clear-cutting alfalfa on insect populations in southern Alberta. *J. Economic Entomology* **85**, 2050–7.

Harris, W.L., Blickenstaff, C.C., Clark, N.A., Steinhauer, A.L., Neal, J.W., Coan, R.M. and Ratcliffe, R.H. (1971) Flaming for control of alfalfa weevil in Maryland. *Maryland Agricultural Experiment Station Bulletin* **4**, 171.

Hawn, E.J. (1963) Transmission of bacterial wilt of alfalfa by *Ditylenchus dipsaci* (Kuhn). *Nematologica* **9**, 65–8.

Hawn, E.J. and Hanna, M.R. (1966) Influence of stem nematode infestations on bacterial wilt reaction and forage yield of alfalfa varieties. *Canadian J. Plant Science* **47**, 203–8.

Hendrickson, R.M. and Plummer, J.A. (1983) Biological control of the alfalfa blotch leafminer in Delaware. *J. Economic Entomology* **76**, 757–61.

Hewitt, W.B., Houston, B.R., Frazier, N.W. and Freitag, J.H. (1946) Leafhopper transmission of the virus causing Pierce's disease of grape and dwarf of alfalfa. *Phytopathology* **36**, 117–28.

Hill, R.R., Newton, R.L., Zeiders, K.E. and Elgin, J.H. (1969) Relationship of the clover root curculio, *Fusarium* wilt, and bacterial wilt in alfalfa. *Crop Science* **9**, 327–9.

Hill, R.R., Murray, J.J. and Zeiders, K.E. (1971) Relationship between clover root curculio injury and severity of bacterial wilt in alfalfa. *Crop Science* **11**, 306–7.

Hill, R.R., Leath, K.T. and Rowe, D.E. (1989) Registration of PL-PhR alfalfa germplasm. *Crop Science* **29**, 1577.

Horber, E. (1980) Types and classification of resistance. In R.G.

Maxwell and P.R. Jennings (eds) *Breeding plants resistant to insects*, pp. 15–21. Wiley, New York.

Hower, A.A. (1975) Potential controls for alfalfa weevil (*Hypera postica*) in Pennsylvania. *Progress Report of the Pennsylvania State University Agricultural Experiment Station*. No. **351**.

Hower, A.A. and Davis, G.A. (1984) Selectivity of insecticides that kill the potato leafhopper (Homoptera: Cicadellidae) and the alfalfa weevil (Coleoptera: Curculionidae) and protect the parasite *Microctonus aethiopoides* Loan (Hymenoptera: Braconidae. *J. Economic Entomology* **77**, 1601–7.

Hughes, R.D. and Bryce, M.A. (1984) Biological characterization of two biotypes of pea aphid, one susceptible and the other resistant to fungal pathogens, coexisting in lucerne in Australia. *Entomologia experimentalis et applicata* **36**, 225–9.

Hughes, R.D., Woolcock, L.T., Toverts, F.A. and Hughes, M.A. (1987) The biological control of the spotted alfalfa aphid, *Therioaphis trifolii* (Monell) f. *maculata*, on lucerne crops in Australia, by the introduced parasitic hymenopteran, *Trioxys complanatus* (Quilis). *J. Applied Ecology* **24**, 515–37.

Hunt, O.J., Griffin, G.D., Murray, J.J., Pedersen, M.W. and Peaden, R.N. (1971) The effects of root knot nematodes on bacterial wilt in alfalfa. *Phytopathology* **61**, 256–9.

Hutchins, A.H. and Pedigo, L.P. (1989) Potato leafhopper-induced injury on growth and development of alfalfa. *Crop Science* **29**, 1005–11.

Hutchison, J.M. and Ashton, F.M. (1979) Germination of field dodder (*Cuscuta campestris*). *Weed Science* **28**, 330–3.

Isaak, A., Sorensen, E.L. and Ortman, E.E. (1963) Influence of temperature and humidity on resistance in alfalfa to the spotted alfalfa aphid and pea aphid. *J. Economic Entomology* **56**, 53–7.

Isaak, A., Sorensen, E.L. and Painter, R.H. (1965) Stability of resistance to pea aphid and spotted alfalfa aphid in several alfalfa clones under various temperature regimes. *J. Economic Entomology* **58**, 140–7.

Johnson, L. (1997) Evaluation of glandular haired alfalfa: a tool for resistance to potato leafhoppers and more. *Proceedings 27th California Alfalfa Symposium*, pp. 189–91. University of California Cooperative Extension Service, Davis, CA.

Keeley, P.E., Thullen, R.J, Miller, J.H. and Carter, C.H. (1979) Comparison of four cropping systems for yellow nutsedge (*Cyperus esculentus*) control. *Weed Science* **27**, 463–7.

