Floriculture and Ornamental Biotechnology ©2008 Global Science Books

Management of Fungus Gnats (*Bradysia* spp.) in Greenhouses and Nurseries

Raymond A. Cloyd*

Kansas State University, Department of Entomology, Manhattan, KS 66506-4004 USA

Correspondence: * rcloyd@ksu.edu

ABSTRACT

Fungus gnats, *Bradysia* spp., were not considered economic insect pests until recently when it was realized they are actually major insect pests of greenhouses and nurseries. The primary species encountered are *Bradysia coprophila* and *B. impatiens*, although other species may be found in greenhouses and nurseries. Both adults and larvae may directly and indirectly disseminate or transmit a wide-range of plant-pathogens including *Botrytis cinerea*, *Thielaviopsis basicola*, *Verticillium albo-atrum*, and *Fusarium avenaceum*. The larvae causes direct damage when feeding on plant roots or tunneling into plant crowns. The presence of high larval populations can result in significant crop losses. Certain growing media influence fungus gnat development and reproduction, and fungus gnat adults are attracted to and tend to lay eggs in growing media that are moist and microbially active. Scouting for fungus gnats is critical in order to detect populations before they reach damaging levels. This involves the use of yellow sticky cards for the adults, and potato disks for the larvae, which are laid on the surface of the growing medium. Currently, there are no thresholds to determine when to implement management strategies against fungus gnats. Fungus gnat management involves a holistic approach requiring implementation of cultural (sanitation and water management), chemical (microbial insecticides and insect growth regulators), and biological control (predatory mites, predatory beetles, and entomopathogenic nematodes) strategies.

Keywords: biological control, contamination, cultural control, growing medium, insecticides, monitoring, pest management

CONTENTS

INTRODUCTION

Fungus gnats, *Bradysia* spp. (Diptera: Sciaridae) were initially considered only minor insect pests, primarily breeding in growing medium containing house plants or in mushroom beds with minimal consideration that they could be a problem in ornamental cropping systems (Ellisor 1934). It wasn't until observations made by Hungerford (1916), Weigel and Sasscer (1923), MacLeod and Butler (1934), and Dennis (1978) that fungus gnats were determined to be of economic importance. Since then, fungus gnats are now recognized as major insect pests in both greenhouses and nurseries (Dennis 1978; Hamlen and Mead 1979), and are one of the few insect pests in which the damaging life stage (e.g. larvae) is located within the growing medium (Cloyd 2000). They are especially a problem under conditions of excessive moisture that commonly occur during propagation, which is associated with cuttings and plug production when plants are initiating root systems (Lindquist 1997; Cloyd 2000). Fungus gnat adults are primarily a nuisance causing minimal plant damage (Cloyd 2000); however, adult females lay eggs that hatch into larvae that are responsible for directly damaging plants by feeding on roots (Hungerford 1916; Wilkinson and Daugherty 1970; Fawzi and Kelly 1982). Furthermore, both the adults and larvae may disseminate plant-pathogens (James *et al.* 1995; Stangellini *et al.* 1999; El-Hamalawi and Stangellini 2005).

BIOLOGY, FEEDING AND DAMAGE

The species most commonly encountered in greenhouses and nurseries are *Bradysia coprophila* Comstock and *B. impatiens* Johannsen (Lindquist *et al.* 1985; Wilkinson and Daugherty 1970; Fenemore 1977; Alberts *et al.* 1981; Lindquist 1994). Fungus gnats have a life cycle that consists of an egg, four larval instars, a pupa, and an adult (**Fig. 1**). A generation may be completed in 20 to 28 days although this is dependent on temperature (Wilkinson and Daugherty 1970; Cloyd 2000). Fungus gnat adults are winged, approximately 3.0 to 4.0 mm in length, with long legs and antennae (**Fig. 1**). Adults tend to fly around or congregate near the surface of the growing medium, and live from 7 to 10 days. Females deposit 100 to 200 eggs into the cracks and crevices of the growing medium. Eggs hatch into white,

Received: 2 October, 2008. Accepted: 27 October, 2008.

