Constraints on Asparagus Production: The Association of *Ophiomyia simplex* (Diptera: Agromyzidae) and *Fusarium* spp.

William R. Morrison III,* Julianna K. Tuell, Mary K. Hausbeck, and Zsofia Szendrei

**ABSTRACT**

Production of asparagus (*Asparagus officinalis* L.) is globally constrained by the “early decline” syndrome. The primary causal agents of early decline include *Fusarium proliferatum* (Matsushima) Nirenberg, *F. oxysporum* Wollenw. f. sp. *asparagi* S.I. Cohen, and *F. subglutinans* Wollenw. & Reinking. These pathogens together contribute to Fusarium crown and root rot (FCRR). Damage to asparagus stems, especially by the asparagus miner (*Ophiomyia simplex* Loew [Diptera: Agromyzidae]), has been associated with and shown to exacerbate FCRR. This review synthesizes the current information on this tripartite interaction, describes management strategies and their efficacy, and highlights needed research. Opportunities for future control of the asparagus miner and associated FCRR are presented. Research areas of interest include investigating the role of semiochemicals in the asparagus miner–Fusarium spp. interaction, identifying effective biological controls for the asparagus miner, and determining source populations of asparagus miner in new asparagus plantings.

Asparagus (*Asparagus officinalis* L.) production has become increasingly constrained globally during the past several decades because of problems with replanting asparagus fields and the early onset of asparagus stand decline (Grogan and Kimble, 1959; Elmer et al., 1996). Grogan and Kimble (1959, p. 122) defined asparagus decline as “a slow decline in the productivity of old asparagus plantings … to the point where the plantings become unprofitable to maintain.” The authors furthermore defined the replant problem as “the inability to establish productive plantings … where plantings have declined” (Grogan and Kimble, 1959, p. 122). Early decline of asparagus can lead to a reduction in the lifespan of planted fields by 5 to 8 yr; farmers are not able to recoup the investment associated with establishing asparagus fields (Elmer et al., 1996).

The fungi *Fusarium subglutinans* Wollenw. & Reinking, *Fusarium proliferatum* (Matsushima) Nirenberg (population D, *Gibberella fujikuroi*; Elmer, 1995), and *Fusarium oxysporum* Wollenw. f. sp. *asparagi* S.I. Cohen have been directly linked as partial causal agents in the premature decline (Keulder, 1999) and in the inability of new plantings to become established and be productive in locations where asparagus was previously grown (Grogan and Kimble, 1959; Elmer et al., 1996), even decades after asparagus.

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**Abbreviations:** FCRR, Fusarium crown and root rot; IPM, integrated pest management.
was last grown (Poll and Huiskamp, 1992). The asparagus miner, *Ophiomyia simplex* Loew (Diptera: Agromyzidae), acts as a putative vector for infection of asparagus plants with *Fusarium*. The larvae cause damage to the plant (Tuell and Hausbeck, 2008), exacerbating the early decline of asparagus fields (Gilbertson et al., 1985).

The purpose of this review is to examine and synthesize the current information about this tripartite interaction between asparagus, the *Fusarium* spp. associated with *Fusarium* crown and root rot (FCRR), and the asparagus miner. We examine potential methods to limit the asparagus miner and thereby reduce FCRR, and discuss future research areas, including the need for an integrated pest management (IPM) approach.

**METHODS**

This review is a synthesis of information regarding FCRR and the asparagus miner. The Michigan State University library collection and online databases, including Web of Science, ScienceDirect, SpringerLink, Google Scholar, and JSTOR, were searched for terms that included but were not limited to “asparagus miner,” “early decline,” “Fusarium crown and root rot,” and “replant problem.” For the purpose of the figures and tallying, the term “experiments” refers to individual experiments within studies, and it is possible to have more than one experiment dealing with a similar subject within a study. A full meta-analysis of the data in the reviewed articles was not possible because of the assumptions of normality were not fulfilled. Therefore, when there was sufficient replication between studies within a subject, nonparametric statistics (Mann–Whitney *U* tests) were used to evaluate differences in variables, since the assumptions of normality were not fulfilled.