Kehr, W.R., Rumbaugh, M.D., Semeniuk, G., Barnes, D.K., Frosheiser, F.I., Manglitz, G.R. and Boe, A.A. (1984) Registration of Daneb I, Daneb I BWI, and Daneb I P2, alfalfa germplasm with multiple pest resistance [*Pseudopeziza medicaginis*, *Pseudopeziza jonesii*, *Cercospora medicaginis*]. *Crop Science* **24**, 1001.

Kennedy, J.S., Day, M.F. and Eastop, V.F. (1962) *A conspectus of aphids as vectors of plant viruses*. Commonwealth Institute of Entomology, London.

Kingsley, P.C., Bryan, M.D., Day, W.H., Burger, T.L., Dysart, R.J. and Schwalbe, C.P. (1993) Alfalfa weevil (Coleoptera: Curculionidae) biological control: spreading the benefits. *Environmental Entomology* **22**, 1234–50.

Knipling, E.F. (1979) The basic principles of insect population suppression and management. *United States Department Agriculture Agricultural Handbook* No. **512**. Superintendent of Documents, Washington, D.C.

Kodira, U.C. and Westerdahl, B.B. (1996) Nematodes. *Pest Management Guidelines for Sugarbeets*. *UCIPM–PMG* No. **24**, pp. C.1–C.2. University of California, Davis, CA.

Koehler, C.S. and Gyrisco, G.G. (1959) Control of *Hypera postica* (Gyllenhal) on second-cutting alfalfa in New York. *J. Economic Entomology* **52**, 590–2.

Kommedahl, T., Kotheimer, J.B. and Bernardini, J.V. (1959) The effects of quackgrass on germination and seedling development of certain crop plants. *Weeds* **7**, 1–12.

Kugler, J.L. and Ratcliffe, R.H. (1983) Resistance in alfalfa to a red form of the pea aphid (Homoptera: Aphididae). *J. Economic Entomology* **76**, 74–6.

Lamp, W.O. (1991) Reduced *Empoasca fabae* (Homoptera: Cicadellidae) density in oat-alfalfa intercrop systems. *Environmental Entomology* **20**, 118–26.

Lamp, W.O., Barney, B.J., Armbrust, E.J. and Kasputa, G. (1984) Selective weed control in spring-planted alfalfa: Effect on leafhoppers and planthoppers (Homoptera: Auchenorrhyacha), with emphasis on potato leafhopper. *Environmental Entomology* **13**, 207–13.

Lanini, W.T., Orloff, S.B., Vargas, R.N., Orr, J.P., Marble, V.L. and Grattan, S.R. (1991) Oat companion crop seeding rate effect of alfalfa establishment, yield, and weed control. *Agronomy J.* **83**, 330–3.

Leath, K.T. (1990) Common leaf spot. In D.L. Stuteville and D.C. Erwin (eds) *Compendium of alfalfa diseases*. 2nd ed., pp. 13–4. American Phytopathological Society Press. St. Paul, MN.

Leath, K.T. and Hower, A.A. (1993) Interaction of *Fusarium oxysporum* f. sp. *medicaginis* with feeding activity of clover root curculio larvae in alfalfa. *Plant Disease* **77**, 799–802.

Leath, K.T. and Pennypacker, B.W. (1990) In D.L. Stuteville and D.C. Erwin (eds) *Compendium of alfalfa diseases*. 2nd ed., pp. 39–41. American Phytopathological Society Press. St. Paul, MN.

Leath, K.T., Erwin, D.C. and Griffin, G.D. (1988) Diseases and nematodes. In A.A. Hanson, D.K. Barnes and R.R. Hill (eds) *Alfalfa and alfalfa improvement*, pp. 621–70. American Society Agronomy, Madison, WI.

Leath, K.T., Stritzke, J.E. and Summers, C.G. (In press) Pests and harvest management. In W.O. Lamp and E.J. Armbrust (eds) *Protection of perennial forage crops*. Wiley & Sons, New York.

Lehman, W.F., Summers, C.G. and Marble, V.L. (1992) Registration of UC 73 nondormant alfalfa germplasm with resistance to Egyptian alfalfa weevil. *Crop Science* **32**, 284.

Lentz, G.L. and Pedigo, L.P. (1975) Population ecology of parasites of the green cloverworm in Iowa. *J. Economic Entomology* **68**, 301–4.

Lindow, S.W. (1985) Foliar antagonists: Status and prospects. In M.A. Hoy and D.C Herzog (eds) *Biological control in agricultural IPM systems*, pp. 395–413. Academic Press, New York.

Lloyd, D.L, Turner, J.W. and Hilder, T.B. (1980a) Effects of aphids on seedling growth of lucerne lines. II. Spotted alfalfa aphid (*Therioaphis trifolii* f. *maculata* (Monell) in field conditions. *Australian J. Experimental Agriculture Animal Husbandry* **20**, 288–93.

Lloyd, D.L., Turner, J.W. and Hilder, T.B. (1980b) Effects of aphids on seedling growth of lucerne lines. I. Blue-green aphid in field conditions (*Acyrthosiphon kondoi* Shinji). *Australian J. Experimental Agriculture Animal Husbandry* **20**, 72–6.

