BIOLOGY AND MANAGEMENT OF THE POTATO LEAFHOPPER, *EMPOASCA FABAE* (HARRIS) (HOMOPTERA: CICADELLIDAE) ON FIELD CROPS IN ONTARIO

E. S. BULLAS APPLETON, C. GILLARD and A.W. SCHAAFSMA
Department of Plant Agriculture
Ridgetown College, University of Guelph, Ridgetown, Ontario N0P 2C0
E-mail: aschaafs@ridgetownc.uoguelph.ca

Abstract   *J. ent. Soc. Ont.* 134: 3-17

The potato leafhopper (PLH), *Empoasca fabae* (Harris) (Homoptera: Cicadellidae) is an economically significant pest of field legume crops (Rosales: Leguminosae) such as soybeans, *Glycine max* L., edible beans *Phaseolus vulgaris* L.*,* alfalfa, *Medicago sativa* L., and potato, *Solanum tuberosum* L. (Solanales: Solanaceae) in Ontario, causing potential losses of $250 million per annum. The PLH is a lacerate-and-flush feeder causing phytotoxicity expressed as hopperburn, resulting in the accumulation of photosynthates above feeding points and reduced rates of photosynthesis, respiration and plant growth. Damage symptoms responsible for yield reductions appear as: distorted leaf veins, yellowing margins and V-shaped wedges of chlorotic tissue, with leaves eventually becoming cupped with necrotic margins. The PLH accomplishes an annual migration, with winters spent in the southernmost regions of the United States, followed by a northward migration to north central and eastern United States and Canada in early spring. Effective monitoring for PLH populations in Ontario crops typically involves sweep net sampling, trifoliate counts and the use of yellow sticky cards. Economic injury levels for the PLH vary with susceptibility of infested crop. Resistant cultivars, trap crops, and seed treatments are discussed as viable alternatives to conventional insecticide applications for PLH control.

Biology

Biology and Development

The potato leafhopper (PLH), *Empoasca fabae* (Harris) (Homoptera: Cicadellidae), has been a well-known pest of edible beans since its description in 1841 (DeLong 1938). Adult PLH are wedge-shaped and pale green and are distinguished by a row of six white spots across the pronotum. The taxonomy of the PLH was not clear until 1931 when DeLong confirmed the importance of the lateral-process and the dorsal spines in the pygofers of the internal genitalia of the males for distinguishing species belonging to this genus (Delong 1938; Medler 1957). The white apple leafhopper (WALH), *Typhlocyba pomaria* McAtee (Homoptera: Cicadellidae), is often confused with the PLH due to its size and shape, but it is much lighter in colour and its host range is more limited (Anonymous 2001). Later instars of WALH nymphs also have two rows of dark dots on the dorsal side of the thorax, and more dots appear on the wing pads when they develop. WALH nymphs and adults primarily move in a forward and backward motion when disturbed, whereas PLHs can move sideways as well as forward and backward (Anonymous 2001).

Immatures pass through five nymphal instars which develop by incomplete metamorphosis. Under constant temperature regimes, the PLH requires approximately 301 degree days (C) to develop from egg to adult when reared on broad bean, *Vicia faba* L. (Rosales: Leguminosae) (Simonet and

Pienkowski 1980). Adult females normally mate within 48 hours of emergence. The preoviposition period under field conditions is from 3-5 days (DeLong 1938).

Females insert eggs directly into the larger veins and petioles of host plant leaves at a rate of about 4 eggs per day when temperatures are greater than 10°C (Fenton and Hartzell 1923; Poos 1932; Sher and Shields 1991). A female has the potential to produce 124 eggs, given that the average longevity of adults is 35 days; females live slightly longer than males (Poos 1932). PLH eggs are difficult to see unless the plant tissue is cleared using lactophenol (Carlson and Hibbs 1962). Eggs hatch within 7-10 days in continuously high summer temperatures, but the incubation period can extend to 23 days during cooler periods (DeLong 1938). Fecundity is 37% lower for PLH reared on alfalfa vs. edible beans (Kieckhefer and Medler 1966). The net reproductive rate, intrinsic rate of increase, oviposition period and population growth rate of PLHs are further reduced on water stressed alfalfa plants, with males slightly more affected than females (Hoffman et al. 1991; Hoffman and Hogg 1991).

Eclosion is related to temperature, with nymphs emerging later in the day during cooler periods (Poos 1932). Initially, the head of the emerging nymph is pushed through the plant epidermis. After an extended period of time, the neonate with conspicuous red eyes emerges until only the tip of the abdomen remains within the plant tissue. With its dorsal side downward, the nymph rapidly liberates and exercises its legs with which it grips the leaf vein and then pries the remaining portion of the abdomen from the leaf tissue. Nymphs begin feeding on the under surface of leaves immediately and complete the development from egg hatch to adult in about 15 days at temperatures between 15-20°C (Poos 1932).