**Biology, Biogeography, and Pathogenicity of *Fusarium* spp.**

Since FCRR was first described in 1908, *Fusarium* spp. have undergone extensive taxonomic revision, having originally been described as *F. moniliforme* J. Sheld. (Snyder and Tous- soun, 1965; Proctor et al., 2010). In 1983, *F. moniliforme* was taxonomically split into *F. proliferatum* and *F. subglutinans* (Nelson et al., 1983). On the other hand, *F. oxysporum* Wollenw. was originally identified as one of the causal agents of FCRR by Cohen and Heald (1941) and later grouped into formae speciales based on subsets of isolates that can infect specific host crops (Snyder and Hansen, 1940; Grogan and Kimble, 1959). However, *F. oxysporum* f. sp. *asperagii* may also be pathogenic to other crops, such as celery (*Apium graveolens* L.) and onion (*Allium cepa* L.) (Armstrong and Armstrong, 1969; Blok and Bollen, 1997; Elmer, 2001). Elmer (2001) has called the monophyletic status of *F. oxysporum* into question, and recent studies have shown that *F. oxysporum* is in fact polyphyletic and may not be a good biological species (Wong and Jeffries, 2006; for review, see Lievens et al., 2008).

*Fusarium* spp. are anamorphic (Gordon and Martyn, 1997) and nearly ubiquitous in both agricultural soils and native soils around the world (Hartung et al., 1990; Vujanovic et al., 2006). Both pathogenic and nonpathogenic strains of *Fusarium* spp. can be found in soils, even those that have not been planted to asparagus (Hartung et al., 1990). *Fusarium oxysporum* may infect young feeder roots, gaining entry at the junction where the feeder roots emerge (Graham, 1955; Smith and Peterson, 1983) between epidermal cells. Subsequently, the fungus moves into the cells, radiating intercellularly into the cortex of the root. Lesions that are small, red, and elliptical develop on the feeder root tips and along the root (Shoemaker, 1965 cf. Elmer, 2001), and may also be evident on the underground portion of the plant stem. Asparagus that is damaged or stressed from cultural practices or other means is more susceptible to FCRR (Nigh, 1990).

Different species of *Fusarium* are found in varying regions in the world: for example, in the Netherlands, *F. culmorum* (W.G. Sm.) Sacc. is associated with FCRR, while *F. proliferatum* and *F. oxysporum* are absent (Blok and Bollen, 1996). It is likely that *F. subglutinans* plays a minor role in the North American FCRR (Elmer et al., 1996), as it is less often isolated from asparagus plants (Vujanovic et al., 2006). In the United States, the primary pathogens associated with FCRR are considered to be *F. proliferatum* (teleomorph *Gibberella fujikuroi*; Elmer, 1995) and *F. oxysporum* f. sp. *asperagii*, which primarily infects the crown–stem region and roots, respectively (Van Bakel and Kerstens, 1970; Gordon and Martyn, 1997). *Fusarium oxysporum* is implicated in infecting and causing FCRR in the root system of asparagus (Van Bakel and Kerstens, 1970), although it has also been isolated from other parts of the asparagus plant (Tuell and Hausbeck, 2008). *Fusarium oxysporum* is thought to play a significant role in newly planted fields, often hindering establishment of asparagus (Cohen and Heald, 1941; Graham, 1955; Endo and Burkholer, 1971), while *F. proliferatum* is thought to affect older fields and thereby plays a key role in the early decline of asparagus.