Lodge, G.M. (1986) Yield and persistence of irrigated lucerne cut at different frequencies at Tamworth, New South Wales. *Australian J. Experimental Agriculture Animal Husbandry* **26**, 165–72.

Loeb, S.C. (1990) Reproduction and population structure of pocket gophers (*Thomomys bottae*) from irrigated alfalfa fields. *Vertebrate Pest Conference* **14**, 76–81.

Long, R.F. (1997) Minor pests of alfalfa hay. *Proceedings 27th California Alfalfa Symposium*, pp. 155–8. University of California Cooperative Extension Service, Davis, CA.

Mackauer, M. and Kambhampati, S. (1986) Structural changes in the parasite guild attacking the pea aphid in North America. In I. Hodek (ed) *Ecology of Aphidophaga*, pp. 471–4. Academia, Prague and W. Junk, Dordrecht.

Manglitz, G.R. and Ratcliffe, R.H. (1988) Insects and mites. In A.A. Hanson, Barnes, D.K. and Hill, R.R. (eds) *Alfalfa and alfalfa improvement*, pp. 671–704. American Society Agronomy, Madison, WI.

Marsh, R.E. (1991) Controlling rodent and rabbit pests in alfalfa. *Proceedings 21st California Alfalfa Symposium*, pp. 102–7. University of California Cooperative Extension Service, Davis, CA.

McGuire, H.H., Walters, J. and Slack, D.A. (1958) The relationship of root-knot nematodes to the development of Fusarium wilt in alfalfa. *Phytopathology* **48**, 344.

McGukin, T. (1983) Alfalfa management strategies for a Wisconsin dairy farm – an application of stochastic dominance. *North Central J. Agricultural Economics* **5**, 47–9.

McKenry, M.V. (1987) Control strategies in high-value crops. In R.H. Brown and B.P. Kerry (eds) *Principles and practices of nematode control in crops*, pp. 329–49. Academic Press, Sydney, Australia.

McMurtry, J.A. (1962) Resistance of alfalfa to spotted alfalfa aphid in relation to environmental factors. *Hilgardia* **32**, 501–39.

McWilliam, J.R. (1968) Lucerne, the plant. *J. Australian Institute Agricultural Science* **34**, 191–3.

Mellors, W.K. and Helgensen, R.G. (1978) Developmental rates for the alfalfa blotch leafminer, *Agromyza frontella*, at constant temperatures. *Annals Entomological Society America* **71**, 886–8.

Mensah, R. (1996) Lucerne strips in cotton-Envirofeast IPM guidelines. *New South Wales Agriculture*, Narrabri, Australia.

Michaud, R., Lehmen, W.F. and Rumbaugh, M.D. (1988) World distribution and historical development. In A.A. Hanson, D.K. Barnes, and R.R. Hill (eds) *Alfalfa and alfalfa improvement*, pp. 25–91. American Society Agronomy, Madison, WI.

Miller, D. and Melton, B. (1983) Description of alfalfa cultivars and germplasm sources. *New Mexico Agriculture Experiment Station Special Report* No. **53**.

Miller, J.C. and Ehler, L.E. (1978) Parasitization of *Spodoptera praefica* larvae in hay alfalfa. *Environmental Entomology* **7**, 744–7.

Miller-Garvin, J.E. and Viands, D.R. (1994) Selection for resistance to Fusarium root rot, and associations among resistance to six diseases in alfalfa. *Crop Science* **34**, 1461–8.

Moellenbeck, D.J., Quisenberry, S.S. and Alison, M.W. (1993) Resistance of alfalfa cultivars to the threecornered alfalfa hopper (Homoptera: Membracidae). *J. Economic Entomology* **82**, 614–20.

Molyneus, R.J. and Ralphs, M.H. (1992) Plant toxins and palatability to herbivores. *J. Range Management* **45**, 13–8.

Muenscher, W.C. (1949) *Weeds*. Macmillan, New York.

Munkvold, G.P. and Caralton, W.M. (1995) Prevalence and distribution of *Aphanomyces euteiches* and *Phytophthora medicaginis* in Iowa alfalfa fields. *Plant Disease* **79**, 1251–3.

National Research Council. (1989) *Alternative agriculture*. National Academy Press, Washington, D.C.

Nelson, C.L., Barnes, D.K., Sheaffer, C.C., Rabae, D.L. and MacDonald, D.H. (1983) Breeding for resistance to the lesion nematode (*Pratylenchus*) in alfalfa. *Proceedings Alfalfa Improvement Conference USDA–ARS*.

Nelson, C.L., Barnes, D.K. and MacDonald, D.H. (1985) Field and growth chamber evaluations for root-lesion nematode resistance in alfalfa. *Crop Science* **25**, 35–9.

Neuenschwander, P., Hagen, K.S. and Smith, R.F. (1975) Predation on aphids in California's alfalfa fields. *Hilgardia* **43**, 53–78.