Mini-Review

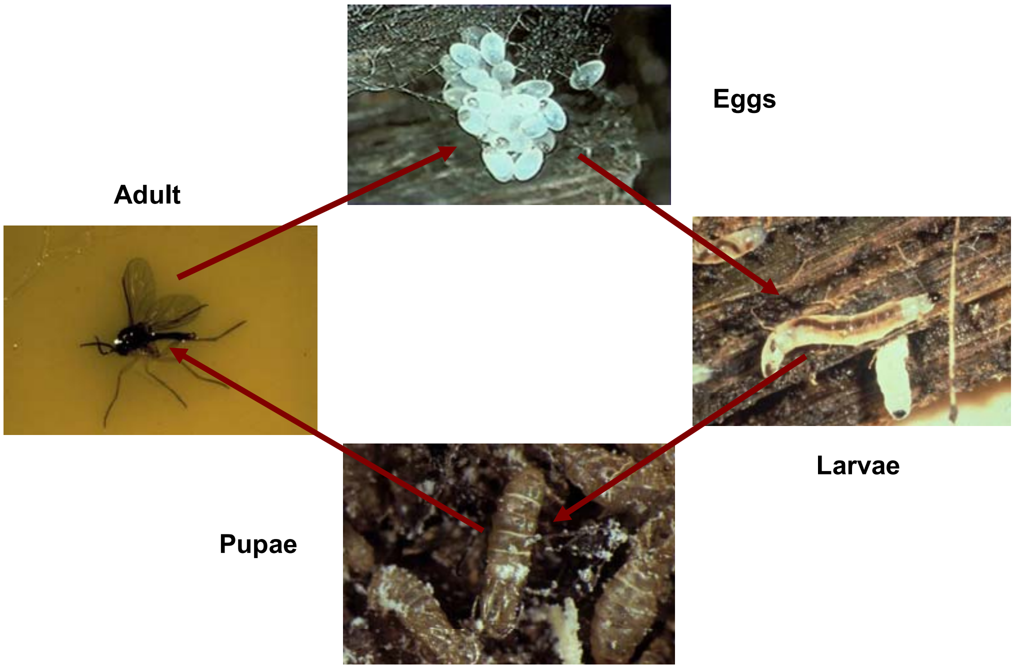

Fig. 1 Life cycle of fungus gnats (*Bradysia* spp.) from egg to adult.

translucent or slightly translucent, legless larvae that are approximately 6.0 mm long. A characteristic diagnostic feature of fungus gnat larvae is a distinct black head capsule (**Fig. 1**) (Ellisor 1934; Cloyd 2000). The larvae, in general, are located within the top 2.5 to 5.0 cm of the growing medium or inside plant tissue (Dennis 1978). In fact, *Bradysia* spp. larvae feed on plant roots, primarily the root hairs, and organic matter in the upper 2.0 cm of growing media (Kennedy 1971). However, the larvae may be distributed throughout the growing medium profile even in the bottom of containers near drainage holes (RAC and ERZ, unpublished data). Fungus gnat larvae may also emerge from the growing medium to feed on leaves and stems (Leath and Newton 1969). Fungus gnat larvae prefer growing media with high moisture contents (Hungerford 1916) and require various bacteria and fungi as an integral or supplemental food source in order to complete development (Baumberger 1919; Brues 1946). Furthermore, the type of food source fed upon by fungus gnat larvae determines abundance and relative fitness of mature adults, and the reproductive potential of females. For example, fungus gnat larvae that consume the mycelia and sclerotia of *Sclerotinia sclerotiorum* (Lib.) de Bary and *Botrytis porri* (Buchw.) develop into "healthy" adults (Anas and Reeleder 1988a); however, larvae that feed on sclerotia and/or mycelium of *Sclerotinia minor* Jagger, *Fusarium solani* Martius, *Botrytis cinerea* (Pers.:Fr), or *Trichoderma viride* Pers typically do not develop into mature adult females or they are sterile (Anas and Reeleder 1988a).

Fungus gnat larvae feed on a wide-range of ornamental plants grown in both greenhouses and nurseries including *Capsicum* spp., *Cyclamen* spp., poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch), *Geranium* spp., transvaal daisy (*Gerbera jamesonii* H. Bolus ex. Hook. f.), *Gloxinia* spp., *Impatiens* spp., bedding plants, and vegetable transplants (Jagdale *et al.* 2004). Young plants and/or seedlings are especially susceptible to injury from larval feeding (Gauthier 1989; Chambers *et al.* 1993), more so than mature plants, unless fungus gnat larval populations are extremely abundant.

Feeding by the larval stages directly damages developing root systems and interferes with the plants' ability to uptake water and essential nutrients (Jarvis *et al.* 1993), resulting in stunted growth. The larvae may also cause indirect damage during feeding by predisposing plants to attack from fungal pathogens via creating wounds that allow entry of soilborne plant-pathogens (Leath and Newton 1969; Gardiner *et al.* 1990; Jarvis *et al.* 1993). Additionally, both the larvae and adults can transmit fungal diseases including *Botrytis* spp., *Pythium* spp., *Fusarium* spp., and *Verticillium* spp. from diseased to non-infected plants (Kalb and Millar 1986; Favrin *et al.* 1988; Keates *et al.* 1989; Gardiner *et al.* 1990; Gillespie and Menzies 1993; James *et al.* 1995). Both the adults and larvae of *B. coprophila* may disseminate spores of *Thielaviopsis basicola* Berk. & Broome to pansy (*Viola* x *Wittrockiana* Gams.) seedlings via surface contamination (Harris 1995). Fungus gnat adults may carry the spores of certain foliar and soilborne plant-pathogens on their bodies including *B. cinerea*, *Fusarium oxysporum* f. sp. *radicis-lycopersici* Jarvis & Shoemaker, *T. basicola*, *Verticillium albo-atrum* Reinke & Berthold, and *Fusarium avenaceum* (Fr.:Fr) (Kalb and Millar 1986; Gillespie and Menzies 1993; James *et al.* 1995; Stangellini *et al.* 1999; El-Hamalawi and Stanghellini 2005). The adults can then disperse the spores of these plant-pathogens throughout a greenhouse or nursery. Fungus gnat (*B. impatiens*) larvae have been shown to ingest the propagules of *Pythium aphanidermatum* (Edson) and macroconidia of *F. avenaceum*, which they disseminate or introduce into young healthy plants during feeding (Jarvis *et al.* 1993; El-Hamalawi and Stanghellini 2005). It also has been reported that the oospores of *Pythium* spp. are able to survive passage through the digestive tract of *B. impatiens* and are intact and viable (able to germinate) after being excreted (Gardiner *et al.* 1990).

