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Potato Leafhopper (Hemiptera: Cicadellidae) Ecology and Integrated Pest Management Focused on Alfalfa

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ABSTRACT. This article summarizes the knowledge to date on biology of the potato leafhopper, *Empoasca fabae* (Harris), including its distribution, development, migration, agricultural host plants, and mechanics of injury to host plants. Damage to alfalfa, potatoes, soybeans, and snap beans, and treatment guidelines, are summarized. Particular attention is given to integrated pest management options in alfalfa, the host plant most frequently incurring economically damaging populations of potato leafhopper. Alfalfa scouting and economic thresholds are discussed along with cultural controls and host plant resistance.

Key Words: potato leafhopper, integrated pest management, migration, host plant resistance, economic threshold

Native to North America, the potato leafhopper, *Empoasca fabae* Harris (Hemiptera: Cicadellidae), migrates northward from the Gulf States each summer to the Midwest and eastern United States, where it is a key agricultural pest in many crops. Populations remaining in the southern United States' overwintering habitats can contribute to crop damage, but it is typically less severe (Fick et al. 2003). The geographic range of the potato leafhopper extends from the eastern seaboard of the United States westward to the Rocky Mountains (Delong 1931a) and northward into the bordering Canadian provinces (Fick et al. 2003). In addition, presence of potato leafhopper in California cropping systems has recently been confirmed from late-summer sweep net samples of uncut alfalfa in Parlier (Fresno Co.), CA, in the mid-Central Valley.[4] Nonetheless, some previous records from California may be based on misidentification of the closely related species, *Empoasca mexara* (Ross and Moore), which also occurs on alfalfa in California (C. D., unpublished data). It remains unknown whether California *E. fabae* overwinter in the Central Valley, or migrate in from southern locations; attempts to collect *E. fabae* in Imperial Co. (southern California) in early summer were unsuccessful.

The potato leafhopper's diverse host plant list of more than 200 plant species includes alfalfa (*Medicago sativa* L.), soybean (*Glycine max* L.) potato (*Solanum tuberosum* L.), and peanut (*Arachis hypogaea* L.), as well as roadside, weedy, and forest plants (Lamp et al. 1994). As the key economic pest of alfalfa in the North Central and Northeast United States, yield losses have been documented up to $66/ha ($27/acre; Lamp et al. 1991).

The first records of *E. fabae* date back to 1841 when it was detected in Massachusetts as a pest on fava bean (*Vicia faba* L.; Harris 1841). By 1931, it was considered an economically important pest in many cultivated crops (Delong 1931b). Unfortunately, because *Empoasca* is a large and complex genus of leafhoppers with hundreds of described species, many of which are nearly identical in external appearance, other species of *Empoasca* have often been misidentified as *E. fabae.* DeLong's (1931b) initial studies of the male genitalia of North American *Empoasca* revealed features that distinguish *E. fabae* from other common *Empoasca* species. However, later studies (Ross and Moore 1957; Ross 1959a,b) revealed that "*E. fabae*" of various authors is a complex of at least 27 closely related species. Thus, positive identification of species belonging to this complex is highly technical. Fortunately, nearly all of the currently recognized species of the complex appear to be restricted to the tropics and only four have so far been recorded from the continental United States: *E. fabae* (widespread), *Empoasca hastosa* (Ross and Moore; Florida), *Empoasca kraemeri* (Ross and Moore), and *E. mexara* (Arizona, CA; Ross 1959a and C. D., unpublished data).

As well as early identification errors, the relationship between the potato leafhopper and crop damage was originally not well understood. Although the effect of potato leafhopper on alfalfa was noted as early as 1907, plant damage symptoms known as alfalfa "yellows" were initially attributed to abiotic factors such as weather and soil nutrient deficiency. Greenhouse experiments at the University of Wisconsin Agricultural Research Station confirmed that alfalfa "yellows" was caused by the potato leafhopper (Granovsky 1928). In potatoes, farmers and researchers originally believed that potato leafhoppers were the vector for a pathogen leading to the characteristic yellowing of leaves (Dudley 1920). Although closely related to some known insect vectors of phytoplasma infecting agriculturally important plants (Galetto et al. 2011), there are no known records of disease transmission to plants by potato leafhopper.

The current pest management strategy in alfalfa for the potato leafhopper is to monitor the pest throughout the season with a sweep net and treat with foliar insecticide when economic threshold populations are reached (DeGooyer et al. 1998, Cullen et al. 2012). A fully developed integrated pest management (IPM) program is composed of multiple strategies for a given pest or pest complex in a cropping system incorporating host plant resistance, biological, cultural, and physical controls when available and chemical control when necessary (Pedigo 1999). Several integrated management strategies have been developed for the potato leafhopper in alfalfa. For example, alfalfa cultivars bred for resistance to the potato leafhopper were first available to farmers in 1997 (Miller 1998). Despite advances in pest management for potato leafhopper in alfalfa, it continues to be considered the most important economic pest of alfalfa through much of its range. As the market value of alfalfa hay has nearly doubled over the past decade (Gould 2012), the potential for economic loss from potato leafhopper has also increased. Thus, a more thorough understanding of potato leafhopper biology and IPM is a timely subject. In this pest profile, we summarize knowledge of potato leafhopper life

[4]Specimens examined for this study were identified by the second author and are deposited in the insect collection of the Illinois Natural History Survey.

history, ecology, scouting procedures, and management options in alfalfa.