Nielson, M.W. and Lehman, W.F. (1980) Breeding approaches in alfalfa. In F.G. Maxwell and P.R. Jennings (eds) *Breeding plants resistant to Insects*, pp. 277–312. Wiley and Sons, New York.

Norris, R.F. (1982) Interaction between weeds and other pests in the agro-ecosystem. In J.L. Hatfield and I.J. Thomason (eds) *Biometerology in integrated pest management*, pp. 343–406. Academic Press, New York.

Norris, R.F. and Ayers, D. (1991) Cutting interval and irrigation timing in alfalfa: Yellow foxtail invasion and economic analysis. *Agronomy J.* **83**, 552–8.

Norris, R.F. and Schoner, C. (1975) Summer annual grasses: problems and control. *Proceedings 5th California Alfalfa Symposium*, pp. 104–12. University of California Cooperative Extension Service, Davis, CA.

Norris, R.F., Cothran, W.R. and Burton, V.E. (1984) Interaction between winter annual weeds and Egyptian alfalfa weevil (Coleoptera: Curculionidae) in alfalfa. *J. Economic Entomology* **77**, 43–52.

Norton, D.C. (1969) *Meloidogyne hapla* as a factor in alfalfa decline in Iowa. *Phytopathology* **59**, 1824–7.

Oloumi-Sadeghi, H., Zavaleta, L.R., Kapusta, G., Lamp, W.O. and Armbrust, E.J. (1989) Effects of potato leafhopper (Homoptera: Cicadellidae) and weed control on alfalfa yield and quality. *J. Economic Entomology* **82**, 923–31.

Onstad, D.W. and Shoemaker, C.A. (1984) Management of alfalfa and the alfalfa weevil (*Hypera postica* Gyllenhal): an example of systems analysis in forage production. *Agricultural Systems* **14**, 1–30.

Onstad, D.W., Shoemaker, C.A. and Hansen, B.C. (1984) Management of potato leafhopper, *Empoasca fabae* (Homoptera: Cicadellidae), on alfalfa with the aid of systems analysis. *Environmental Entomology* **13**, 1046–58.

Orloff, S.B., Salmon, T.P. and Gorenzel, W.P. (1995) Vertebrate pests. In S.B. Orloff and H.L. Carlson (eds) *Intermountain alfalfa management*, pp. 85–93. University of California Publication **3366**, Oakland, CA.

Papavizas, G.C. and Lumsden, R.D. (1980) Biological control of soilborne fungal propagules. *Annual Review Phytopathology* **18**, 389–413.

Parr, J.C., Pass, B.C. and Nordin, G.L. (1993) Compatibility of *Zoophthora phytomoni* (Entomophthorales: Entomophthoraceae) and *Bathyplectes anurus* (Hymenoptera: Ichneumonidae) in Kentucky alfalfa fields. *Environmental Entomology* **22**, 674–8.

Peaden, R.N., Evans, D.W. and Elgin, J.H. (1995) Registration of $W12SR_2W_1Fu_1$ alfalfa germplasm. *Crop Science* **35**, 287–8.

Peters, E.J. and Linscott, D.L. (1988) Weeds and weed control. In A.A. Hanson, D.K. Barnes and R.R. Hill (eds) *Alfalfa and alfalfa improvement*, pp. 705–35. American Society Agronomy, Madison, WI.

Peterson, R.K.D., Hibley, L.G. and Danielson, S.D. (1995) Alfalfa consumption by adult clover leaf weevil (Coleoptera: Curculionidae) and development of injury equivalents for stubble defoliators. *J. Economic Entomology* **88**, 1441–44.

Pickering, J. and Gutierrez, A.P. (1991) Differential impact of the pathogen *Pandora neoaphidis* (R. & H.) Humber (Zygomycetes: Entomophthorales) on the species composition of *Acyrthosiphon* aphids in alfalfa. *Canadian Entomologist* **123**, 315–20.

Pienkowski, R.L. and Medler, J.T. (1962) Effects of alfalfa cutting on the potato leafhopper, *Empoasca fabae*. *J. Economic Entomology* **55**, 973–8.

Pimentel, D. and Wheeler, A.G. (1973) Species and diversity of arthropods in the alfalfa community. *Environmental Entomology* **2**, 659–68.

Pinter, P.J., Hadley, N.F. and Lindsay, J.H. (1975) Alfalfa crop micrometerology and its relation to insect pest biology and control. *Environmental Entomology* **4**, 153–62.

Pitcairn, M.J. and Gutierrez, A.P. (1989) Biological control of *Hypera postica* and *Hypera brunneipennis* (Coleoptera: Curculionidae) in California, with reference to the introduction of *Tetrastichus incertus* (Hymenoptera: Eulophidae). *Pan-Pacific Entomologist* **65**, 420–8.