The developmental times of eggs and nymphs, as well as overall longevity, decrease as mean temperatures increase (Sher and Shields 1991). Cold hardiness tends to increase as PLHs develop from egg through adult (Specker et al. 1990). When spring temperatures drop below 5°C, nymphs may drop into soil cracks where temperatures are slightly warmer than ambient (Shields and Sher 1992). As the proportion of individuals in soil crevices increases with decreasing temperature this behaviour has been categorized as a strategic response to unfavourable conditions in northern breeding grounds (Shields and Sher 1992). In Ontario there are three to four generations during the summer months.

Distribution and Host Range

The PLH overwinters predominantly in the southernmost portions of the United States. In the Gulf states, PLH reproduces on castor bean and other wild host plants during the winter, where populations increase before migration into north central and eastern United States and Canada in the spring (DeLong 1938; Pienkowski and Medler 1964). Physical and climactic factors, particularly elevation, relative humidity and rainfall, are responsible for the PLH's eastern distribution. DeLong reported that the PLH is of economic importance in eastern regions that are below 950 m in elevation with an average relative humidity of 40-60% (DeLong 1938). For PLHs to reach economically significant populations, high temperature must be combined with normal humidity and precipitation (DeLong 1938). However, monitoring of weather patterns over the past 15 years in Ontario has demonstrated that PLHs are becoming more abundant, causing an increase in damage under hot, dry conditions.

The PLH has been identified on over 200 host plants. In the south, trees such as hickory, oak and southeastern pines are typically a source of reinfestation for seasonal crops (Poos 1935; Taylor 1995). Alfalfa is usually the crop first infested after arrival of PLHs in Ontario. In late May, potatoes and beans become infested with adults dispersing from alfalfa by means of low-level flight. Following each alfalfa harvest, adult PLHs return to feed on the succulent regrowth.

Migration and Dispersal

Warm south winds and air masses moving north up the Mississippi Valley trigger a northward migration each spring, resulting in the infestation of many important crops in north central and eastern United States and Canada. Pienkowski and Medler (1964) suggested that a low-pressure trough in conjunction with a low-level jet stream on the face of a cold front is required for long-distance transport of PLHs.

The PLH accomplishes an annual migration, with its autumn return to the overwintering area in reproductive diapause assisted by the movement of the fall weather systems, particularly low pressure fronts with calm winds or winds with a southerly flow (Shields and Testa 1999). For long distance migration, the PLH must either fly or be carried to altitudes as high as 1220 m (Medler 1957; Pienkowski and Medler 1964; Shields and Testa 1999). At this altitude, PLH may be transported approximately 30% faster than individuals at 300 m above ground level (Pienkowski and Medler 1964). Temperature fluctuations impose limits upon the transport of PLHs in upper air currents. When the surrounding atmospheric temperature drops below 12˚C, the flight termination threshold, PLHs fold their wings and descend until temperatures above 12˚C are encountered (Taylor and Reling 1986). The activity period leading to flight into the planetary boundary layer (the part of the troposphere extending upward from the earth's surface to 100 to 3000m where long-range transport occurs) begins about one hour before sunset and ends 30 minutes after sunset. In one study, PLH reached peak densities at 152 m, 20 minutes after sunset (Shields and Testa 1999). Migratory flight appears to be correlated with declining barometric pressure 12 hours prior to the normal evening activity period, which occurs around sunset (Shields and Testa 1999). Migratory PLHs are precipitated out of the air by downdrafts, exhaustion, termination of flight, precipitation with rain or cooling.

Depending on location, collections in late spring in northern breeding grounds are predominantly females (Medler 1957). When conditions for migration are favourable, PLHs may be detected on alfalfa in Ontario as soon as early May. After females have reached northern breeding areas, short distance dispersal occurs throughout fields of preferred crops. Approximately 90% of all flight activity associated with short-distance dispersal occurs during the dark hours (Medler 1957). The majority of this movement takes place before midnight, with a peak 30 minutes after sunset; often this is a calm period with particularly low wind velocity (Dysart 1962). Precipitation triggers an increase in short distance dispersal due to the impact of falling raindrops (Dysart 1962).

