

Swede Midge (Diptera: Cecidomyiidae), Ten Years of Invasion of Crucifer Crops in North America

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ABSTRACT The Swede midge, *Contarinia nasturtii* Kieffer (Diptera: Cecidomyiidae), a common insect pest in Europe, is a newly invasive pest in North America that constitutes a major threat to cruciferous vegetable and field crops. Since its first identification in Ontario, Canada, in 2000, it has rapidly spread to 65 counties in the provinces of Ontario and Quebec and has recently been found in canola (one of two cultivars of rapeseed, *Brassica napus* L. and *Brassica campestris* L.) in the central Prairie region where the majority of Canada's 6.5 million ha (16 million acres) of canola is grown. The first detection of Swede midge in the United States was in 2004 in New York cabbage (*Brassica oleracea* L.), but it has now been found in four additional states. Here, we review the biology of Swede midge, its host plant range, distribution, economic impact, pest status, and management strategies. We provide insight into this insect's future potential to become an endemic pest of brassica crops in North America. We also proposed research needed to develop tactics for handling this invasive pest in brassica crops.

KEY WORDS *Contarinia nasturtii*, invasive species, North America, integrated pest management

Cruciferous plants (Brassicaceae=Cruciferae) form a diverse set of wild and cultivated plants encompassing >375 genera (Jones and Luchsinger 1979). In temperate regions, cultivated crucifers include vegetables and oil-bearing field crops in the genera *Brassica* L. and *Raphanus* L. Regardless of the crop use, cultivated crucifers can be attacked by 50–60 insect species, of which ≈20 are major pests (Finch and Thompson 1992). The major insect species attacking crucifers belong to the orders Lepidoptera, Coleoptera, Hemiptera, Diptera, and Thysanoptera. All different parts and stages of crucifer plants can be damaged by insects belonging to one or more of these orders.

Considerable efforts have been made to develop components that can be used in integrated pest management (IPM) programs for the most important crucifer pests on high-value cruciferous vegetables. For example, in cabbage (*Brassica oleracea* L.) degree-day models can be used to predict flights of adult cabbage maggot, *Delia radicum* (L.), to help time early season insecticide treatments and cultural management practices (e.g., Jyoti et al. 2003). However, host plant resistance has been the most reliable practice for controlling onion thrips, *Thrips tabaci* Lindeman, a serious

cosmetic pest of headed cabbage (Shelton et al. 1998). However, by far the most effort has been devoted to developing thresholds for foliar-feeding Lepidoptera (e.g., Shelton et al. 1983), and these continue to be refined for use in extension-oriented publications (OMAFRA 1996, Eastman et al. 2005, Reiners and Petzoldt 2010). In the New York cabbage IPM program, early adoption of thresholds for control of Lepidoptera led to a 49% decrease in insecticide use and a 54% increase in the effectiveness of each insecticide application (Andaloro et al. 1983). Because of the success of these thresholds, it has been estimated that >80% of all cabbage growers in New York use major components of the IPM guidelines for insect management on cabbage (Reiners and Petzoldt 2010). We believe there are similar high adoption rates of IPM practices for cruciferous vegetables in other states and in Canada. However, the advances made to such IPM programs over the last several decades are at risk because of a new invasive insect pest that has resulted in some growers reverting to weekly spray programs.

Swede midge, *Contarinia nasturtii* Kieffer (Diptera: Cecidomyiidae), is a gall-forming pest of cruciferous plants that is common and endemic in Europe (Harris 1966) and southwestern Asia (Barnes 1946, Darvas et al. 2000). Host plants of Swede midge include most cultivated cruciferous vegetables (e.g., broccoli, cabbage, cauliflower, Brussels sprouts, and kale [all forms of *B. oleracea*]), cruciferous weeds, and canola (one of two cultivars of rapeseed, *Brassica napus* L. and *Brassica campestris* L.) (Barnes 1946, Stokes 1953a,b; Darvas et al. 2000; Hallett 2007; Chen et al. 2009b). Plant damage results from larval feeding which causes mis-