**Symptoms, Severity, and Cost of *Fusarium* Crown and Root Rot**

Fusarium crown and root rot of asparagus symptoms include wilting, dwarfing, chlorosis, browning of vascular tissue, death to the growing point, and damping off in seedlings (Eskelsen and Schreiber, 1997; USDA, 1999). The pathogen spreads basipetally toward the crown, often causing premature plant death. Symptoms of infection are usually observed during midsummer, and infection with *Fusarium* spp. can also result in the complete destruction of the feeder roots and withering of the storage roots (Elmer et al., 1996). Damage from FCRR can be exacerbated by exposure to viral agents including AV-1, AV-2, and tobacco streak virus (Evans and Stephens, 1989; Knaflowski et al., 2008), asparagus allelopathic residues
The Biology and Role of the Asparagus Miner as a Vector

The asparagus miner is a bivoltine organism (Ferro and Gilbertson, 1982; Lampert et al., 1984; Tuell, 2003), and its only known host is asparagus (Spencer, 1973). In the United States, the asparagus miner occurs wherever asparagus is grown, including the major asparagus-producing regions of Washington (Eichmann, 1943), Michigan (Tuell, 2003), and California (Essig, 1913). The asparagus miner has also been recorded from other asparagus-growing regions in the world, including central Hungary, France, and Germany (Dingler, 1934). The asparagus miner was likely introduced to the United States from Europe (Dingler, 1934; Spencer, 1973) when asparagus was brought to the New World by French Huguenots (Schofield, 1946), despite being first recorded from Pennsylvania in 1869 by H. Loew.

Adults of the asparagus miner oviposit on the stem of the asparagus near the soil surface, and once the eggs hatch, the larvae start producing mines and shafts in the cortex of the asparagus stems (Barnes, 1937). The damage from the miner is considered to have a negligible effect on plant vigor (Dingler, 1934; Barnes, 1937; Eichmann, 1943). The asparagus miner typically has two generations per season, and asparagus plantings may exhibit nearly 80 to 100% mining predisposes the upper stems of asparagus to fungal disease, and the overwintering pupae serve as a form of inoculum of Fusarium spp. for the next growing season (Ferro and Gilbertson, 1982).

Increased incidence of the asparagus miner has been linked to increased severity in FCRR infection in asparagus (Damicone et al., 1987) and decreased yields. High populations of asparagus miner may exacerbate FCRR, resulting in decline of the asparagus yield until it is no longer profitable to harvest.

Managing Fusarium Disease

Most studies have focused on F. oxysporum (Fig. 2). There have been many attempts to limit FCRR through cultural, fumigant, and biological control approaches, including (i) using nonpathogenic Fusarium spp. (Reid et al., 2002); (ii) salting with NaCl (Reid et al., 2001; Elmer, 2004); (iii) using arbuscular mycorrhizae (Counts and Hausbeck, 2008); (iv) incorporating asparagus root residues (Bloch and Bollen, 1996); (v) performing biological soil disinfection (Bloch et al., 2008); (vi) using fungicides, including benomyl, thiophanate-methyl, and fluquinconazole (Counts and Hausbeck, 2008); (vii) employing antibiotics from Streptomyces griseus (Smith et al., 1990); and (viii) developing genetic resistance against Fusarium by gametophyte selection (Pontaroli and Camadro, 2001). These measures have exhibited varying levels of efficacy (Table 1).
Of the examined experiments, the vast majority of them target *F. oxysporum* (Fig. 2). There are very few studies that have specifically looked at *F. proliferatum*, the main agent currently implicated in the early decline of asparagus. This is likely due to the high degree of morphological similarity between *F. proliferatum* and *F. oxysporum* (Proctor et al., 2010). Advances in polymerase chain reaction–based (Yergeau et al., 2005) and genomics methods make it possible to correctly identify *F. proliferatum* and *F. oxysporum* by using calmodulin gene sequences (Mule et al., 2004).