Host Selection and Preferences

The PLH has several preferred hosts. Leguminous hosts are preferred, followed by potatoes and other species of *Solanum*. Common bean seedlings have a much higher sugar content than emerging potato plants, perhaps explaining why the potato plants do not attract the PLH until the plants have reached a considerable size and maximum sugar content (DeLong 1938). As the PLH feeds, sucrose increases in infested plants, making the plant attractive for continued feeding (Hibbs et al. 1964). PLHs also demonstrate variable settling behaviour. On alfalfa, stems are preferred over leaves. Contrastingly, on broad bean, fewer PLHs are found on stems while the use of abaxial leaf surfaces corresponds with availability (Backus et al. 1990). The preference for the abaxial surface of leaves compared to the upper surface may be attributed to higher transpiration rates, and consequently higher humidity on the undersides of leaves (DeLong 1938).

Many factors affect the frequency and intensity of PLH infestations. Favourable weather conditions are important for the build-up of heavy populations of this pest (Poos and Wheeler 1943). The stage of development, condition, abundance and continuity and the inherent characteristics of preferred host plants at the time of infestation can dramatically affect the rate of PLH oviposition and nymphal development (Poos and Wheeler 1943). The developmental stage

of the host also affects selection behaviour, as younger, more succulent tissue is favoured (Poos and Wheeler 1943).

Although it is difficult to precisely determine what attracts PLHs to host plants, preliminary evidence suggests that preferred varieties of edible beans are selected on the basis of visual properties rather than olfactory cues (Bullas et al. unpublished). Lime green, spring green and yellow sticky card traps attract the highest numbers of adults in free-choice tests (Chu et al. 2000). These hues have relatively low reflectance values in the blue region of the spectrum (400-460 nm) and moderately high reflectance in the green, yellow, and orange spectral regions (490-600 nm), characteristic of the abaxial surfaces of many leguminous leaves (Chu et al. 2000). PLHs are least attracted to colour card traps with low reflectance values at all wavelengths, such as black and dark green, and those with moderately high reflectance in the blue and red regions of the spectrum (Chu et al. 2000). Sampling of numerous potential native and exotic cultivated and natural hosts indicates that PLHs prefer species belonging to the family Fabaceae, with 61.8% of the host species represented by this family (Lamp et al. 1994).

Feeding Habits and Damage

In alfalfa and other preferred crops, the injection of copious amounts of watery, digestive saliva into the plant and the mechanical damage that occurs during laceration result in the deformation and blockage of sieve elements (Backus and Hunter 1989). Photosynthate accumulates above the blockage and causes phytotoxicity (Backus and Hunter 1989).

Early investigators believed that the PLH was strictly a phloem-feeding pest (Hunter and Backus 1989). However, the occurrence of dark green material in the gut, visible through the transparent abdominal cuticle resulting from the consumption of significant quantities of non-translocated, membrane-bound plant pigments such as chlorophyll, supports the hypothesis that PLHs ingest from the mesophyll as well as the phloem (Hunter and Backus 1989). Feeding behaviour may vary on different host plant species (Backus and Hunter 1989). For example, the PLH is classified as a lacerate-and-flush feeder that preferentially ingests from mesophyll tissue on broad beans and from phloem tissue on alfalfa (Hunter and Backus 1989). When the size of plant cells changes in response to environmental stress factors, probing behaviour by the PLH is modified. Water deficiency in alfalfa results in a shift from multiple-cell laceration to phloem ingestion, which is less likely to induce hopperburn than the probing behaviour typically associated with optimal moisture levels (Al-Dawood et al. 1996).

When stylets are damaged during feeding or probing and sheath saliva is deposited in the phloem, cells may collapse and the xylem tissue may be reduced in size, quantity and total cross-sectional area of mature tracheary elements. Ultimately, this may be expressed as leaf curl and eventually as necrosis (Ecale and Backus 1995). Other wound responses to PLH-induced injury include: cell wall loosening and collapse; organelle degradation and cell necrosis; increased mitotic activity in surviving cells; enlargement of nuclei and nucleoli; thickening of secondary cell walls; formation of wound phloem; transfer cell generation; and, premature formation of starch granules in cortical parenchyma chloroplasts (Zhou and Backus 1999). An increase in carbohydrates in damaged tissues suggests a feedback mechanism that enhances the nutritional suitability of the host, subsequently improving plants as hosts for the development of immatures (Granovsky 1930; Hibbs et al. 1964).