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shapen plants with twisted stems, crumpled leaves, swollen growing tips, multiple heads, and the formation of galls on leaves and flowers (Bardner et al. 1971, Allen et al. 2008, <http://www.nysaes.cornell.edu/ent/swedemidge/biology.html>), all of which can severely reduce product quantity, quality and marketability. In many parts of Europe, Swede midge is considered a major pest with frequent crop losses in spite of regular chemical treatments (den Ouden et al. 1987). Before 2000, it was not known to occur in North America, although damage symptoms typical of Swede midge on cruciferous crops were observed in Ontario, Canada, in 1996 (Hallett and Heal 2001).

In June 2000, the first Swede midge in North America was captured using yellow sticky traps in Ontario, Canada (Hallett and Heal 2001). Subsequently, Canadian researchers launched a Swede midge survey in cruciferous crops, and good evidence was found that Swede midge occurred in nine counties in Ontario and one county in Quebec in 2001. The number of infested counties in these provinces increased from 18 in 2005 to 49 in 2006 and 65 in 2008 (CFIA 2008). In 2007 and 2008, additional Canadian records were found in Nova Scotia, Prince Edward Island, Manitoba, and Saskatchewan (CFIA 2008). Detection was aided by the use of pheromone traps that became available in 2004 (Hillbur et al. 2005). In the United States, Swede midge was first reported in Niagara County, NY, in September 2004, although symptomatic plants had been observed in the field for several years (Kikkert et al. 2006). By the end of 2005, Swede midge was detected in five major cabbage-producing counties (Erie, Genesee, Monroe, Orleans, and Wyoming) in New York state. An additional 13 counties in New York and one each in Massachusetts (Hampshire), New Jersey (Sussex), and Connecticut (New Haven) have been reported having Swede midge based on molecular and morphological identifications of adults caught in pheromone traps (Chen et al. 2007, 2009b). To date, Swede midge has been detected in a total of 26 counties in New York, in addition to the three in surrounding states. An additional Swede midge infestation in Ottawa Co., OH, was confirmed in late 2009 based on Swede midge mitochondrial cytochrome oxidase subunit I gene (*COI*) sequence data (M.C. et al., unpublished data).

In the past 10 yr, Swede midge infestations in North America have spread rapidly and created intense responses from vegetable and canola farmers, especially in some areas of Canada. Crop losses due to Swede midge on some farms in Ontario, CA, have been reported to be as much as 85% (Hallett and Heal 2001). Researchers in the United States and Canada have been actively testing various strategies to control Swede midge and prevent its further spread in North America. To understand its pest status and management options, here we summarize present knowledge on its biology and control strategies (e.g., chemical, cultural control, and biological control) in North America. This is done to alert the larger entomological community in North America of this newly invasive

pest and to present a concise review of its biology and management.

Swede Midge Description and Life Cycle

In Ontario and Quebec, Canada, where Swede midge were first detected and remain the locations in North America where they are most abundant, adults (1.5–2 mm) emerge in mid- to late May, after overwintering in the soil in larval cocoons (Hallett et al. 2007, 2009b; Corlay and Boivin 2008). Mating occurs soon after emergence and females then begin to look for suitable hosts. Eggs are laid in clusters of two to 50 eggs on meristematic tissue, young leaves, or flowers of their host plants (Barnes 1946), with each female laying ≈ 100 eggs during her short lifetime (1–5 d). Eggs are small (≈ 0.3 mm) with color changing from transparent to a creamy white during the egg developmental period. The larval stage is the only life stage that can damage cruciferous plants. Swede midge larvae have a well-developed mouth apparatus consisting of the labrum, labium, mandibles, and maxillae. The exact feeding mechanism of Swede midge larvae is not clear; however, it is believed to be similar to other Cecidomyiidae species, i.e., larvae inject salivary fluids into the plant via highly specialized mandibles, and these substances react with plant cell components and cause physiological alterations in the plant, which allow the larva to suck liquids through its mouth (Hatchett et al. 1990). Larvae are initially ≈ 0.3 mm in length and reach a final size of 3–4 mm. They are transparent and become increasingly more yellow with age and are lemon-yellow at maturity. The larvae feed for 7–21 d before they drop to the ground to pupate. During periods of drought, larvae in the soil may remain dormant, with growth resuming after rainfall or irrigation (Readshaw 1966).