Prather, T., Vargas, R. and Mueller, S. (1993) Grass interseeding in aging alfalfa stands: implementation and evaluation. *Proceedings 23rd California Alfalfa Symposium*, pp. 128–35. University of California Cooperative Extension Service, Davis, CA.

Purcell, A.H. (1981) Pierce's disease. *Grape Pest Management, Secion II – Diseases*, pp. 62–70. Publ. **4105**. Agricultural Sciences Publication, University of California, Berkeley, CA.

Rahman, F. and Peaden, R.N. (1993) Incidence of viruses on alfalfa in western North America. *Plant Disease* **77**, 160–2.

Regev, U., Gutierrez, A.P. and Feder, G. (1976) Pests as a common property resource: a case study of alfalfa weevil and control. *American J. Agricultural Economics* **58**, 188–96.

Reynolds, H.W. (1955) Varietal susceptibility of alfalfa to two species of root-knot nematodes. *Phytopathology* **45**, 70–2.

Reynolds, H.W. and O'Bannon, J.H. (1960) Reaction of sixteen varieties of alfalfa to two species of root-knot nematodes. *Plant Disease Reporter* **44**, 441–3.

Richard, C., Aeghdadi, A. and Martin, J.G. (1991) *Aphanomyces euteiches*, a novel root pathogen to alfalfa in Quebec. *Plant Disease* **73**, 319.

Rincker, C.M., Marble, V.L., Brown, D.E. and Johansen, C.A. (1988) Seed production practices. In A.A. Hanson, D.K. Barnes and R.R. Hill (eds) *Alfalfa and alfalfa improvement*, p. 985–1021. American Society Agronomy, Madison, WI.

Rizvi, S.S.A. and Nutter, F.W. (1993) Seasonal dynamics of alfalfa foliar pathogens in Iowa. *Plant Disease* **77**, 1126–35.

Roberts, S.J., Zavaleta, L.R., Grube, A.H., Armbrust, E.J. and Pausch, R.D. (1987) Evaluation of a pest control technique: Fall-spray control of alfalfa weevil (Coleoptera: curculionidae) in alfalfa fields. *J. Economic Entomology* **80**, 559–66.

Rodriguez, R., Leath, K.T. and Hill, R.R. (1990) Pathogenicity of *Phoma medicaginis* var. *medicaginis* to roots of alfalfa. *Plant Disease* **74**, 680–3.

Ruesink, W.G. (1976) Modeling of pest populations in the alfalfa ecosystem with special reference to the alfalfa weevil. In R.L. Tummala, D.L. Haynes and B.A. Croft (eds) *Modeling for Pest Management*. Michigan State University Press, Ann Arbor, MI.

Salter, R., Miller-Garvin, J.E. and Viands, D.R. (1994) Breeeding for resistance to alfalfa root rot caused by *Fusarium* species. *Crop Science* **34**, 1213–16.

Sawyer, A.J. and Fick, G.W. (1987) Potential for injury to alfalfa by alfalfa blotch leafminer (Diptera: Agromyzidae): Simulations with a plant model. *Environmental Entomology* **16**, 575–85.

Schaber, B.D., Harper, A.M. and Entz, T. (1990) Effect of swathing alfalfa for hay on insect dispersal. *J. Economic Entomology* **83**, 2427–33.

Scheibner, R.A. (1969) Winter flaming helps control alfalfa weevil. *Hoards Dairyman* **114(4)**, 250–1.

Schlinger, E.I. and Dietrick, E.J. (1960) Biological control of insect pests aided by strip-farming alfalfa in an experimental program. *California Agriculture* **14(1)**, 8–9.

Schmierer, J.L. and Orloff, S.B. (1995) Weeds. In S.B. Orloff and H.L. Carlson (eds) *Intermountain alfalfa management*, pp. 51–64. University of California Publication **3366**, Oakland, CA.

Schmierer, J.L., Orloff, S.B. and Benton, R.W. (1995) Stand establishment. In S.B. Orloff and H.L. Carlson (eds) *Intermountain alfalfa management*, pp. 9–18. University of California Publication **3366**, Oakland, CA.

Schoner, C. and Norris, R.F. (1975) Windrow effects of weevils and weeds. *Proceedings 5th California Alfalfa Symposium*, pp. 41–8. University of California Cooperative Extension Service, Davis, CA.

Schrald, J.L. and Lei, J.D. (1991) Evaluation of a rapid ELISA test kit for detection of *Xylella fastidiosa* in landscape trees. *Plant Disease* **75**, 200–3.

Searls, E.M. (1934) The effect of cutting schedules upon the occurrence of the potato leafhopper (*Empoasca fabae*) and alfalfa yellows in Wisconsin. *J. Economic Entomology* **27**, 80–8.

Searls, E.M. (1935) Further studies on the effect of controlling the potato leafhopper (*Empoasca fabae* Harris) in alfalfa by designed cutting. *J. Economic Entomology* **28**, 831–3.