The extent of disruption of the translocation process depends upon the developmental stage of the host and the pest. For example, late instar nymphs or adult females appear to cause more damage than early instar nymphs or adult males (Zaky 1981, Flinn et al. 1990). In alfalfa, feeding by fourth instar nymphs significantly reduces the amount of photoassimilate transported to injured tissues, whereas feeding by adults or first instars leads to greater concentrations of assimilate in

the stem below feeding sites (Nielsen et al. 1999). Young vegetative alfalfa plants show reduced translocation rates to shoots, tips and crowns, while translocation is reduced to the crown only in late vegetative plants. A reduction in the basal translocation of photoassimilates induced by lacerate-and-flush feeders may reduce carbon storage and mobilization, nitrogen fixation and winter survival (Lamp et al. 2001). In one study, photosynthate transport to tips of exposed alfalfa stems was reduced up to 62% when compared to plants not exposed to PLH feeding (Nielsen et al. 1990). In contrast, translocation in reproductive plants was not affected by PLH injury (Nielsen et al. 1999). Although infested alfalfa requires more time to reach first bloom, injured plants can ultimately compensate for reductions in nutrient yield associated with later bloom. Therefore harvest based on occurrence of first bloom is preferred to minimize losses in digestible energy (Hutchins and Pedigo 1990).

Disruption of physiological processes in the plant severely affects regrowth rates and survival of alfalfa stands (Lamp et al. 2001). The consequences of intense feeding late in the growth cycle should be considered when pest management initiatives are considered, to ensure persistence of stands over time rather than primarily focusing on the growth of the current crop (Lamp et al. 2001). Transport processes are dramatically affected by PLH feeding during the early stages of plant development when pest management decisions can prevent yield losses. Although the time of arrival of PLHs is not related to the severity of damage, the frequency and number of arriving PLHs, weather conditions during the growing season and crop management all contribute to the ultimate extent of damage experienced by infested crops (Maredia et al. 1998).

Symptoms of Damage

Hopperburn, the disease-like condition induced by PLH feeding, results in reduced rates of photosynthesis, respiration, and plant growth, causing considerable yield losses. The initiation of hopperburn is associated with a cascade of biochemical and physiological changes in vascular tissues that persist for 4 to 8 days (Al-Dawood et al. 1996). This cascade begins with the enhancement of natural wound responses to the injection of saliva, followed by various forms of healing (Al-Dawood et al. 1996). Hopperburn is characterized by distortion of leaf veins and a consequent yellowing of the tissue around the margin and at the tip of the leaf. Symptoms in alfalfa commence as V-shaped wedges of chlorotic tissue radiating from the midpoint of the midrib to the tip of the leaflet (Nielsen et al. 1990). With continued feeding, there is cupping of the margins as the leaf turns from yellow to brown and becomes dry and brittle (DeLong 1940). A central area along the midrib, especially at the base near the petiole, is the last portion of the leaf to change colour. Dwarfing may occur in leaves, stems and/or petioles, and floral development may be reduced or arrested in affected plants.

The expression of hopperburn varies slightly between hosts. In alfalfa, this damage is known as "leafhopper yellowing" although it may appear in shades of pink, red and purple as well as yellow (Poos and Wheeler 1943). Damaged alfalfa plants are stunted and less vigorous and tend to show less regrowth following cutting, lower protein levels, and increased winter mortality. Because leaves contain the majority of digestible protein found in alfalfa plants, damage may result in crude protein loss as high as 28.6% (Hower and Flinn 1986). Most damage to alfalfa occurs after infestations of the second and third cuttings, as early season populations rarely reach damaging numbers unless the first cutting is delayed.

On peanut, the disease-like injury inflicted by PLHs is referred to as "pouts" and is first expressed by burning of the tips and margins of the leaves; then progresses to yellowing and dwarfing of the foliage (Poos and Wheeler 1943).

Hopperburn in edible beans is expressed as yellowing and downward curling of leaves, followed by necrosis, stunted growth, reduced pod number, reduced number of seeds per pod, and reduced

seed weight when infestations are severe (Schoonhoven et al. 1978). The severity of damage is correlated with yield reductions in unprotected plots of susceptible cultivars (Lindgren and Coyne 1994).

Management

Economic Importance

The PLH is a serious pest of many agricultural crops in Ontario, particularly edible bean, potato, alfalfa, peanut *Arachis hypogeae* L. (Rosales: Leguminosae) and soybean. Traditionally, PLHs could be expected sporadically in hot, dry seasons in the more southern regions of Ontario such as the counties of Kent and Essex and the Regional Municipality of Niagara. With the increased occurrence of hot, dry summers, the frequency of economic infestations of PLHs have increased in the last 15 years, and more frequent damage is now seen in Middlesex, Huron and Perth Counties to the north and east of the traditional area.

In 2001, approximately 61,650 ha of edible beans, 17,320 ha of potatoes, 853,900 ha of alfalfa, and 900,400 ha of soybeans were grown in Ontario (Anonymous 2001). Although some peanuts are grown in Ontario, the total area is considered insignificant, and their contribution to the agricultural economy is low. While soybean is a major cash crop in Ontario, economic losses are rare because PLHs are mainly repelled by dense leaf pubescence (Elden and Lambert 1992).