Seasonal development of Swede midge was studied in Ontario and Quebec, Canada, by using pheromone traps and emergence cages (Goodfellow 2005, Corlay and Boivin 2008). In Quebec, three to four generations of Swede midge were detected in 2004 and 2005 (Corlay and Boivin 2008). Based on MidgEmerge, a new predictive model developed using DYMEEX and Ontario and Quebec data on Swede midge adults and larvae, Hallett et al. (2009b) determined that currently there are four overlapping generations of Swede midge per year and two emergence phenotypes in North America with the last adult flights occurring in late September to early October.

Swede Midge Detection and Identification

It is difficult to detect Swede midge in the field because adults are short lived; pupae burrow into the soil; and the small larvae feed cryptically, near growing tips of plants and between tightly compressed leaves and petioles. Depending upon sampling time, larvae may be absent from plants exhibiting damage symptoms, making positive determination of an infestation difficult. Characteristic damage symptoms on plants (e.g., swollen, distorted or twisted young shoots and

leaf stalks, blind heads due to death of the meristem, brown scars on petioles or stems, and the presence of secondary bacterial rots) are often used as visual cues for the presence of Swede midge in fields (Allen et al., 2008, <http://www.nysaes.cornell.edu/ent/swedemidge>). However, these damage symptoms may easily be mistaken for common physiological (heat or frost stress) or nutritional problems (molybdenum deficiency), mechanical damage or other insect feeding. Other detection tools, such as sticky cards, incandescent and blacklight traps, fine mesh emergence tents, and sweep netting have been proposed, but they are not very practical due to low efficiency and indiscriminating captures (Hallett et al. 2007). Hillbur et al. (2005) found that a 1:2:0.02 mixture of (2S,9S)-diacetoxyundecane:(2S,10S)-diacetoxyundecane:(S)-2-acetoxyundecane extracted from the female's ovipositor could effectively attract Swede midge males under laboratory and field conditions with very high species specificity. The Swede midge sex pheromone blend maintained its attractiveness to Swede midge males for only 2 wk in fields if cotton dispensers were used; however, if polyethylene dispensers were used, its attractiveness could extend to >6 wk in Switzerland (Boddum et al. 2009). However, under Ontario field conditions, cotton wicks and polyethylene dispensers were found to be attractive for only 2 and 4 wk, respectively (R.H.H. et al. unpublished data). Availability of the pheromone blend greatly increases the ease and efficacy of Swede midge detection in fields. Hallett et al. (2007) reported that pheromone traps captured significantly more Swede midge than emergence traps, light traps and sticky cards, and subsequent work determined white Jackson traps (Scentry Biologicals, Inc., Billings, MT) to be more effective than other trap types and colors (R.H.H. et al. unpublished data).