Sheesley, B., Grimes, D.W., McClellan, W.D., Summers, C.G. and Marble, V. (1974) Influence of wheel traffic on yield and stand longevity of alfalfa. *California Agriculture* **28(10)**, 6–8.

Shelton, A.M., Robertson, J.L., Tang, J.D., Perez, C., Eigenbrode, S.D., Preisler, H.K., Wilsey, T. and Cooley, R.J. (1993) Resistance of diamondback moth (Lepidoptera: Plutellidae) to *Bacillus thuringiensis* subspecies in the field. *J. Economic Entomology* **86**, 697–705.

Shoemaker, C.A. and Onstad, D.W. (1983) Optimization analysis of the integration of biological, cultural and chemical control of alfalfa weevil (Coleoptera: Curculionidae). *Environmental Entomology* **12**, 286–95.

Simonet, D.E. and Pienkowski, R.L. (1979) Impact of alfalfa harvest on potato leafhopper populations with emphasis on nymphal survival. *J. Economic Entomology* **72**, 428–3.

Smith, O.F. (1958) Registration of Lahontan alfalfa. *Agronomy J.* **50**, 684–5.

Smith, R.F. and Hagen, K.S. (1956) Enemies of the spotted alfalfa aphid. *California Agriculture* **10(4)**, 8–10.

Smith, R.F. and Hagen, K.S. (1959) Impact of commercial insecticide treatments. *Hilgardia* **29**, 131–54.

Sorensen, E.L., Horber, E.K. and Stuteville, D.L. (1983) Registration of KS80 alfalfa germplasm resistant to the blue alfalfa aphid, pea aphid, spotted alfalfa aphid, anthracnose, and downy mildew. *Crop Science* **23**, 599.

Sorensen, E.L., Horber, E.K. and Stuteville, D.L. (1985) Registration of KS108GH5 glandular-haired alfalfa germplasm with multiple pest resistance. *Crop Science* **25**, 1132.

Sorensen, E.L., Horber, E.K. and Stuteville, D.L. (1986a) Registration of KS94 GH6 glandular-haired alfalfa germplasm with multiple pest resistance. *Crop Science* **26**, 1088.

Sorensen, E.L., Stuteville, D.L. and Horber, E.K. (1986b) Registration of KS189 alfalfa germplasm with resistance to five diseases and two insects. *Crop Science* **26**, 204–5.

Sorensen, E.L., Byers, R.A. and Horber, E.K. (1988) Breeding for insect resistance. In A.A. Hanson, D.K. Barnes and R.R. Hill (eds) *Alfalfa and alfalfa improvement*, pp. 859–902. American Society Agronomy, Madison, WI.

Sorensen, E.L., Stuteville, D.L., Horber, E.K. and Dickerson, O.J. (1989a) Registration of KS204 alfalfa germplasm with resistance to five diseases, three insects, and the stem nematode. *Crop Science* **29**, 239.

Sorensen, E.L., Stuteville, D.L., Horber, E.K. and Peaden, R.N. (1989b) Registration of K81-7Ve2 alfalfa germplasm with resistance to five diseases and four insects. *Crop Science* **29**, 492.

Sorensen, E.L., Stuteville, D.L., Horber, E.K. and Skinner, D.Z. (1992) Registration of KS219 alfalfa germplasm with resistance to eight pests. *Crop Science* **32**, 502–3.

Sorensen, E.L., Stuteville, D.L., Horber, E.K. and Skinner, D.Z. (1994) Registration of KS223 glandular-haired alfalfa germplasm with multiple pest resistance. *Crop Science* **34**, 544.

Spencer, W.T. (1974) Observation on the control of the alfalfa blotch leafminer (*Agromyza frontella*) in alfalfa using chemical and cultural techniques. MS Thesis, University of New Hampshire, Durham NH.

Stary, P. (1970) Routine alfalfa (*Medicago sativa*) cutting program and its influence on pea aphid (*Acyrthosiphon pisum* Harris) populations. *Oecologia* **5**, 374–9.

Stern, V.M. (1969) Interplanting alfalfa in cotton to control lygus bugs and other insect pests. *Proceedings Tall Timbers Conference on Ecological Animal Control by Habitat Management* No. **1**, pp. 55–69. Tall Timbers Research Station, Tallahassee, FL.

Stern, V.M., Smith, R.F., van den Bosch, R. and Hagen, K.S. (1959) The integrated control concept. *Hilgardia* **29**, 81–101.

Stern, V.M., van den Bosch, R. and Leigh, T.F. (1964) Strip-cutting of alfalfa for lygus bug control. *California Agriculture* **18(4)**, 5–6.

Stern, V.M., van den Bosch, R., Leigh, T.F., McCutcheon, O.D., Sallee, W.R., Huston, C.E. and Garber, M.J. (1967) Lygus control by strip-cutting alfalfa. *University of California Agricultural Extension Service* Publication No. **AXT–241**. University of California, Oakland, CA.