Although fungus gnats are considered an insect pest of greenhouses and nurseries, they may also serve as a biological control agent against certain soilborne pathogenic fungi (Garcia-Garza *et al.* 1997). For example, fungus gnat larvae feed on and reduce the survival of sclerotia of *S. sclerotiorum* and also increase the susceptibility of this pathogen to infection by the mycoparasite, *T. viride* (Anas and Reeleder 1988b).

MANAGEMENT

Growing medium

The growing medium type and components may influence the population dynamics of fungus gnats, and may provide a favorable substrate for development and reproduction of fungus gnats (Jagdale *et al.* 2004). For example, as the components of growing media become less uniform, porosity increases, which results in more open spaces present on the growing medium surface. These open spaces are sites where adult fungus gnat females can lay eggs (Anas Reeleder 1988b). It was determined by Binns (1973) that fungus gnat adult females laid eggs in crevices, which provided a more humid environment than on the surface, thus enhancing egg hatching and survival rate compared to eggs laid directly on the growing medium surface.

Growing media that contain a high level of microbial activity are preferred for fungus gnat breeding (Freeman 1983). Furthermore, growing media containing abundant organic matter tend to have larger pore spaces that provide ideal egg-laying sites for fungus gnat females (Anas and Reeleder 1988b). Any differences in fungus gnat female oviposition preferences among growing media are likely due to the species (fungus) and activity of microbial colonies present in the growing medium (Kennedy 1974; Anas and Reeleder 1988a). Decomposition, during the production cycle, of growing media containing hardwood bark increases the water-holding capacity and decreases air porosity, which may provide a favorable site for females to lay eggs thus potentially leading to increased fungus gnat populations (Hoitink 1989). Coconut coir has been implicated as a substrate that may inhibit fungus gnats; however, Evans *et al.* (1998) demonstrated that fungus gnats survived and reproduced just as well in a coir-based growing medium than a peat-based growing medium.

Currently, the selection of growing media that are either repellent or not attractive to reproductively mature females is being investigated as a sustainable strategy in reducing fungus gnat populations in both greenhouses and nurseries. Growing media vary in attracting fungus gnat adults (Lindquist 1994). In fact, it has been proposed that less attractive growing media may result in an increase in plant injury because fungus gnat larvae will feed on plant roots instead of fungi in the growing medium and that plant disease suppressive growing media may be more attractive to fungus gnats due to the greater microbial activity (Lindquist 1994). However, studies have demonstrated that fungus gnat adults are attracted to particular growing media. For example, Meers and Cloyd (2005) reported that adults of the fungus gnat, *Bradysia* sp. nr. *coprophila* Lintner (Diptera: Sciaridae) tended to lay eggs more often in Metro-Mix 560 (The Scott's Company; Marysville, OH) than either Sunshine LC1 Mix (SunGro Horticulture, Inc.; Bellevue, WA) or SB300 Universal Professional Growing Mix (Strong-Lite Horticulture Products; Pine Bluff, AK) growing media. Metro-Mix 560 consists of composted pine bark (35-45%) and coconut coir pith (20-30%) whereas the primary components of both Sunshine LC1 Mix and SB300 Universal Professional Growing Mix are Canadian sphagnum peat moss (75%) and composted pine bark (50%), respectively. Lindquist *et al.* (1985) indicated that fungus gnat adult emergence was higher in a growing medium amended with composted hardwood bark than a composted pine bark growing medium.

Adult fungus gnats are likely to be more attracted to or prefer moist growing media containing peat moss (Baker 1994) since these growing media have a higher level of fungal activity (Baker 1994; Olson *et al*. 2002), and certain fungi serve as a food source for fungus gnat adults (Kennedy 1974; Anas and Reeleder 1988a; Gardiner *et al.* 1990). Furthermore, the moisture content of the growing medium is critical in regards to fungus gnat survival (Olson *et al.* 2002; Cloyd and Dickinson 2008). For example, fungus gnat populations were lower in both extremely "wet" and "dry" growing media with the highest survival rates occurring in growing media with a 52% moisture content (Olson *et al.* 2002).

Cloyd *et al.* (2007a) reported that a higher percentage of fungus gnat adults were attracted to moist SB300 Universal Professional Growing Mix (92%) than to the same growing medium that had been oven dried (8%). It was also demonstrated that fungus gnat adults preferred the SB300 growing medium even if they were reared on Sunshine LC1 Mix. Many species of fungus gnats feed in compost piles so it is not surprising that they may enter greenhouses with compost or they are attracted to compost already present in the greenhouse or nursery (Freeman 1983). However, this had not been quantitatively demonstrated until Cloyd and Zaborski (2004) discovered that fungus gnats may be introduced into commercial greenhouse and nursery facilities via bagged soilless growing media or rooted plant plugs from wholesale distributors. As such, the authors' suggested that pasteurization of bagged soilless growing media may be necessary in order to avoid dealing with fungus gnat populations.