Accurate identification of Swede midge has proven difficult, especially based on its morphological characteristics. Species identification based on morphological characters depends on examination of adult specimens. Swede midge wing venation is reduced with a straight radial vein and cubital fork in the middle third of the wing, whereas cross veins are absent; adults have long, filiform antennae with 12 flagellomeres on each antenna; female antennal segments are cylindrical with each flagellomere \approx 2 times longer than wide, whereas each flagellomere of a male antenna is divided into two separate nodes surrounded by a thread like looped sensillum (Harris 1966, Hallett and Heal 2001). However, it is often very difficult to observe these characteristics in field-collected specimens captured on sticky card traps or sticky surfaces in pheromone traps. In 2004, Frey et al. (2004) developed a polymerase chain reaction (PCR)-based molecular method for the Swede midge identification. This PCR-based Swede midge identification method involves two rounds of PCR reactions, with the first PCR reaction to amplify a 440-bp fragment of the *COI* gene from the specimens and with the second PCR reaction (i.e., nested PCR) to amplify a 285-bp Swede midge-specific fragment with a pair of Swede midge-

specific primers. This PCR-based method has been modified for more rapid identification of the Swede midge and successfully used for identification of Swede midge specimens collected in the United States (Kikkert et al. 2006; Chen et al. 2009b).

Although the Swede midge pheromone blend has been reported to have high species specificity in Europe (Hillbur et al. 2005), based on our experience, other midge species are regularly captured by the pheromone blend in New York state. Thus, capture in a pheromone trap and the accompanying molecular identification is required for accurate identification of the insect.

Host Range, Distribution, and Economic Impact

The Swede midge reportedly feeds on all cultivars of *B. oleracea*, *B. napus*, *Brassica rapa* L., and *Raphanus sativus* L., and many common cruciferous weed species, such as mustard (*Brassica* spp.), wild radish (*Raphanus raphanistrum* L.), shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.], field pepperweed [*Lepidium campestre* (L.) R. Br.], field pennycress (*Thlaspi arvense* L.), and yellow rocket (*Barbarea vulgaris* R. Br.) (Stokes 1953a,b; Hallett 2007; Chen et al. 2009b). A comprehensive list of Swede midge host plant species is available on the Cornell University Swede midge website (<http://www.nysaes.cornell.edu/ent/swedemidge>). Although Swede midge has a wide range of host plants, different host species show different susceptibility to Swede midge damage (Hallett 2007). In a choice test, Chen et al. (2009b) found that Swede midge significantly preferred cauliflower plants for oviposition over six common cruciferous weed species. It is unclear what role cruciferous weeds play in terms of Swede midge occurrence and population dynamics, but cruciferous weeds may serve as a reservoir to maintain Swede midge populations in agroecosystems when no suitable crop hosts are available (Chen et al. 2009b).

Temperature and moisture are considered to be the two most important factors responsible for Swede midge population distribution and growth (Readshaw 1961). Using a bioclimatic model, Olfert et al. (2006) determined that all Canadian provinces have suitable conditions for Swede midge establishment, with some areas being very favorable for Swede midge population growth. A revised version of that model (Mika et al. 2008) indicated potential for establishment south to Georgia, west to Colorado, Wyoming, Montana, and parts of Washington and Oregon. Both models used only natural rainfall. When irrigation was included in the model, some western states, including California, a major broccoli-producing state, became included in the potential range of infestation. With such an extensive potential range, the introduction of Swede midge into additional areas could result in the widespread distribution of Swede midge throughout North America. Under multiple climate change scenarios, Mika et al. (2008) project an increase to five generations per year, as well as substantial increases in areas designated as favorable or very favorable for Swede

midge establishment and population growth in North America, with the Canadian prairies, northern Ontario and Quebec, and the eastern seaboard and midwestern United States becoming most vulnerable to Swede midge establishment.

Swede midge can be a devastating pest to cruciferous crops because it damages growing tips of the plants, which makes it impossible for plants to recover. In addition, a wide range of host plants, multiple invasion paths (such as soil, transplant movement, wind, adult flight), cryptic feeding behavior, short-lived adults, and a lack of effective control methods allow Swede midge populations to thrive and cause significant losses. Crop losses on some Canadian farms due to Swede midge have been reported to be as much as 85% (Hallett and Heal 2001). In some areas of Europe, Swede midge infestations may account for 100% loss of the crop, despite treatment with insecticides.