The most extensively examined management practices include salting, and the use of nonpathogenic *Fusarium* spp. to compete with pathogenic *Fusarium* spp. Salting with NaCl is significantly better than employing nonpathogenic *Fusarium* species (Mann–Whitney U test: $U = 0, P < 0.0199$). Salting used to be standard practice among asparagus growers to control weeds in the 19th and beginning of the 20th centuries (Elmer et al., 1996), but fell into disuse with the advent of modern herbicides to counter weeds. The long-term consequences from salting fields may be a change in soil pH, salinity, and other parameters important for the yield of asparagus plantings (Hodupp, 1983). Reid et al. (2001) found that two annual applications of NaCl to a commercial production field in Michigan did not significantly affect levels of pH, potassium, magnesium, or calcium, nor did it increase the salinity in the soil from 15 cm. However, NaCl applications did increase salinity in the soil to 5.4 mS m$^{-1}$ in a deeper (15–30 cm) layer. Most studies where NaCl successfully reduced FCRR severity were conducted in greenhouses, growth chambers, or small field plots. The field-plot research was
conducted in severely declined asparagus plantings of a small, noncommercial scale and may not represent larger commercial production fields. When commercial field trials with salt were conducted in Michigan, there was no increase in the yield of asparagus (Reid et al., 2001). In addition, NaCl exacerbates Phytophthora crown and root rot, which is recognized as an important pathogen of asparagus in Michigan (Saude et al., 2008) and California (Falloon et al., 1991). As a result of these combined factors, salting is not a recommended strategy to control Fusarium spp.

Another cultural method that has been investigated is biological soil disinfestation (Table 1; Blom et al., 2008), which has been used to manage F. redolens Wollenw., with positive results. This process requires growers to dig up to 80 cm in the ground to deposit grass clippings and subsequently cover the entire field in airtight plastic. Because this method has not been attempted for other species of Fusarium and is labor intensive, more research is needed before any conclusive recommendations can be made.

Biological control has also been investigated as a means to manage FCRR. This has been performed using non-pathogenic Fusarium spp. (Blok and Bollen, 1996; Elmer, 2004; Counts and Hausbeck, 2008).

Much prior investment has been directed to developing Fusarium-resistant asparagus cultivars (e.g., Stephens et al., 1989; Dan, 1994; Dan and Stephens, 1995; He et al., 2002; He and Wolyn, 2005). However, this has not yielded a viable commercial cultivar. A promising long-term approach to combat FCRR involves gametophyte selection of asparagus plants resistant to Fusarium spp. (Pontaroli et al., 2000; Pontaroli and Camadro, 2001).

Select fungicides, fumigants, and an antibiotic significantly reduced FCRR, particularly thiophanate-methyl, metam-potassium, Telone C-35 (Dow AgroSciences, Indianapolis, IN), and faeriefungin (Table 1). Fungicides and fumigants have not been widely used to reduce FCRR, but field trials are ongoing (Hausbeck and Cortright, 2008). Further development and testing of fungicidal compounds targeting Fusarium spp. would benefit growers.

Stress is an important factor in promoting FCRR in asparagus (Nigh, 1990). Sandy soils, which are predominant in many asparagus-growing regions, especially in Michigan, are very porous and do not retain water, which may lead to water stress conditions for asparagus fields. Research into irrigation methods and timing to reduce environmental stress for asparagus could reduce FCRR severity.

Asparagus growers rely on herbicides for weed control, especially in young plantings. Growers have become concerned with specific herbicides and their observed negative effects on asparagus fern growth. Greenhouse trials were conducted to evaluate the effect of select herbicides on asparagus growth, and the application of mesotrione resulted in a reduction in crown weight. Field trials revealed that mesotrione can be phytotoxic to asparagus and could result in decreased yields (Rodriguez-Salamanca, 2010). Future research should investigate the effect that certain management regimes (including herbicides) have on asparagus plant vigor and the progression of FCRR. Overall, an effective strategy for combating FCRR should include a multipronged approach that includes fungicides, continuing selection for resistance against Fusarium spp., and certain cultural techniques such as avoiding herbicides that are phytotoxic to asparagus and irrigation to avoid environmental stress in asparagus.