Stuteville, D.L. and D.C. Erwin (eds) (1990) *Compendium of alfalfa diseases*. American Phytopathological Society, St. Paul, MN.

Summers, C.G. (1975) Efficacy of insecticide and dosage rates applied for control of the Egyptian alfalfa weevil and pea aphid. *J. Economic Entomol.* **68**, 864–6.

Summers, C.G. (1976) Population fluctuations of selected arthropods in alfalfa: influence of two harvesting practices. *Environmental Entomology* **5**, 103–10.

Summers, C.G. (1988) Cultivar and temperature influence on development, survival, and fecundity in four successive generations of *Acyrthosiphon kondoi* (Homoptera: Aphididae). *J. Economic Entomology* **81**, 515–21.

Summers, C.G. (1989) Effect of selected pests and multiple pest complexes on alfalfa productivity and stand persistence. *J. Economic Entomology* **82**, 1782–91.

Summers, C.G. and Cothran, W.R. (1972a) Egyptian alfalfa weevil: Winter and early spring treatments for control in California. *J. Economic Entomology* **65**, 1476–81.

Summers, C.G. and Cothran, W.R. (1972b) Timing of insecticide applications against the Egyptian alfalfa weevil: Control and effects on non-target insects. *Proceedings 2nd California Alfalfa Symposium*, pp. 1–7. University of California Cooperative Extension Service, Davis, CA.

Summers, C.G. and Gilchrist, D.G. (1991) Temporal changes in forage alfalfa associated with insect and disease stress. *J. Economic Entomology* **84**, 1353–63.

Summers, C.G. and Godfrey, L.D. (1997) Sowbugs/mites. *University of California pest management guidelines for alfalfa hay*, pp. A–18. UCPMG **2**. University of California, Davis, CA.

Summers, C.G. and Lehman, W.F. (1976) Evaluation of non-dormant alfalfa cultivars for resistance to the Egyptian alfalfa weevil. *J. Economic Entomology* **69**, 29–34.

Summers, C.G. and McClellan, W.D. (1975a) Interaction between Egyptian alfalfa weevil feeding and foliar disease: Impact on yield and quality in alfalfa. *J. Economic Entomology* **68**, 487–90.

Summers, C.G. and McClellan, W.D. (1975b) Effect of common leafspot on yield and quality of alfalfa in the san Joaquin Valley of California. *Plant Disease Reporter* **59**, 504–6.

Summers, C.G. and Newton, A.S. (1986) The leafhopper (*Empoasca* spp.) complex in California alfalfa: Impact on yield and quality. *Proceedings 16th California Alfalfa Symposium*, pp. 124–128. University of California Cooperative Extension Service, Davis, CA.

Summers, C.G. and Newton, A.S. (1989) Relationship of herbivore-imposed stress to weeds in alfalfa. *Environmental Entomology* **18**, 958–63.

Summers, C.G., Coviello, R.L. and Cothran, W.R. (1975) The effect on selected entomophagous insects of insecticides applied for pea aphid control in alfalfa. *Environmental Entomology* **4**, 612–4.

Summers, C.G., Gilchrist, D.G. and Norris, R.F. (eds) (1981) *Integrated pest management for alfalfa hay.* University of California Publication No. **4104**, Oakland, CA.

Summers, C.G., Hagan, K.S. and Stern, V.M. (1994) *University of California pest management guidelines for alfalfa hay.* UCPMG **2**, University of California, Davis, CA.

Syrett, P. and Penman, D.R. (1980) Studies of insecticide toxicity to lucerne aphids and their predators. *New Zealand J. Agricultural Research* **23**, 575–80.

Temme, D.G., Harvey, R.G., Fawcett, R.S. and Young, A.W. (1979) Effects of annual weed control on alfalfa forage quality. *Agronomy J.* **71**, 51–4.

Teuber, L.R., Gilchrist, D.G., Martensen, A.N., Cowling, W.A. and Bohling, S. (1982) UC 1249 and UC 1250, Stemphylium leafspot resistant alfalfa germplasm. *Crop Science* **23**, 805–6.

Teuber, L.R., Rupert, M.E., Gibbs, L.K. and Taggard, K.L. (1997) Breeding resistant alfalfa holds promise for silverleaf whitefly management. *California Agriculture* **51(3)**, 25–9.

Therrien, P. and McNeil, J. (1985) Effects of removing the plant canopy on pupal survival and adult emergence in alfalfa blotch leafminer, *Agromyza frontella* (Diptera: Agromyzidae). *Canadian Entomologist* **117**, 153–61.

Thies, J.A., Barnes, D.K., Rabas, D.L., Sheaffer, C.C. and Wilcoxson, R.D. (1992) Seedling date, carbofuran, and resistance to root-lesion nematode affect alfalfa stand establishment. *Crop Science* **32**, 786–92.

Thompson, L.S. and Willis, C.B. (1970) Effect of nematicides on root lesion nematodes and forage legume yields. *Canadian J. Plant Science* **50**, 577–81.