Crucifers are an extremely important group of vegetables grown throughout the United States. The main fresh market vegetable crucifers (broccoli, cabbage, and cauliflower) were grown on nearly 121,406 ha (300,000 acres) nationwide and had a total value of US\$1.3 billion in 2009 (USDA-ERS 2010). In addition to these cruciferous vegetables, canola (rapeseed) is another host for Swede midge and is annually grown on 445,155 ha (>1.1 million acres) in the United States. More than 6,474,981 ha (16 million acres) of canola is grown in Canada (Statistics Canada 2010). In 2005, Swede midge was first reported to have caused damage to field-planted spring canola plants in Ontario, Canada (<http://www.inspection.gc.ca/english/plaveg/protect/rmd/rmd-08-03e.shtml>). Damage to canola is dependent upon crop phenology at time of Swede midge infestation and may range from slight to severe (R.H.H., unpublished data). Because of the proximity of infested areas in Canada, >8,498 ha (>21,000 acres) of crucifers (cabbage, broccoli, cauliflower, Chinese cabbage, and Brussels sprouts) grown in the northeastern United States, a value exceeding US\$100 million, is particularly vulnerable to invasion by this pest. Swede midge has become established in parts of New York state, which may further serve as a source for movement to other states in the United States (Kikkert et al. 2006). Substantial economic losses caused by Swede midge are likely to occur if effective control strategies are not developed and implemented.

Control Strategies

Since the first identification of Swede midge in North America in 2000 (Hallett and Heal 2001), different control strategies, such as insecticidal control, cultural control, host plant resistance, and biological control, have been extensively tested under laboratory, greenhouse, and open field conditions by researchers in Canada and the United States.

Insecticidal Control. One of the first actions taken for an immediate control of Swede midge and prevention of further spread in North America was to screen synthetic insecticides labeled for crucifer veg-

etables. Initial field efficacy trials in Ontario, Canada, in 2001–2002, focused on the pyrethroids, due to their use in Europe for Swede midge control, and led to registration of λ -cyhalothrin for Swede midge control in Canada in 2003 (Hallett et al. 2009a). Twenty insecticides belonging to 12 different classes were evaluated using foliar spray, soil drenches, or seed treatment in U.S. laboratory trials against Swede midge adults and larvae (Wu et al. 2006). Acephate, λ -cyhalothrin, acetamiprid, chlorpyrifos and methomyl were effective as foliar spray insecticides against larvae, and except for acetamiprid, they were also effective on adults. Acetamiprid, imidacloprid, and thiamethoxam were very effective when applied as soil drench and provided 100% control of Swede midge larvae for 7 wk. Clothianidin and thiamethoxam provided 100% control when used as seed treatments. Because the movement of vegetable seedlings could be an important reason for the rapid spread of Swede midge in North America, Chen et al. (2007) evaluated the efficacy of foliar sprays of acetamiprid on Swede midge on cauliflower seedlings. Acetamiprid caused 99.5, 100, and 99.8% mortality of larvae when cauliflower seedlings were sprayed before inoculation with Swede midge 0 and 4 d after inoculation, respectively. The efficacy of acetamiprid was reduced to 69.9% when seedlings were sprayed at 8 d after the inoculation because Swede midge larvae could successfully pupate and emerge after the spray. Thus, acetamiprid can provide effective control of Swede midge on seedlings at the early stage of insect occurrence.