Cultural

Water management and sanitation are essential in alleviating problems with fungus gnats in both greenhouses and nurseries. For example, nurseries that have water accumulating and algae present tend to have "high" fungus gnat populations, which result in more damage to conifer seedlings. Furthermore, fungus gnats are typically more abundant in greenhouses and nurseries with soil floors then those with cement flooring (Keates *et al.* 1989). An approach to managing fungus gnat larvae that has been consistently recommended over the years includes allowing the soil or growing medium to dry-out occasionally, particularly the upper 2.5 to 7.6 cm. The "dry" surface is supposed to be less attractive to ovipositing females and even if any eggs are laid, they fail to hatch due to a lack of moisture (Ellisor 1934). However, allowing plant material to go "dry" is not a feasible option in either a greenhouse or nursery production system since it is essential to provide sufficient moisture for plant growth and development. Another cultural strategy that has been discussed by practitioners is the incorporation of abrasive materials such as diatomaceous earth (DE) into growing media or applying DE to the surface of growing media. Diatomaceous earth is composed of siliceous skeletons of diatoms (Ebeling 1971) that either remove the cuticular waxes, absorb oils and waxes in the outer cuticle, or rupture the cuticle thus causing extensive loss of water from the insect body (Korunic 1998). It had been suggested that incorporating DE into commercial growing media or applying DE on the growing medium surface would negatively affect fungus gnat adults as they emerge and/or prevent egg-laying by females (Quarles 1992). However, neither incorporation into growing media nor applications to the growing medium surface had any affect on fungus gnats (Cloyd and Dickinson 2005; Cloyd *et al.* 2007b). Additionally, a layer of sand (1.3 mm) placed over the top of the growing medium was proposed as a way to reduce fungus gnat infestations by creating an unattractive surface for ovipositing females (Hungerford 1916; Ellisor 1934); nonetheless, not even a 3.1 mm layer of sand was effective in preventing fungus gnat adult emergence or inhibiting female fungus gnats from laying eggs (Cloyd *et al.* 2007b). Since fungus gnat adults are attracted to light (Cloyd *et al.* 2007c), it might be possible to place yellow sticky cards near some type of light source in order to capture adults, which could reduce the population of ovipositing females.

Scouting

Scouting or monitoring is an essential component of pest management programs in detecting the presence of fungus gnats early, before populations build-up to damaging levels. Rutherford *et al.* (1985) determined the distribution and abundance of fungus gnat adults using white sticky cards, and extracted soil cores to assess the number of larvae per volume of soil. However, there was no apparent correlation between the number of adults captured on the white sticky cards and larval abundance in the soil. Yellow sticky cards, placed near the growing medium surface, are typically used for monitoring fungus gnat adults (Lindquist 1994) whereas potato disks or wedges placed on the surface of the growing medium are utilized in detecting the presence of larvae

(Harris *et al.* 1995; Lindquist 1997). The larvae are attracted to and congregate underneath the potato disks (Harris *et al.* 1995). Cabrera *et al.* (2003) demonstrated that potato disks recover a significantly higher percentage of larvae (38%) than carrot disks (23%) and that a monitoring duration of 48 hours is more efficient in recovering larvae than 24 hours. Attempts have been made to correlate the number of adults on yellow sticky cards with larvae present on potato disks; however, no such relationships have been established (Harris *et al.* 1995). Another issue is that there are no thresholds, which are the levels or numbers of insect pests that warrant the need to implement control measures, to assist greenhouse producers and nursery managers in making reliable estimates of fungus gnat larval densities in growing media. Furthermore, there is a lack of information pertaining to relationships between the density of fungus gnat larvae and plant damage, which would be useful in knowing when to execute either chemical or biological control strategies.

Chemical

Insecticides are typically used to deal with fungus gnats in greenhouses and nurseries (Hamlen and Mead 1979; Lindquist *et al.* 1985). Insecticides currently labeled for use against both fungus gnat adults and larvae in the USA are listed in **Table 1**. Since the larvae are the life stage that directly causes plant damage, most insecticides are applied as a drench to the growing medium (Hamlen and Mead 1979). These include microbial insecticides, insect growth regulators, and conventional insecticides (**Table 1**). The microbial insecticide *Bacillus thuringiensis* subsp. *israelensis* (Bti) tends to be more effective on the 1st and 2nd instars than the older (3rd and 4th) instars (Molloy *et al.* 1981; Osborne *et al.* 1985). Several different types of insect growth regulators are widely used to manage fungus gnats in greenhouse and nursery production systems (Ludwig and Oetting 2001; van Epenhuijsen *et al.* 2001); however, because insect growth regulators are only active on the larvae they must be applied before fungus gnat populations are abundant. Drench applications of the neonicotinoid-based insecticides including imidacloprid (Marathon; OHP, Inc., Mainland, PA), thiamethoxam (Flagship; Syngenta Professional Products, Greensboro, NC), and dinotefuran (Safari; Valent U.S.A. Corp., Walnut Creek, CA) have been shown to be effective against most fungus gnat larval instars (Cloyd and Dickinson 2006). In our research, we have found the insect growth regulators pyriproxyfen (Distance; Valent U.S.A. Corp., Walnut Creek, CA) and cyromazine (Citation; Syngenta Professional Products, Greensboro, NC), and the pyrrole insecticide/miticide chlorfenaypyr (Pylon; OHP, Inc., Mainland, PA) to be very effective against the larvae of the fungus gnat, *B.* sp nr. *coprophila* (Cloyd 2006; Cloyd and Chiasson 2007). Fungus gnat adults may be controlled with conventional insecticides such as those classified as pyrethroids in **Table 1**. However, pyrethroid-based insecticides are, in general, harmful to natural enemies and nontarget organisms (Croft and Whalon 1982; Smith and Stratton 1986), which may disrupt existing biological control programs for other arthropod (insect and mite) pests.

Table 1 The active ingredient (common name), trade name, and classification of insecticides labeled for use against fungus gnat (*Bradysia* spp.) adults and larvae in greenhouses and nurseries within the USA.