Controlling Asparagus Miner Populations

The asparagus miner remains an understudied species, especially considering its role as a putative vector in the spread of FCRR in asparagus fields. Repeated applications of the insecticide diazinon after the harvesting season reduced asparagus miner incidence and severity of FCRR, and increased yield (Damicone et al., 1987). An action threshold has not been established for timing insecticide applications that target the asparagus miner, presenting added difficulty. Although a sampling regime for the asparagus miner that uses canopy-level sticky traps has been shown to help (Tuell, 2003), sticky traps are not species specific, and can therefore be time-consuming to process. A sampling regime that uses fewer traps, or a trap with a species-specific lure, may increase the efficiency of monitoring asparagus miner populations.

It is important to utilize IPM strategies to reduce reliance on insecticides and to manage populations of asparagus miner. One method is to incorporate biological control into a management regime for the asparagus miner, but there has only been limited research on the parasitoids of the species. In the United Kingdom, Giard (1904 c.f. Barnes, 1937) described a parasitoid, Dacnusa rondani Giard (Hymenoptera: Braconidae), on asparagus miner. About three decades later, also in the United Kingdom, Barnes (1937) described three additional hymenopteran parasitoids of the asparagus miner: Pedioius epigonus (Walker) (Eulophidae; formerly Pleurotus epigonus; Spencer, 1973), Sphegigaster sp. (Pteromalidae), and misidentified Chorebus rondanii (Giard) (Braconidae) as Dacnusa bathyzona Marshall (Griffiths, 1967). However, none of these biological control agents were evaluated for their efficacy, nor have any parasitoids been described in the United States. This aspect of research provides potential for the future management of both the asparagus miner and the associated FCRR.

Semiochemicals are chemicals emitted from plants or insects that may be used as a tool in an IPM program to manage the asparagus miner. To our knowledge, there have been no studies on the response of the asparagus miner to the volatiles of asparagus. If compounds that are attractive to the asparagus miner are identified, these could
Table 1. Overview of different techniques used to control Fusarium crown and root rot (FCRR).