Thyr, B.D., Hunt, O.J., Hartman, B.J., Dean, J.G., McCoy, T.J. and Knous, T.R. (1984a) Registration of alfalfa germplasm NMP-14 with resistance to the common leaf spot pathogen *Pseudopeziza medicaginis* (Lib.) Sacc. [*Medicago sativa*]. *Crop Science* **24**, 388–9.

Thyr, B.D., Hunt, O.J., Hartman, B.J., McCoy, T.J. and Knous, T.R. (1984b) Registration of alfalfa germplasms NMP-11, NMP-12, and NMP-13 resistant to common leaf spot fungus *Pseudopeziza medicaginis* (Lib.) Sacc. [*Medicago sativa*]. *Crop Science* **24**, 387.

Tickes, B.R. (1989) Gopher control in alfalfa. *Proceedings 1989 Nevada Alfalfa Symposium*, pp. 121–5. University of Nevada, Reno NV.

Toscano, N.C. (1976) Managing complexes of pests for major cropping systems. *Proceedings 6th California Alfalfa Symposium*, p. 106. University of California Cooperative Extension Service, Davis, CA.

Townshend, J.L., Meskine, M. and Barron, G.L. (1989) Biological control of *Meloidogyne hapla* on alfalfa and tomato with the fungus *Meria coniospora*. *J. Nematology* **21**, 179–83.

University of California (1984) *Integrated pest management for cotton in the western region of the United States.* Publication No. **3305**. University of California, Oakland, CA.

United States Environmental Protection Agency (1996) Protecting endangered species. *Pesticides and Toxic Substances* **(H–7506C)**, 15 p. Washington DC.

van den Bosch, R. and Stern, V.M. (1962) The integration of chemical and biological control of arthropod pests. *Annual Review Entomology* **7**, 367–86.

van den Bosch, R., Schlinger, E.I., Hall, J.C. and Puttler, B. (1964) Studies on succession, distribution and phenology of imported parasites of *Therioaphis trifolii* (Monell) in southern California. *Ecology* **45**, 602–21.

van den Bosch, R. and Stern, V.M. (1969) The effect of harvesting practices on insect populations in alfalfa. *Proceedings Tall Timbers Conference on Ecological Animal Control by Habitat Management* No. **1**, pp. 47–51. Tall Timbers Research Station, Tallahassee, FL.

van Keuren, R.W. and Matches, A.G. (1988) Pasture production and utilization. In A.A. Hanson, D.K. Barnes and R.R. Hill (eds) *Alfalfa and alfalfa improvement*, pp. 515–538. American Society Agronomy, Madison, WI.

Ward, C.E., Dowdy, A.K., Berberet, R.C. and Stritzke, J.F. (1990) Economic analysis of alfalfa integrated management practices. *Southern J. Agricultural Economics* **22**, 109–15.

Welty, R.E., Baker, K.R. and Lindsey, D.L. (1980) Effects of *Meloidogyne hapla* and *M. incognita* on Phytophthora root rot of alfalfa. *Plant Disease* **64**, 1097–99.

Whisson, D. (1997) Vertebrate pest control in alfalfa hay. *Proceedings 27th California Alfalfa Symposium*, pp. 147–54. University of California Cooperative Extension Service, Davis, CA.

Whyte, R.O., Nilsson-Leissner, G. and Trumble, H.C. (1953) *Legumes in agriculture*. FAO Agricultural Studies Series No. **21**, Rome, Italy.

Wiersma, D.W., Grau, C.R. and Undersander, D.J. (1995) Alfalfa cultivar performance with differing levels of resistance to Phytophthora and Aphenomyces root rots. *J. Production Agriculture* **8**, 259–64.

Wilcoxson, R.G., Barnes, D.K., Frosheiser, F.I. and Smith, D.M. (1977) Evaluating and selecting alfalfa for reaction to crown rot. *crop Science* **17**, 93–6.

Williams, C.K. (1996) Ecological challenges to controlling wild rabbits in Australia using virally-vectored immunocontraception. *Proceedings 17th Vertebrate Pest Control Conference*, p. 24–30. University of California, Davis, CA.

Willis, C.B. and Thompson, L.S. (1979) Effects of phenamiphos, methyl bromide, and fallowing of *Pratylenchus penetrans*, yield of *Medicago sativa*, and *Fusarium* infections. *J. Nematology* **11**, 265–9.

Wilsie, C.P. (1962) *Crop adaptation and distribution*. Freeman, San Francisco.

Wilson, M.C., Stewart, J.K. and Vail, H.D. (1979) Full season impact of the alfalfa weevil, meadow spittlebug, and potato leafhopper in an alfalfa field. *J. Economic Entomology* **72**, 830–4.

Yeargan, K.V. (1985) Alfalfa: status and current limits to biological control in the eastern U.S. In M.A. Hoy and E.C. Herzog (eds) *Biological control in agricultural IPM systems*, pp. 521–36. Academic Press, New York.