Active Ingredient (common name)	Trade Name	Classification
Adults		
Bifenthrin	Talstar	Pyrethroid
Chlorpyrifos + Cyfluthrin	Duraplex	Organophosphate + Pyrethroid
Cyfluthrin	Decathlon	Pyrethroid
Fenpropathrin	Tame	Pyrethroid
Fluvalinate	Mavrik	Pyrethroid
Petroleum oil	PureSpray Green	Horticultural oil
Potassium salts of fatty acids	M-Pede	Insecticidal soap
Larvae		
Acetamiprid	TriStar	Neonicotinoid
Azadirachtin	Azatin/Ornazin	Botanical
Bacillus thuringiensis subsp. *israelensis*	Gnatrol	Microbial
Chlorfenapyr	Pylon	Pyrrole
Chlorpyrifos	DuraGuard	Organophosphate
Cyromazine	Citation	Insect growth regulator
Diflubenzuron	Adept	Insect growth regulator
Dinotefuran	Safari	Neonicotinoid
Imidacloprid	Marathon	Neonicotinoid
Kinoprene	Enstar II	Insect growth regulator
Pyriproxyfen	Distance	Insect growth regulator
Thiamethoxam	Flagship	Neonicotinoid

Biological

The use of biological control against fungus gnats has been readily adopted by greenhouse producers throughout the USA due to the commercial availability of effective biological control agents. Biological control agents (=natural enemies) such as predatory mites and beetles, and entomopathogenic nematodes have been used extensively to manage fungus gnat larval populations in greenhouses and nurseries (Gillespie and Quiring 1990; Chambers *et al.* 1993; Lindquist 1994; Harris *et al.* 1995). The soil-dwelling predatory mite, *Hypoaspis miles* (Berlese) [=*Stratiolaelaps scimitus* (Womersley)] is commercially available from most biological control distributors and is used in greenhouses to manage fungus gnat larvae; however, fungus gnat eggs and pupae are not attacked (Gillespie and Quiring 1990; Wright and Chambers 1994; Walter and Campbell 2003). Optimum development and reproduction of *H. miles* occurs at temperatures between 15 and 30°C (Ydergaard *et al.* 1997). The rove beetle, *Atheta coriaria* Kraatz has been investigated as a potential biological control agent of fungus gnats (Carney *et al.* 2002) preferring fungus gnat larvae over oatmeal in choice tests conducted under laboratory conditions (Birken and Cloyd 2007). However, further controlled studies are needed in order to fully evaluate the impact that rove beetle adults and larvae have on the population dynamics of fungus gnats. The entomopathogenic nematode, *Steinernema feltiae* Filipjev, which is available commercially from a number of distributors [Nemasys (Becker-Underwood, Inc.; Ames, IA), NemaShield (Bio Works, Inc.; Victor, NY), Horticultural Scanmask (Biologic Comp.; Willow Hill, PA), and Entonem (Koppert U.S.A; Romulus, MI)] has been shown to be effective against fungus gnat larvae (Lindquist 1994; Gouge and Hague 1995). However, entomopathogenic nematodes must be applied before fungus gnat populations' build-up to damaging levels. The ability of entomopathogenic nematodes to control fungus gnats is influenced by a number of factors including application rate, timing of application, host plant, and entomopathogenic nematode strain used. In addition, the infectivity of entomopathogenic nematodes against fungus gnat larvae may differ depending on the growing medium type and moisture content (Jagdale *et al.* 2004; Georgis *et al.* 2006) and the fungus gnat larval stages may exhibit differences in susceptibility to entomopathogenic nematodes depending on the strain and even larval instars present (Harris *et al.* 1995). Finally, temperature is a major factor that may influence control of fungus gnat larvae by *S. feltiae* because the entomopathogenic nematode requires temperatures between 8 and 30°C for infection, and 10 and 25°C for reproduction (Grewal *et al.* 1994). It must be noted that there are concerns regarding the quality of commercially available entomopathogenic nematode products that are purchased by greenhouse producers and nursery managers (Gaugler *et al.* 2000; Caamano *et al.* 2008). An issue associated with the use of biological control agents for control of fungus gnats is compatibility between or among the different natural enemies. Although there is limited information associated with assessing intraguild predation, Jandricic *et al.* (2006) demonstrated that *S. feltiae* was compatible with *A. coriaria*; however, *A. coriaria* larvae were fed upon by the predatory mite, *Hypoaspis aculeifer* (Canestrini). In addition to the above mentioned biological control agents, preliminary results have shown that the entomopathogenic fungus, *Beauveria bassiana* (Balsamo) Vuellemin infects shore fly, *Scatella tenuicosta* Collin adults under laboratory conditions (Filotas *et al.* 2005). Although further investigation is required, applications of entomopathogenic fungi may eventually be an alternative means of dealing with fungus gnats.

SUMMARY

Fungus gnats (*Bradysia* spp.) are a major insect pest in greenhouse and nursery cropping systems because both the adults and larvae may cause direct and/or indirect plant damage resulting in possible economic losses. The challenge associated with dealing with fungus gnats is to approach management "holistically" by utilizing all the strategies described in this paper including scouting and growing medium selection, which are extremely important in alleviating problems with fungus gnats. Furthermore, greenhouse producers and nursery managers that implement proper water management and sanitation practices such as eliminating weeds and algae from production areas, and properly time the use of both insecticides and natural enemies will experience fewer problems with fungus gnats in ornamental cropping systems such as greenhouses and nurseries.