During the early phase of regional colonization by Swede midge in Canada, field trials conducted in 2001 and 2002 indicated that foliar insecticide applications were effective in keeping damage within marketable limits for cabbage and broccoli plants (Hallett et al. 2009a). However by 2005 and 2006, insecticide treatments were rarely able to maintain damage levels within marketable limits (i.e., damage rating <1). This was in spite of the fact that early season applications (e.g., seed treatments, greenhouse plug tray drenches, band sprays, or a combination) of neonicotinoid insecticides (e.g., imidacloprid, acetamiprid, and clothianidin) could provide control of Swede midge for several weeks (Hallett et al. 2009a). Low efficacy of synthetic insecticides under field conditions in some areas of Canada was initially assumed to be associated with insecticide resistance, spray coverage, and density-dependent efficacy of insecticide applications (e.g., high Swede midge population pressure resulting in a higher number of survivors). Parallel comparison studies between a field-collected Canadian Swede midge population and a laboratory strain originating from Switzerland indicated that both strains had similar susceptibilities to seven common insecticides, which suggested that insecticide resistance would not be a key reason for the insecticide control failure in the field (Hallett et al. 2009a). In addition, no significant density-dependent and spray coverage effects were found in laboratory studies with Swede midge occurring on cauliflower plants when acetamiprid was used as a foliar spray; however, the insecticide treat-

ment was only able to control Swede midge for 9 d in fields (M.C. et al., unpublished data). Residual efficacy trials indicate that foliar applications of registered products have 4–10 d residual activity against Swede midge (R.H.H., unpublished data). Therefore, rather than high population pressure or insecticide resistance, multiple and overlapping generations of Swede midge, in conjunction with short residual activity of insecticides, might be the key reasons for failure of control in Canada. Such results further indicate that proper insecticide application timing, and multiple management tactics, will be crucial in achieving acceptable control of Swede midge. A recent field test in Canada, undertaken where Swede midge populations are quite high, showed that a drench of imidacloprid provided complete control for >25 d (A.M.S. et al., unpublished data).

Cultural Control. Along with insecticidal strategies, control of Swede midge with cultural practices also has been investigated in North America. Because Swede midge spends its pupal stage in soil, the role of soil abiotic factors, such as soil type and moisture content, have been explored for regulating population establishment and abundance. Under laboratory conditions, Chen and Shelton (2007) evaluated the impacts of six different types of soils collected in New York state on Swede midge pupation and emergence. Swede midge emergence was significantly reduced in extremely wet or dry soils, regardless of soil type, suggesting that soil type alone is not a major factor regulating Swede midge abundance. Optimal moisture content for Swede midge emergence varied from 25 to 75% among different soils. Chen and Shelton (2007) found that most Swede midge pupated within the top 1 cm of the soils and that the addition of >5 cm of soil cover could effectively reduce the emergence number and delay the time of emergence in laboratory studies. However, tillage was not found to reduce emergence in the field, probably because tillage did not bury all pupae at the maximum tillage depth but distributed them throughout the soil column (R.H.H. et al., unpublished data). In addition, tillage probably increased the depth to which precipitation could percolate and loosened the soil column, thus stimulating emergence and facilitating the movement of pupae to the surface (R.H.H. et al., unpublished data).

Because crop rotation has proven to be effective to control other midge species in different crop systems (Golightly and Woodville 1974, Faheemah and Sulaiman 1990), rotation also has suggested for Swede midge (Taylor 1912, Rygg and Braekke 1980, Theunissen et al. 1997, ISMTF 2005). However, there were no published data to validate this claim. Under confined laboratory conditions, Chen et al. (2009a) evaluated the control effects of 11 simulated cauliflower–sweet corn (*Zea mays* L.) and cauliflower–kidney bean (*Phaseolus vulgaris* L.) crop rotation systems on Swede midge, also taking into account the potential role of cruciferous weeds. The effectiveness of one cycle of nonhost crop rotation could be reduced if cruciferous weeds were present; however, two consecutive cycles of nonhost plant crop rotations provided full control

of Swede midge, regardless of the presence of the cruciferous weeds. Similarly, a 3-yr field survey demonstrated that cruciferous weeds may not be able to maintain a Swede midge population in fields for >2 yr in the absence of preferred cultivated host plants, i.e., cruciferous vegetables (Chen et al. 2009b). These laboratory and field studies suggest that crop rotation could be a powerful component of a Swede midge management program. However, considering reports that some proportion of the population may remain in diapause for more than one winter (Rygg and Braekke 1980), and the availability of a wide range of cruciferous weeds, control of Swede midge by using crop rotation needs to be evaluated in conjunction with weed management and field sanitation efforts.