The damage inflicted by the PLH has the potential to reduce yields by 20-30% in alfalfa and potatoes and as much as 60% in edible beans; this corresponds to potential losses of a quarter of a billion dollars in Ontario per annum. With a total annual farm gate value of $60,000,000 (Anonymous 2001), the potential loss for edible beans is $12,000,000 without considering the value-added costs further down the food supply chain. In 2001, potatoes and alfalfa had total farm gate values of $87,444,000 and $305,900,000 respectively. This translates to potential losses of about $52,470,000 for potato and $183,540,000 for alfalfa.

Losses in alfalfa are currently underestimated by producers (Peter Johnson OMAF extension specialist, pers. communication), especially in the northern counties where growers are unaccustomed to scouting for PLHs. The majority of economic losses in forage legumes are linked to reductions in biomass associated with shorter stems (Lefko et al. 2000a).

The cost of protection against the PLH varies amongst crops. In edible beans, most growers apply dimethoate from one to four times per season. Based on the average production figures and estimates of treated areas, and at a cost of about $36 per ha including application and insecticide costs, growers spend close to $2.25 million annually for each insecticide treatment. It is more difficult to calculate the cost of control in potatoes, because PLH protection is often secondary to protection from other insects such as aphids or the Colorado potato beetle, *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae). Ten years ago, 10% of the alfalfa producers in the Niagara region sprayed once per season for PLH. More recently, about 50% of these producers applied at least one insecticide per season for PLH and 10 % applied an insecticide as required by monitoring thresholds after every harvest (Winnicki, Clark AgriService, pers. communication). While PLH-resistant alfalfa cultivars have recently been introduced, currently less than 5% of the new seedings comprise resistant cultivars (Welbanks, Pioneer Hi-Bred Canada, pers. communication). Growers within the Niagara region have planted PLH-resistant cultivars at an extra seed cost of about $25.00/ha, but have found that some insecticide treatments are still required (Winnicki, Clark AgriService, pers. communication).

Monitoring and Action Thresholds

It is difficult to accurately predict the arrival and magnitude of spring PLH populations, and management strategies are usually reactive rather than proactive (Maredia et al. 1998). In some

northern regions, large influxes of adult PLHs arrive without warning and result in major economic losses in regional crops before management of the pest can be implemented (Maredia et al. 1998).

Preventative management strategies for control of the PLH require an understanding of the relationship between weather, pest status and arrival times. A variety of techniques have been investigated for sampling the PLH, including sweep netting, pan traps, *in situ* counts, D-vac sampling, and the use of other traps, but few techniques are adequate for preventative management decisions (DeGooyer et al. 1998). Delong (1940) stated that although counting the entire catch obtained by 100 full sweeps of a standard sweep net provided an index of species present, the results obtained by this method were highly variable and of limited value. However, in spite of the questionable precision of this technique, alfalfa is commonly monitored in early July or after the first cutting by taking 20 sweeps in five representative areas of the field. Crop height in each sampled area is also considered. As the height of alfalfa increases, the number of PLHs necessary to cause economic damage also increases. For example, economic thresholds for PLHs are 0.2 adults/net sweep, 0.5 adults/net sweep, 1.0 adult or nymph/sweep net and 2.0 adults or nymphs/sweep net for stem heights of 7.5 cm, 15 cm, 20-25 cm and 30-35 cm respectively (Wilson 1981). Sampling should be performed on warm, calm days.

Yellow sticky traps oriented horizontally and level with the top of the canopy can provide effective relative estimates of PLH densities in alfalfa (DeGooyer et al. 1998). However, higher accuracy is obtained from counts of nymphs per 25 or 50 trifoliate leaves randomly selected from a plot. Nymphs are preferred for monitoring because adults are highly mobile and move among plants, rows and fields within a particular area, and eggs are not visible unless leaf tissue has been cleared.

Monitoring for adults in potatoes involves 10 random sweep net samples, with management decisions based on a treatment threshold of 5 to 10 PLHs per sweep (Whalen 2000). Nominal thresholds in beans are based on the number of nymphs per leaf with consideration of the stage of plant development. In Ontario, treatment is recommended when an average of 0.25 nymphs per leaf are detected at the unifoliate stage or 0.5, 1.0, or 2.0 nymphs at second trifoliate, fourth trifoliate and first bloom, respectively (Anonymous 2002a). Sweep nets to sample adults in edible beans are not recommended under humid conditions because of the high risk of spreading bacterial disease.