REFERENCES

Alberts SA, Kennedy MK, Carde RT (1981) Pheromone-mediated anemotactic flight and mating behavior of the sciarid fly *Bradysia impatiens*. *Environmental Entomology* **10**, 10-15

Anas O, Reeleder RD (1988a) Feeding habits of *Bradysia coprophila* on fungi and plant tissue. *Phytoprotection* **69**, 73-78

Anas O, Reeleder RD (1988b) Consumption of sclerotia of *Sclerotinia sclerotiorum* by larvae of *Bradysia coprophila*: influence of soil factors and interactions between larvae and *Trichoderma viride*. *Soil Biology and Biochemistry* **20**, 619-624

Baker JR (1994) *Insects and Related Pests of Flowers and Foliage Plants: Some Important, Common and Potential Pests in The Southeastern United States*, AG-136. North Carolina Cooperative Extension Service, 106 pp

Baumberger JP (1919) A nutritional study of insects with special reference to micro-organisms and their substrata. *Journal of Experimental Zoology* **28**, 1-81

Binns ES (1973) Laboratory rearing, biology and chemical control of the mushroom sciarid *Lycoriella auripila* (Diptera: Lycoriidae). *Annals of Applied Biology* **73**, 119-126

Birken EM, Cloyd RA (2007) Food preference of the rove beetle, *Atheta coriaria* Kraatz (Coleoptera: Staphylinidae) under laboratory conditions. *Insect Science* **14**, 53-56

Brues CT (1946) Insect dietary. An account of the food habits of insects. Harvard University Press, Cambridge, MA, 466 pp

Caamano EX, Cloyd RA, Solter LF, Fallon DJ (2008) Quality assessment of two commercially available species of entomopathogenic nematodes: *Steinernema feltiae* and *Heterorhabditis indica*. *HortTechnology* **18 (1)**, 84-89

Cabrera AR, Cloyd RA, Zaborski ER (2003) Effect of monitoring technique in determining the presence of fungus gnat, *Bradysia* spp. (Diptera: Sciaridae), larvae in growing medium. *Journal of Agricultural and Urban Entomology* **20 (1)**, 41-47

Carney VA, Diamond JC, Murphy GD, Marshall D (2002) The potential of *Atheta coriaria* Kraatz (Coleoptera: Staphylinidae), as a biological control agent for use in greenhouse crops. *IOBC/WPRS Bulletin* **25 (1)**, 37-40

Chambers RJ, Wright EM, Lind RJ (1993) Biological control of glasshouse sciarid flies (*Bradysia* spp.) with the predatory mite, *Hypoaspis miles*, on cyclamen and poinsettia. *Biocontrol Science and Technology* **3**, 285-293

Cloyd RA, Dickinson A (2008) Procedure to enhance the recovery rate of fungus gnat, *Bradysia* sp. nr. *coprophila* Lintner (Diptera: Sciaridae) adults from growing medium. *HortScience* **43 (5)**, 1528-1530

Cloyd RA, Dickinson A, Larson RA, Marley KA (2007a) Effect of growing media and their constituents on fungus gnat, *Bradysia* sp. nr. *coprophila* (Lintner) adults. *Insect Science* **14**, 467-475

Cloyd RA, Dickinson A, Kemp KE (2007b) Effect of diatomaceous earth and *Trichoderma harzianum* T-22 (Rifai Strain KRL-AG2) on the fungus gnat *Bradysia* sp. nr. *coprophila* (Diptera: Sciaridae). *Journal of Economic Entomology* **100 (4)**, 1353-1359

Cloyd RA, Dickinson A, Larson RA, Marley KA (2007c) Phototaxis of fungus gnat, *Bradysia* sp. nr *coprophila* (Lintner) (Diptera: Sciaridae), adults to different light intensities. *HortScience* **42 (5)**, 1217-1220

Cloyd RA, Chiasson H (2007) Activity of an essential oil derived from *Chenopodium ambrosioides* on greenhouse insect pests. *Journal of Economic Entomology* **100 (2)**, 459-466

Cloyd RA, Dickinson A (2006) Effect of *Bacillus thuringiensis* subsp. *israelensis* and neonicotinoid insecticides on the fungus gnat *Bradysia* sp nr. *coprophila* (Lintner) (Diptera: Sciaridae). *Pest Management Science* **62**, 171-177

Cloyd RA (2006) Fungus gnats and IGRs. *GrowerTalks* **70 (2)**, 114-116

Cloyd RA, Dickinson A (2005) Effects of growing media containing diatomaceous earth on the fungus gnat *Bradysia* sp. nr. *coprophila* (Lintner) (Diptera: Sciaridae). *HortScience* **40 (6)**, 1806-1809

Cloyd RA, Zaborski ER (2004) Fungus gnats, *Bradysia* spp. (Diptera: Sciaridae), and other arthropods in commercial bagged soilless growing media and rooted plant plugs. *Journal of Economic Entomology* **97(2)**, 503-510

Cloyd RA (2000) Fungus gnat and shorefly management strategies: panel discussion. In: King AI, Greene ID (Eds) *Proceedings of 16th Conference on Insect and Disease Management on Ornamentals*, Society of American Florists, Alexandria, VA, pp 57-59

Croft BA, Whalon ME (1982) Selective toxicity of pyrethroid insecticides to arthropod natural enemies and pests of agricultural crops. *Entomophaga* **27**, 3-21

Dennis DJ (1978) Observations of fungus gnat damage to glasshouse cucurbits. *New Zealand Journal of Experimental Agriculture* **6**, 83-84

Ebeling W (1971) Sorptive dusts for pest control. *Annual Review of Entomology* **16**, 123-158