Other cultural practices include the use of barriers to prevent Swede midge adults from moving into fields and managing planting and harvesting dates of crucifer crops. Previous studies have shown that 1.4-m-high mesh fencing can reduce Swede midge damage to broccoli (Wyss and Daniel 2004). The use of a harvestable barrier crop also may prove effective in reducing host finding, and thus damage, by the Swede midge, and this is currently under investigation (R.H.H. et al., unpublished data). Barriers may be effective in fields newly planted to crucifers and those in which crop rotation is practiced. However, it is not an appropriate approach in fields with continual crucifer production, except potentially where the field is planted and barrier erected after the emergence of the overwintered generation of midges. The timing of crop planting also may be manipulated to reduce the risk of damage by Swede midge. Planting only early season crucifer crops could reduce damage on plants at the early life stages when plants are most vulnerable to Swede midge. Broccoli production in some parts of Sweden was reportedly abandoned as a result of high Swede midge infestations in the late 1970s (B. Jonsson, personal communication). Although broccoli is susceptible to Swede midge infestation in all growing stages, crop phenology is an important factor in the severity of damage occurring. Susceptibility of cabbage to Swede midge declines once heading has occurred. Winter canola (i.e., fall-planted) and early planted spring canola experience little damage compared with late planted spring canola (R.H.H. and M. K. Sears, unpublished data).

Host Plant Resistance. Host plant resistance is a major component of IPM and has been successfully used for insect pest management (Stoner 1992, Smith 2005). Swede midge feeds on a wide range of cruciferous plants (Barnes 1946; Stokes 1953a,b; Darvas et al. 2000; Hallett 2007; Chen et al. 2009b), but these plants display different degrees of susceptibility. The relative resistance and susceptibility of broccoli, cabbage, cauliflower, and Brussels sprouts to Swede midge was investigated in a 3-yr Ontario field study conducted shortly after the discovery of Swede midge (Hallett 2007). In general, broccoli cultivars experienced more severe damage than cabbage, cauliflower, and Brussels sprouts. 'Paragon', 'Eureka', and 'Packman' broccoli (Stokes Seed Ltd., St. Catharines, ON, Canada) were

highly susceptible to the Swede midge, whereas 'Triathlon' and 'Regal' broccoli showed reduced susceptibility to damage and slower development of damage symptoms. No differences in damage severity and progression of damage symptoms were found between normal and red cultivars of cabbage and cauliflower. In two different planting patterns (monoculture and mixture planting), 23 common cultivars of cabbage, broccoli, cauliflower, and mustard (Harris Seeds, Rochester, NY) in the northeastern United States were evaluated for host plant tolerance to Swede midge both under laboratory and field conditions in New York State. Cauliflower cultivar 'American-Taka' was the most susceptible under both planting patterns, while cabbage 'Lectro' and Mustard 'Greenwave' were the most tolerant (Chen et al. unpublished data). Such information could be used for identifying potential sources of resistance to the Swede midge, improving vegetable breeding programs, and providing growers with planting recommendations.