<table>
<thead>
<tr>
<th>Management strategy</th>
<th>Target</th>
<th>Amount</th>
<th>Type</th>
<th>Description</th>
<th>Efficacy against FCRR</th>
<th>Change in condition</th>
<th>Citations</th>
</tr>
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<tbody>
<tr>
<td>Salting</td>
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<tr>
<td>NaCl</td>
<td>Foa</td>
<td>10 g L⁻¹ H₂O</td>
<td>Greenhouse</td>
<td>100 mL applied 1 wk after planting</td>
<td>Significant reduction in FCRR</td>
<td>39% decrease in root lesions, 16% increase in root weight</td>
<td>Elmer, 2008</td>
</tr>
<tr>
<td>NaCl</td>
<td>Foa</td>
<td>1% NaCl</td>
<td>Greenhouse</td>
<td>Added 100 mL after infection with Foa</td>
<td>Significant and strong reduction in FCRR</td>
<td>35% decrease in root lesions, NS increase in root weight</td>
<td>Elmer, 2004</td>
</tr>
<tr>
<td>NaCl</td>
<td>Foa and Fp</td>
<td>560–1120 kg ha⁻¹</td>
<td>Commercial field</td>
<td>Applied three times during April</td>
<td>NS</td>
<td>NS</td>
<td>Reid et al., 2001</td>
</tr>
<tr>
<td>NaCl</td>
<td>Foa and Fp</td>
<td>1120 kg ha⁻¹</td>
<td>Research field</td>
<td>Applied three times during April</td>
<td>No direct measure of FCRR</td>
<td>13% increase in the no. of stalks &gt; 0.79 cm</td>
<td>Reid et al., 2001</td>
</tr>
<tr>
<td>NaCl</td>
<td>Foa and Fp</td>
<td>0.32 g pot⁻¹</td>
<td>Greenhouse</td>
<td>Cl equivalent to other treatments</td>
<td>Significant reduction in FCRR</td>
<td>15.3% decrease in root rot, 0.55 g more fresh weight per plant</td>
<td>Reid et al., 2001</td>
</tr>
<tr>
<td>NaCl</td>
<td>Foa and Fp</td>
<td>17.1–34.2 mM</td>
<td>Growth chamber</td>
<td>Cl equivalent to other treatments</td>
<td>Significant and strong reduction in FCRR</td>
<td>27.4% decrease in root lesions from Fp, and 33.1% decrease in root lesions from Foa</td>
<td>Reid et al., 2001</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>Foa and Fp</td>
<td>17.1 mM</td>
<td>Growth chamber</td>
<td>Cl equivalent to other treatments</td>
<td>Significant and strong reduction in FCRR</td>
<td>14.8% decrease in root lesions from Fp, and NS decrease in root lesions from Foa</td>
<td>Reid et al., 2001</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>Foa and Fp</td>
<td>0.40 g pot⁻¹</td>
<td>Greenhouse</td>
<td>Cl equivalent to other treatments</td>
<td>NS</td>
<td>NS</td>
<td>Reid et al., 2001</td>
</tr>
<tr>
<td>NH₄Cl</td>
<td>Foa and Fp</td>
<td>34.2 mM</td>
<td>Growth chamber</td>
<td>Cl equivalent to other treatments</td>
<td>Significant and strong increase in FCRR</td>
<td>11.6% increase in root lesions from Fp, and 16.1% increase in root lesions from Foa</td>
<td>Reid et al., 2001</td>
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<td>NH₄Cl</td>
<td>Foa and Fp</td>
<td>0.29 g pot⁻¹</td>
<td>Greenhouse</td>
<td>Cl equivalent to other treatments</td>
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<td>Reid et al., 2001</td>
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<tr>
<td>MnCl₂</td>
<td>Foa and Fp</td>
<td>8.55 mM</td>
<td>Growth chamber</td>
<td>Cl equivalent to other treatments</td>
<td>NS</td>
<td>NS</td>
<td>Reid et al., 2001</td>
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<tr>
<td>MnCl₂</td>
<td>Foa and Fp</td>
<td>0.53 g pot⁻¹</td>
<td>Greenhouse</td>
<td>Cl equivalent to other treatments</td>
<td>NS</td>
<td>NS</td>
<td>Reid et al., 2001</td>
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<tr>
<td>Cultural practices</td>
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<tr>
<td>Biological soil disinfestation</td>
<td>NaCl</td>
<td>Fr</td>
<td>Abandoned field</td>
<td>Grass added at 80-cm soil depth and covered with airtight plastic</td>
<td>Significant and strong reduction</td>
<td>28.4–45.8% decrease in FCRR</td>
<td>Blok et al., 2008</td>
</tr>
<tr>
<td>AM† fungi addition</td>
<td>Foa</td>
<td>1.2 mL plant⁻¹ or 1.57 g L⁻¹</td>
<td>Commercial field</td>
<td>Addition by crown dip or irrigation</td>
<td>NS</td>
<td>NS</td>
<td>Counts and Hausbeck, 2008</td>
</tr>
<tr>
<td>Root residue</td>
<td>Foa</td>
<td>20 g kg⁻¹</td>
<td>Greenhouse</td>
<td>Sterilized asparagus root residues added</td>
<td>NS</td>
<td>NS</td>
<td>Blok and Bollen, 1996</td>
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<tr>
<td>Trichoderma harzianum</td>
<td>Foa</td>
<td>0.02 kg L⁻¹ or 55.6 g row-m⁻¹</td>
<td>Commercial field</td>
<td>Addition by crown dip or irrigation</td>
<td>Significant better stand count</td>
<td>9.5% better stand count</td>
<td>Counts and Hausbeck, 2008</td>
</tr>
<tr>
<td>Foxononetin</td>
<td>Foa</td>
<td>20 mg L⁻¹ H₂O</td>
<td>Greenhouse</td>
<td>Isoflavone that promotes AM fungi colonization, applied as 100-mL drench once after planting</td>
<td>Significant reduction in FCRR</td>
<td>7% reduction in root lesions</td>
<td>Elmer, 2008</td>
</tr>
<tr>
<td>Foxononetin</td>
<td>Foa</td>
<td>20 mg L⁻¹ H₂O</td>
<td>Research field</td>
<td>Soaked for 20 min in field</td>
<td>FCRR not directly measured</td>
<td>12% increase in the 3-yr total marketable spear weights</td>
<td>Elmer, 2008</td>
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<tr>
<td>Gametophyte selection</td>
<td>Foa</td>
<td>50–200 seeds treatment⁻¹</td>
<td>Commercial field</td>
<td>Controlled crosses exposed to 6% TOF</td>
<td>Significant reduction in FCRR</td>
<td>3.78–10.34% decrease in affected</td>
<td>Pontaroli and Camadro, 2001</td>
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<td>Lime</td>
<td>Foa and Fp</td>
<td>6719 kg ha⁻¹</td>
<td>Commercial field</td>
<td>Applied in the spring</td>
<td>No direct measure of FCRR</td>
<td>NS</td>
<td>Reid et al., 2001</td>
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(cont’d)
Table 1. Continued.