El-Hamalawi ZA, Stangellini ME (2005) Disease development on lisianthus following aerial transmission of *Fusarium avenaceum* by adult shore flies, fungus gnats, and moth flies. *Plant Disease* **89 (6)**, 619-623

Ellisor LO (1934) Notes on the biology and control of *Neosciara ocellaris* (Comstock) (Diptera, Sciaridae). *Iowa State Journal of Science* **9**, 25-36

Evans MR, Smith JN, Cloyd RA (1998) Fungus gnat population development in coconut coir and sphagnum peat based substrates. *HortTechnology* **8**, 406-409

Favrin RJ, Rahe JE, Mauza B (1988) *Pythium* spp. associated with crown rot and cucumbers in British Columbia greenhouses. *Plant Disease* **72**, 683-687

Fawzi TH, Kelly WC (1982) Cavity spot of carrots caused by feeding of fungus gnat larvae. *Journal of American Society of Horticultural Science* **107**, 1177-1181

Fenemore PG (1977) Fungus gnats – little known pests of glasshouse plants. *Commercial Horticulture* **9 (2)**, 14-15

Filotas M, Castrillo L, Vandenberg J, Sanderson J, Wraight S (2005) Novel isolates of the entomopathogenic fungus *Beauveria bassiana* for biological control of the shore fly, *Scatella tenuicosta*. *IOBC/WPRES Bulletin* **28 (1)**, 95-98

Freeman P (1983) Sciarid flies. In: Fitton MG (Ed) *Handbook for the Identification of British Insects* (Vol 9, Part 6), Royal Entomological Society of London, 68 pp

Garcia-Garza JA, Reeleder RD, Paulitz TC (1997) Degradation of sclerotia of *Sclerotinia sclerotiorum* by fungus gnats (*Bradysia coprophila*) and the biocontrol fungi *Trichoderma* spp. *Soil Biology and Biochemistry* **29 (2)**, 123-129

Gardiner RB, Jarvis WR, Shipp JL (1990) Ingestion of *Pythium* spp. by larvae of fungus gnat *Bradysia impatiens* (Diptera: Sciaridae). *Annals of Applied Biology* **116**, 205-212

Gaugler R, Grewal P, Kaya HK, Smith-Fiola D (2000) Quality assessment of commercially produced entomopathogenic nematodes. *Biological Control* **17**, 100-109

Gauthier NL (1989) A new alternative to chemicals for fungus gnat control. *Connecticut Greenhouse Newsletter* **151**, 13-16

Georgis R, Koppenhofer AM, Lacey LA, Belair G, Duncan LW, Grewal PS, Samish M, Tan L, Torr P, van Tol RWHM (2006) Successes and failures in the use of parasitic nematodes for pest control. *Biological Control* **38 (1)**, 103-123

Gillespie DR, Menzies JG (1993) Fungus gnats vector *Fusarium oxysporum* f. sp. *radicis-lycopersici*. *Annals of Applied Biology* **123**, 539-544

Gillespie DR, Quiring DMJ (1990) Biological control of fungus gnats, *Bradysia* spp. (Diptera: Sciaridae), and western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), in greenhouses using a soil-dwelling predatory mite, *Geolaelaps* sp. nr. *aculeifer* (Canestrini) (Acari: Laelapidae). *Canadian Entomologist* **122**, 975-983

Gouge DH, Hague NGM (1995) Glasshouse control of fungus gnats, *Bradysia paupera*, on fuchsias by *Steinernema feltiae*. *Fundamentals of Applied Nematology* **18 (1)**, 77-80

Grewal PS, Selvan S, Gaugler R (1994) Thermal adaptation of entomopathogenic nematodes: niche breadth for infection, establishment, and reproduction. *Journal of Thermal Biology* **19**, 245-253

Hamlen RA, Mead FW (1979) Fungus gnat larval control in greenhouse plant production. *Journal of Economic Entomology* **72**, 269-271

Harris MA (1995) Dissemination of the phytopathogen *Thielaviopsis basicola* by the fungus gnat *Bradysia coprophila* and biological control of these pests by *Fusarium proliferatum* and steinernematid nematodes. Ph.D Dissertation, University of Georgia, Athens, GA, 59 pp

Harris MA, Oetting RD, Gardner WA (1995) Use of entomopathogenic nematodes and a new monitoring technique for control of fungus gnats, *Bradysia coprophila* (Diptera: Sciaridae), in floriculture. *Biological Control* **5**, 412-418

Hoitink HAJ (1989) Integrated control of *Pythium*, *Rhizoctonia* and *Fusarium* diseases. In: *Proceedings of the Fifth Conference on Insect and Disease Management of Ornamentals*, February 26-28, 1989, Society of American Florists, Alexandria, VA, pp 116-121

Hungerford HB (1916) Sciari maggots injurious to potted plants. *Journal of Economic Entomology* **9**, 538-549

Jagdale GB, Casey ML, Grewal PS, Lindquist RK (2004) Application rate and timing, potting medium, and host plant effects on the efficacy of *Steinernema feltiae* against the fungus gnat, *Bradysia coprophila*, in floriculture. *Biological Control* **29**, 296-305

James RL, Dumroese RK, Wenny DL (1995) *Botrytis cinerea* carried by adult fungus gnats (Diptera: Sciaridae) in container nurseries. *Tree Planters' Notes* **46**, 48-53