Biological Control. Invasive species are generally believed to be more successful in the new region of invasion than in their native region due in part to the absence of coevolved natural enemies, resulting in lower age specific mortality of the invasive species (Drake 2003). In Europe, its region of origin, Swede midge larvae are parasitized by *Pirene eximia* Haliday (Hymenoptera: Chalcididae) (Bovien and Knudsen 1950), *Synopeas* sp. (Hymenoptera: Platygasteridae) (Rogerson 1963, Readshaw 1966, 1968), and *Platygaster* sp. (Hymenoptera: Platygasteridae) (Readshaw 1966). As a relatively new invader to North America, no specialized natural enemies have been found in the region (Corlay et al. 2007), although *Medetera* sp. (Diptera: Dolichopodidae) reportedly prey on Swede midge adults (Goodfellow 2005). Corlay et al. (2007) found that polyphagous coccinellid predators *Harmonia axyridis* (Pallas) and *Coccinella septempunctata* L. could prey on Swede midge larvae under laboratory conditions with the former showing a higher voracity than the latter. However, it is unlikely that lady beetles would forage for Swede midge larvae living between tightly compressed tissue of whole plants. The entomopathogenic nematode *Heterorhabditis bacteriophora*, at an inoculation rate of 1,000 infective juveniles per larva, caused 90–100% mortality to Swede midge larvae in loam, sandy loam, clay, and muck soils (Corlay et al. 2007). The soil bacterium *Bacillus thuringiensis* subsp. *israeliensis*, when used as foliar spray in the laboratory, caused significant mortality to Swede midge larvae on infested broccoli plants (Wu et al. 2006), which is in agreement with other studies in which the *B. t. israeliensis* strain showed activity to dipteran species (Oestergaard et al. 2007). Vegetable cropping systems harbor great diversities of biological control agents (Word-Burkness et al. 2007) that may be helpful for overall suppression of Swede midge. However, to economically and sustainably control Swede midge, further study is needed to identify and use more effective natural enemies of the pest.

Challenges and Conclusions

Once well-established in an area, the Swede midge is virtually impossible to eradicate. Consequently, the Canadian Food Inspection Agency and USDA Animal Plant Health Inspection Agency both changed the status of Swede midge from a regulated or reportable/actionable pest to a deregulated or nonreportable/nonactionable pest in April 2009 (CFIA 2009, <http://blogs.cce.cornell.edu/cvp/archives/63>). Based on our research and that of others, it is evident that no single control strategy is able to provide complete control of Swede midge. Only an IPM approach that incorporates cultural techniques, sound chemical practices, and use of potentially effective biological control agents, could possibly suppress Swede midge populations below economic thresholds. Although we have learned much about Swede midge in the last 10 yr in North America, much remains unclear and more challenges are yet to come.

Based on our experience, the Swede midge has a scattered distribution in the United States and seems to have had many separate introduction points. Although no longer considered a quarantine pest in Canada or the United States, preventing introductions to new regions within these countries is critical to minimizing the potential future impact of Swede midge. Further research is needed to evaluate the impacts of various invasion paths (such as soil, transplant movement, wind, adult flight) on population establishment and vegetable production. Although a considerable amount of research on understanding Swede midge biology and exploring management strategies has been done in Europe with European strains (Hornig 1953; Readshaw 1966, 1968; Thygesen 1966; Rygg and Braekke 1980; den Ouden et al. 1987; Theunissen et al. 1997; Wyss and Daniel 2004), genetic variances between North America strains and European strains need investigation to track the regional infestation patterns of specific strains. Inconsistent control efficacies between laboratory and field conditions on Swede midge by using synthetic insecticides and soil manipulation require more research to characterize the roles of various biotic and abiotic factors affecting Swede midge control, such as different emergence phenotypes (Hallett et al. 2009b), insecticide deployment methods, and residual insecticide activity.

Swede midge is becoming an increasingly important pest of crucifers in North America, and its control has proven difficult. It is imperative that better management strategies be implemented while it is still a relatively new pest, including novel insecticides and biotechnology. A *B. t. israeliensis* strain showed activity against Swede midge (Wu et al. 2006) and other Bt insecticidal proteins (e.g., Cry4Ba and Cry11Ba) are currently being tested at Cornell University. These proteins could be used for generating Swede midge-resistant genetically modified crucifers, which may be able to address the cryptic feeding behavior of Swede midge larvae.

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