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<thead>
<tr>
<th>Management strategy</th>
<th>Target</th>
<th>Amount</th>
<th>Type</th>
<th>Description</th>
<th>Efficacy against FCRR</th>
<th>Change in condition</th>
<th>Citations</th>
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<tbody>
<tr>
<td>Nonpathogenic Fusarium spp.</td>
<td>Foa</td>
<td>427 kg ha(^{-1}) or 397 g dm(^{-1})</td>
<td>Commercial field</td>
<td>Addition by crown dip or irrigation</td>
<td>NS</td>
<td>NS</td>
<td>Counts and Hausbeck, 2008</td>
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<td></td>
<td>Foa</td>
<td>10(^4) spores mL(^{-1})</td>
<td>Greenhouse</td>
<td>Roots of plants soaked in 500 mL</td>
<td>NS</td>
<td>NS</td>
<td>Elmer, 2004</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>10(^4) spores mL(^{-1})</td>
<td>Greenhouse</td>
<td>Roots of plants soaked in 500 mL</td>
<td>NS</td>
<td>NS</td>
<td>Elmer, 2004</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>5 × 10(^5) spores mL(^{-1})</td>
<td>Research field</td>
<td>Crowns dipped in 10 L for 20 min</td>
<td>NS</td>
<td>NS decrease in root lesions, NS increase in stand counts, NS decrease in disease rating</td>
<td>Elmer, 2004</td>
</tr>
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<td></td>
<td>Foa</td>
<td>10(^4) spores mL(^{-1})</td>
<td>Greenhouse</td>
<td>Roots of plants soaked in 500 mL</td>
<td>Significant reduction in FCRR</td>
<td>10% reduction in root lesions</td>
<td>Elmer, 2004</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>10(^4) spores mL(^{-1})</td>
<td>Greenhouse</td>
<td>Roots of plants soaked in 500 mL</td>
<td>Significant reduction in FCRR</td>
<td>12% increase in the 3-yr total marketable spear weights</td>
<td>Elmer, 2008</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>5 × 10(^5) spores mL(^{-1})</td>
<td>Research field</td>
<td>Crowns dipped in 10 L for 20 min</td>
<td>Significant decrease in FCRR</td>
<td>NS decrease in root lesions, NS increase in stand counts, 13.8% decrease in disease rating</td>
<td>Elmer, 2004</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>10(^4) spores mL(^{-1})</td>
<td>Greenhouse</td>
<td>Roots of plants soaked in 500 mL</td>
<td>Significant increase in root weight</td>
<td>27.3% greater root weight with NaCl, 16.7% greater root weight without NaCl</td>
<td>Elmer, 2004</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>10(^4) spores mL(^{-1})</td>
<td>Greenhouse</td>
<td>Roots of plants soaked in 500 mL</td>
<td>Significant reduction in FCRR</td>
<td>8% reduction in root lesions</td>
<td>Elmer, 2008</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>10(^4) spores mL(^{-1})</td>
<td>Research field</td>
<td>Soaked for 20 min in field</td>
<td>FCRR not directly measured</td>
<td>12% increase in the 3-yr total marketable spear weights</td>
<td>Elmer, 2008</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>5 × 10(^5) spores mL(^{-1})</td>
<td>Research field</td>
<td>Crowns dipped in 10 L for 20 min</td>
<td>Significant decrease in FCRR</td>
<td>NS decrease in root lesions, NS increase in stand counts, 15.4% decrease in disease rating</td>
<td>Elmer, 2004</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>10(^4) spores mL(^{-1})</td>
<td>Greenhouse</td>
<td>Roots of plants soaked in 500 mL</td>
<td>Significant increase in root weight</td>
<td>25.6% better stand condition</td>
<td>Counts and Hausbeck, 2008</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>0.6 g L(^{-1}) or 76.5 kg ha(^{-1})</td>
<td>Commercial field</td>
<td>Fungicide addition by crown dip or irrigation trial</td>
<td>NS</td>
<td>NS</td>
<td>Counts and Hausbeck, 2008</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>1.20 g L(^{-1}) or 5.67 g 30.5 row-m(^{-1})</td>
<td>Commercial field</td>
<td>Fungicide addition by crown dip or irrigation trial</td>
<td>NS</td>
<td>NS</td>
<td>Counts and Hausbeck, 2008</td>
</tr>
<tr>
<td></td>
<td>Foa</td>
<td>1.20 g L(^{-1})</td>
<td>Commercial field</td>
<td>Fungicide addition by crown dip or irrigation trial</td>
<td>Significant better stand condition</td>
<td>25.6% better stand count</td>
<td>Counts and Hausbeck, 2008</td>
</tr>
<tr>
<td>Cannonball 50WP</td>
<td>Foa and Fp</td>
<td>14.2 g 378.5 L(^{-1})</td>
<td>Commercial field</td>
<td>Crown soak</td>
<td>Significant increase in vigor</td>
<td>Reduced Foa and Fp by 1520 CFU g soil(^{-1})</td>
<td>Hausbeck et al., 2006</td>
</tr>
</tbody>
</table>