Jandricic S, Scott-Dupree CD, Broadbent AB, Harris CR, Murphy G (2006) Compatibility of *Atheta coriaria* with other biological control agents and reduced-risk insecticides used in greenhouse floriculture integrated pest management programs for fungus gnats. *Canadian Entomologist* **138**, 712-722

Jarvis WR, Shipp JL, Gardiner RB (1993) Transmission of *Pythium aphanidermatum* to greenhouse cucumber by the fungus gnat *Bradysia impatiens* (Diptera: Sciaridae). *Annuals of Applied Biology* **122**, 23-29

Kalb DW, Millar RL (1986) Dispersal of *Verticillium albo atrum* by the fungus gnat (*Bradysia impatiens*). *Plant Disease* **70**, 752-753

Keates SE, Sturrock RN, Sutherland JR (1989) Populations of adult fungus gnats and shore flies in British Columbia container nurseries as related to nursery environment, and incidence of fungi on the insects. *New Forests* **3**, 1-9

Kennedy MK (1974) Survival and development of *Bradysia impatiens* (Diptera: Sciaridae) on fungal and non-fungal food sources. *Annals of the Entomological Society of America* **67**, 745-749

Kennedy MK (1971) The significance of fungi in the ecology of *Bradysia impatiens*. MSc thesis, Cornell University, Ithaca, NY, 66 pp

Korunic Z (1998) Diatomaceous earths, a group of natural insecticides. *Journal of Stored Product Research* **34**, 87-97

Leath KT, Newton RC (1969) Interaction of a fungus gnat, *Bradysia* sp. with *Fusarium* spp. on alfalfa and red clover. *Phytopathology* **59**, 257-258

Lindquist RK (1997) Integrated pest management of poinsettia pests: fungus gnats. *Ohio Florists' Association Bulletin* **813**, 5-8

Lindquist RK (1994) Integrated management of fungus gnats and shore flies. In: Robb K (Ed) *Proceedings of 10th Conference on Insect and Disease Management on Ornamentals*, Society of American Florists, Alexandria, VA, pp 19-21

Lindquist RK, Faber WR, Casey ML (1985) Effect of various soilless root media and insecticides on fungus gnats. *HortScience* **20**, 358-360

Ludwig SW, Oetting RD (2001) Evaluation of medium treatments for management of *Frankliniella occidentalis* (Thripidae: Thysanoptera) and *Bradysia coprophila* (Diptera: Sciaridae). *Pest Management Science* **57 (12)**, 1114-1118

MacLeod GF, Butler FG (1934) Studies of millipede and gnat injuries to potato tubers. *Journal of Economic Entomology* **27**, 106-108

Meers TL, Cloyd RA (2005) Egg-laying preference of female fungus gnat *Bradysia* sp. nr. *coprophila* (Diptera: Sciaridae) on three different soilless substrates. *Journal of Economic Entomology* **98**, 1937-1942

Molloy D, Gaugler R, Jamnback H (1981) Factors influencing efficacy of *Bacillus thuringiensis* var. *israelensis* as a biological control agent of black fly larvae. *Journal of Economic Entomology* **74**, 61-64

Olson DL, Oetting RD, van Iersel MW (2002) Effect of soilless potting media and water management on development of fungus gnats (Diptera: Sciaridae) and plant growth. *HortScience* **37**, 919-923

Osborne LS, Boucias DG, Lindquist RK (1985) Activity of *Bacillus thuringiensis* var. *israelensis* on *Bradysia coprophila* (Diptera: Sciaridae). *Journal of Economic Entomology* **78**, 922-925

Quarles W (1992) Diatomaceous earth for pest control. *IPM Practitioner* **14 (5/6)**, 1-11

Rutherford TA, Trotter DB, Webster JM (1985) Monitoring fungus gnats (Diptera: Sciaridae) in cucumber greenhouses. *Canadian Entomologist* **117**, 1387-1394

Smith TM, Stratton GW (1986) Effects of synthetic pyrethroid insecticides on nontarget organisms. *Residue Reviews* **97**, 93-120

Stangellini ME, Rasmussen SL, Kim DH (1999) Aerial transmission of *Thielaviopsis basicola*, a pathogen of corn-salad, by adult shore flies. *Phytopathology* **89 (6)**, 476-479

van Epenhuijsen CW, Page BBC, Koolaard JP (2001) Preventative treatments for control of fungus gnats and shore flies. *New Zealand Plant Protection* **54**, 42-46

Walter DE, Campbell NJH (2003) Exotic vs endemic biocontrol agents: would the real *Stratiolaelaps miles* (Berlese) (Acari: Mesostigmata: Laelapidae), please stand up? *Biological Control* **26**, 253-269

Weigel CA, Sasscer ER (1923) Insects injurious to ornamental greenhouse pests. *U. S. Department of Agriculture Farmers Bulletin* **1362**, 47-48

Wilkinson JD, Daugherty DM (1970) The biology and immature stages of *Bradysia impatiens* (Diptera: Sciaridae). *Annals of Entomological Society of America* **63**, 656-660

Wright EM, Chambers RJ (1994) The biology of the predatory mite *Hypoaspis miles* (*Acari: Laelapidae*), a potential biological control agent of *Bradysia paupera* (*Dipt.: Sciaridae*). *Entomophaga* **39 (2)**, 225-235

Ydergaard S, Enkegaard A, Brodsgaard HF (1997) The predatory mite *Hypoaspis miles*: temperature dependent life table characteristics on a diet of sciarid larvae, *Bradysia paupera* and *B. tritici*. *Entomologia Experimentalis et Applicata* **85**, 177-187