Economic Injury Levels

Economic injury levels (EIL) for the PLH are commonly expressed as the number of injury equivalents per production unit. The EIL is equivalent to the cost of management per production unit divided by the market value per production unit, multiplied by the yield loss per insect and the proportionate reduction of the insect population (Ogunlana and Pedigo 1974; Hunt et al. 2000). Due to varying levels of resistance or susceptibility, the EIL for the PLH varies with the infested crop and variety. PLH resistance creates a significant yield advantage, warranting the calculation of separate EILs for susceptible and resistant cultivars (Lefko et al. 2000a). The absence of well-defined EILs for PLHs has led to the prophylactic application of insecticides (Ogunlana and Pedigo 1974). The EIL is dynamic and must be adjusted according to current market values and environmental conditions (Ogunlana and Pedigo 1974). Considering these factors, Ogunlana and Pedigo (1974) calculated a gain threshold for PLHs in soybeans for aerial application of malathion at the rate of 100 kg/ ha. This gain threshold translated into an EIL, which ranged from 1 PLH/2 trifoliates to 18 PLH/2 trifoliates at the R7 stage of development when beans are beginning to form.

Seedling soybeans are most at risk when late planting is followed by a large migration of PLHs (Hunt et al. 2000). Seedling soybean leaves (VC through V4) are primarily composed of young, expanding tissue with softer, less abundant pubescence and consequently are more susceptible

to PLHs than older, hardened-off leaves (Hunt et al. 2000). Therefore, the EIL for soybeans increases with plant maturity, and ranges from 1.4-3.6 PLH/plant at the V1 stage (2 trifoliate leaves) to 6.5-16.7 PLH/plant at V4 (Hunt et al. 2000). Onstad et al. (1984) described a similar relationship for alfalfa in a model which incorporated pest density, infestation period, weather, crop condition and the management tactic selected.

Natural Enemies

Due to its capacity to rapidly attain damaging populations and move freely, the PLH is not a suitable candidate for biological control initiatives. Preliminary trials showed that chrysopids and coccinellids, both natural predators of the PLH, consumed only 23 and 10 nymphs, respectively, over a five-day period (Fenton and Hartzell 1923). Despite the fact that up to 40% of PLH eggs are effectively parasitized by the small hymenopteran *Anagrus armatus* (Ashmead) (Hymenoptera: Mymaridae), this parasitoid was unable to maintain sufficient control under field conditions (McGuire unpublished).

Zoophthora radicans (Brefeld) Batko (Zygomycetes: Entomophthorales) (synonym: *Erynia radicans* (Brefeld)), a fungus, causes natural epizootics in PLH populations under a narrow environmental regime (Magalhaes et al. 1991). The formation of appressoria, the infectious structure of this fungus, depends upon temperatures between 25° and 30°C, the presence of nitrogen and carbon sources in specific concentrations, and a specific volume of water covering the conidia prior to germination (Magalhaes et al. 1991). Since such precise requirements are not often experienced under Ontario growing conditions, *Z. radicans* is not currently viewed as a reliable control agent for this province.

Insecticides

Insecticides are the primary means of control for the PLH. Bordeaux mixture, a stomach poison, was the first effective insecticide used to control PLH infestations in potatoes (Fenton and Hartzel 1923). Once adults were detected, a calendar-spray program was initiated with applications at 10-day to two-week intervals. Later, pyrethrum extracts applied to PLHs on bean plants killed all individuals within a few hours, but had no impact on hatching nymphs or eggs (DeLong 1940).

In the 1970s granular formulations of disulfoton, carbofuran and phorate were applied to control PLHs in white beans (Judge et al. 1970). In recent years, organophosphorus insecticides such as dimethoate and phorate and some pyrethroids have been widely used for PLH control. Current recommendations for edible beans in Ontario involve the banded application of phorate applied at planting and/or foliar application of dimethoate when population estimates exceed thresholds (Anonymous 2001). Chloronicotinyl insecticides such as imidichloprid, clothianidin and thiamethoxam applied as a seed treatment have shown some promise for control of PLHs in edible beans (Gillard et al. unpublished). This new class of chemistry is favoured because of its novel mode of action, systemic properties and low environmental risk.

Producers rely mainly on foliar insecticides to control PLHs in alfalfa. Control initiatives must be implemented before symptoms are recognized because plants do not recover well once the transport system of the plant has been disrupted. Therefore applications should be made in strict accordance with damage thresholds. While the application of methoxychlor can substantially increase alfalfa yields when PLH pressure is high, there is considerable regulatory pressure to end the use of chlorinated hydrocarbons (Davis and Fick 1995). Currently, in Ontario, foliar applications of dimethoate, azinphos-methyl or cyhalothrin-lambda are recommended. While cyhalothrin-lambda is preferred from a user and environmental safety viewpoint, the organophosphorus insecticides are more cost effective.