(cont’d)
potentially be used for baits in traps, making population sampling more precise and effective.

Research is also needed on the identification of source populations of asparagus miner in new plantings of asparagus. It is not known where asparagus miner populations originate and if they use alternative hosts; it is assumed that they come from volunteer asparagus plants (N. Myers, personal communication, 2010). The types of habitats or vegetation outside production fields that harbor the asparagus miner should be identified and methods pursued to suppress immigrating populations.

**CONCLUSIONS AND FUTURE RESEARCH**

There are >250,000 ha of asparagus globally (Benson, 2009), representing a major investment of economic resources. Fusarium crown and root rot is a significant barrier to increased productivity. Moreover, FCRR is a difficult disease to manage and therefore efforts to date have focused on exclusion of the pathogen via soil fumigation of seedling nurseries, crown fungicidal soaks, and cultural strategies, including a neutral pH of the soil, no tillage, and other horticultural techniques (e.g., no over-picking) to enhance plant vigor. Due to the link between FCRR and the asparagus miner, it is necessary to address each. An IPM strategy is needed to address the following: (i) the role of pheromones in attracting asparagus miner to asparagus, and the pheromones driving mating behavior; (ii) identifying habitats that act as reservoirs of asparagus miner for newly planted fields; (iii) identifying and increasing the efficacy of natural enemies of the asparagus miner; (iv) developing an economic threshold for pesticide application to guide management of the asparagus miner; (v) alleviating human-induced plant damage (e.g., the impact of specific herbicides weakening the asparagus crown and making it more vulnerable); (vi) using cultural techniques to reduce natural stresses to asparagus; and (vii) delivering effective pesticides and fungicides via drip irrigation to the root zone. A program that results from research advances will manage asparagus miner and FCRR in a cost-effective manner with minimal impact on ecosystems.

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