PLHs on potatoes in Ontario are usually controlled secondarily to other major pests such as Colorado potato beetle or aphids (Anonymous 2004). Many of the potatoes in Ontario are treated with in-furrow granular imidacloprid to control Colorado potato beetle. Due to its systemic properties, this application of imidacloprid provides extended protection against PLHs. There are a number of foliar insecticides from several classes of pesticide chemistry that may be used if PLH problems continue throughout the season (Anonymous 2002b).

Host Plant Resistance

Resistant crop lines are feasible alternatives to chemical control practices, and have limited input costs and environmental concerns (Murray et al. 2001). Three main types of resistance all affect PLH host selection. Antibiosis is a direct form of resistance that is detrimental to the pest, causes reduced fecundity, and induces morphological defects or mortality. Antixenosis is circuitous, insects are repelled, and this is ultimately expressed as non-preference for a particular variety (Painter 1951; Kogan and Ortman 1978). Tolerance may be defined as the ability of a plant to support a pest population without sustaining damage that would compromise a susceptible plant (Painter 1951; Lefko et al. 2000b).

Cultivars of edible beans, *Phaseolus vulgaris* (Rosales: Leguminosae) differ in their resistance to the PLH. The inheritance of resistance factors in *P. vulgaris* is polygenic and is increased by recurrent selection (Cardona and Kornegay 1999). Breeding programs have successfully increased tolerance to PLH feeding damage, which has been incorporated into a number of bean market types (Cardona and Kornegay 1999). In Ontario, several small white-seeded experimental lines appear promising, combining resistance to PLHs, high yields, and good canning qualities (Cardona and Kornegay 1999). Non-volatile surface compounds often prevent or alter feeding behaviour by means of antixenotic and antibiotic resistance, while physiological tolerance mechanisms reduce the response of the host to feeding (Shockley and Backus 2002).

White beans might be classed as an intermediately susceptible market class to PLH because insect survival is not affected but reproduction is impeded (Ghosh et al. 1968). In another study conducted by Ghosh et al. (1968), PLHs reared on red kidney beans had an initial mortality rate of 50% rising to 100% by the second week of exposure, suggesting that this variety showed signs of antibiosis, perhaps due to unique plant lectins. A lethal protein called phytohemagglutinin (PHA) is produced as a defence mechanism by some species of Fabaceae (Habibi et al. 1993). When ingested, this compound rapidly kills PLHs. This defence mechanism appears promising for manipulation via DNA recombinant technology to achieve resistance in susceptible host plants (Habibi et al. 1993).

In summary, edible bean lines with low hopperburn scores associated with low nymphal populations may express antixenosis, whereas lines with high nymphal populations and low hopperburn scores, may predominantly be physiologically tolerant to PLHs (Kornegay et al. 1986; Schaafsma et al. 1998).

Most authors report that trichome morphology and density on edible beans do not play a major role in tolerance to PLHs (Schaafsma et al. 1998; Shockley and Backus 2002; Ranger and Hower 2001). Blends of volatile compounds, particularly viscous trichome exudates, are more likely to contribute to PLH resistance in alfalfa (Ranger and Hower 2001). The normal dense pubescence commonly found in most soybean cultivars provide a high level of resistance to the PLH, and significantly reduce feeding damage and oviposition and have increased adult mortality, in contrast to glabrous varieties which are much more susceptible to damage (Ogunlana and Pedigo 1974; Elden and Lambert 1992).

Traditional field-screening has been used by alfalfa breeding companies to select genotypes that appear resistant to hopperburn (Shockley and Backus 2002). Because mechanisms of resistance

are chemically and physically based, adult PLHs may be repelled or not attracted by volatiles, while glandular hairs may impede development of nymphs (Ranger and Hower 2001). Genotype G98A has been identified as the most repellent and consequently the most resistant variety of alfalfa, in contrast to Ranger, the least repellent and most susceptible alfalfa cultivar (Shockley et al. 2002). Trichomes on glandular-haired varieties of alfalfa are the source for the physio-chemical defensive parameter that makes G98A and 1-27-1 resistant (Shockley et al. 2002). More PLH mortality is observed on these genotypes than on all others (Shockley et al. 2002). Less feeding damage and lower nymphal populations were observed on the alfalfa germplasm B16-PLH, which has highly pubescent stems and is desirable due to its height, rapid growth, and winter hardiness when compared with Ranger and other susceptible varieties (Elden and Elgin 1989). The effects of trichomes and PLH resistance are indirectly linked to hopperburn resistance which involves additional resistance factors (Shockley et al. 2002). Alfalfa that is resistant to the PLH produces more dry matter than susceptible genotypes, due to more nodes, longer internodes, longer stems and less hopperburn. These genotypes therefore can maintain more leaves, which leads to higher total crop yield and forage value (Lefko et al. 2000a). AmeriGuard 301, Trailblazer, 5347LH and the experimental line XAE49, are tolerant alfalfa cultivars that perform better than susceptible cultivars when PLH populations are high (Lefko et al. 2000b). In alfalfa, there appears to be a chemical basis for the marked non-preference or antixenotic mechanism of resistance (Horber et al. 1974). Saponins appear to deter PLHs in alfalfa and appear more toxic at higher concentrations (Horber et al. 1974).

Similar instances of resistance are apparent in potatoes; when PLH populations are high, larger, more succulent varieties show considerably less damage and have higher yields than susceptible cultivars (Fenton and Hartzell 1923). There is a negative correlation between total glycoalkaloid concentrations and nymphal survival, duration of settling, ingestion as well as non-feeding on *Solanum* species (Raman *et al.*1979).

Trap-Cropping
The distinct preferences of phytophagous insects for particular varieties or growth stages of host plants may be exploited by modification of crop management practices. Intercropping systems provide diversity of host and nonhost vegetation that results in substantially lower pest populations when compared with monocultures (Brewer and Schmidt 1995). Typical intercrops employ the same proportions of host and non-host vegetation, thereby altering host selection habits and consequently reducing population densities (Miklasiewicz and Hammond 2001). A soybean-wheat cropping system initially contains significantly fewer female PLHs, and consequently a smaller population over the course of the year, relative to a uniform planting of soybean (Miklasiewicz and Hammond 2001). Similar suppression of the PLH occurs when alfalfa is intercropped with grassy weeds, forage grasses or oats (Lamp et al. 1984; Lamp 1991). The adoption of intercropping at the farm level has been low because of the rapid and visible control of pests achieved with insecticide application and the complexities that can be encountered with intercropping systems on a large scale.

Trap-cropping, a special type of intercropping, involves the planting of a crop or variety more attractive to the insect pest along with the less attractive main crop. Trap-cropping is most successful if the two plantings are of the same species, because their harvest times will coincide and the trap variety will contribute to the total yield of the harvest (Brewer and Schmidt 1995). The trap-cropping system is most effective when the trap cultivar is more attractive than the main cultivar during the critical period of pest colonization. When presented with a more favourable substitute, pests tend to move into the trap-crop where they may then be controlled by insecticides or some other means. This management tactic leads to a reduction in insecticide application as the trap variety or crop,

commonly planted as border rows, may constitute less than 20% of the entire crop. Management costs and environmental impact are reduced because it is not necessary to treat the entire field.

The behaviour of the PLH lends itself to trap-cropping in edible beans. Short distance dispersal of this pest is mainly restricted to border rows of adjacent fields, which coincides with the typical orientation of trap plantings. With the distinct varietal preferences exhibited by PLHs, a large proportion of the pest population could potentially be diverted from the main crop into the preferred trap cultivar. Saxena et al. (1988) found significantly higher yields in trap fields of a susceptible cultivar of rice compared with a control field not treated to control Cicadellidae.

Under field conditions, 'Berna Dutch brown' bean is preferred by the PLH over all other varieties grown in Ontario (Wylde 1999). Preliminary work (Bullas et al. unpublished) has suggested that plantings of this variety in combination with chloronicotinyl seed treatments is a promising control strategy. A major concern with the use of Berna Dutch brown bean plants as a trap-crop is its limited market. Growers cannot afford to remove a significant percentage of their acreage from production. For this approach to be successful in edible bean production, a significant profit advantage would be required to offset the opportunity cost of the trap-crop. Trap-cropping is a feasible management practice that may enhance yields while preserving the ecological integrity of the agroecosystem. Problems such as insecticide resistance, pest resurgence, adverse impacts on non-target organisms and secondary outbreaks of pests, commonly associated with the overuse of pesticides, can be reduced with the use of trap-crops.

Conclusions

Potato leafhoppers in Ontario field crops tend to be increasing in incidence and severity due to more frequent hot and dry summers. The potato leafhopper is no longer considered a sporadic pest because infestations are more frequent and regular and require extensive monitoring and treatment. Given that a relatively low number of potato leafhoppers in a crop can result in significant damage, more attention to monitoring is required for early detection. Alternatives to broadcast insecticide applications such as trap-crops, seed treatments and plant resistance are needed and crop producers need to be educated in the adoption of these practices.

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