Description of Life Stages and Life History

Egg. Eggs are oviposited into the stems of host plants (Delong 1938). To examine the eggs, the stem must either be dissected or stained using McBride's stain (Backus et al. 1988). They are cylindrical, translucent, pale green, and ≈0.8 by 0.25 mm (Hutchins 1987). Once oviposited, time to eclosion ranges from 7 to 14 d, with warmer temperatures promoting faster development (Hogg 1985).

Nymph. Potato leafhoppers have five nymphal instars (Fig. 1). Instars can be distinguished by color, size, and presence of external wing pads. The first instar is pale white with red eyes, and extremely small. Subsequent instars gain more of the vibrant yellow-green color typical of adults. Wing pads (Fig. 2) begin developing in the third instar. Sizes of the instars range from 1 mm for first instars to 3 mm (in length) for fifth instars (Hutchins 1987). Developmental time is more rapid in warmer temperatures and ranges from 9 to 18 d to complete all five instars (Hogg 1985). All nymphal stages resemble the adult body shape in that the head segment is wider than the abdomen, which gives the body a wedge-shaped appearance. Potato leafhopper nymphal movement is distinct from adults in that nymphs scuttle sideways. However, both nymphs and adults are able to use specialized legs (Fig. 2) for jumping.

Adult. The presence of fully developed wings and ability to fly makes adults morphologically and functionally distinct from the nymphs. Adults are ≈3 mm long by 0.5–1 mm wide. They are bright yellow-green colored with six white spots behind the eyes on top of the head (Fig. 3). Mating can take place as soon as 48 h after adult emergence (Delong 1938). Once females have mated, they oviposit two to five fertile eggs, individually, each day for the remainder of their lives (Delong 1938, Decker et al. 1971). Optimal temperatures for egg laying are 70–75°F (Kieckhefer and Medler 1964). The average life span of an adult in the field is 30 d; however, in the laboratory, adults can live up to 3 mo (Delong 1938).

Migratory Patterns. Potato leafhoppers overwinter as adults in reproductive diapause (females are unmated) throughout the Gulf Coast States (Louisiana, Mississippi, Alabama, and parts of Florida and Texas; Decker and Cunningham 1968) and the Southern Pines region, including eastern Arkansas, Tennessee, South Carolina, North Carolina, and Virginia (Taylor and Shields 1995a). In the overwintering habitats, reproductive diapause ends and mating begins in late February as populations shift from pines to legumes (Taylor and Shields 1995a). Populations migrate to the northern and eastern United States with the occurrence of warm, long-distance southerly winds (Carlson et al. 1992). However, the timing of this event is not an indicator of pest pressure or severity of crop damage (Maredia et al. 1998).

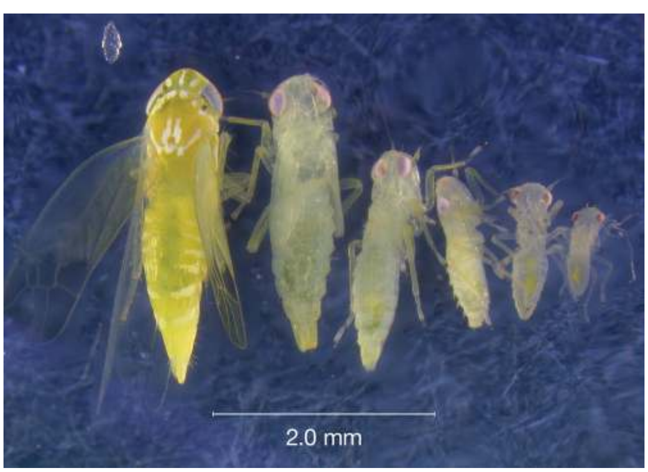

Fig. 1. All five nymphal instars and adult potato leafhopper, left.

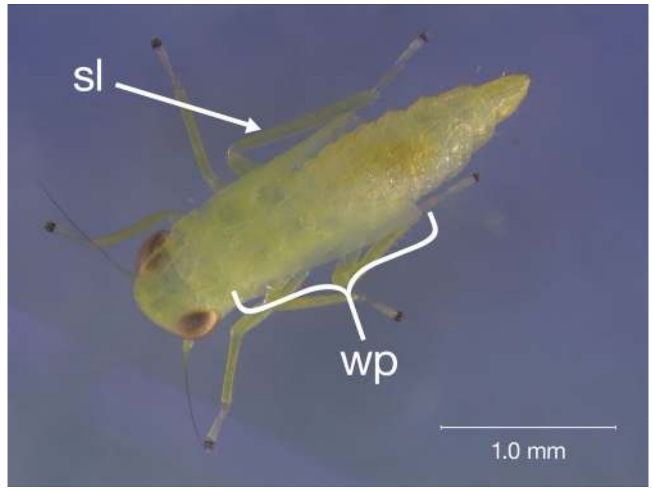

Fig. 2. Late-instar potato leafhopper with wing pads (wp) and specialized legs (sl) used for jumping.

Each year, the first potato leafhopper populations arriving in the north are largely female-biased (Medler and Pienkowski 1966) and occur sometime in May (Maredia et al. 1998). Arriving females are typically mated (Medler and Pienkowski 1966) and will oviposit for the duration of their lives (Delong 1938, Decker et al. 1971). Field studies indicate a female-biased sex ratio near 4:1 through most of the season, until it approaches 1:1 toward the end of the growing season (Medler and Pienkowski 1966, Decker et al. 1971, Flinn et al. 1990, Emmen et al. 2004). Development from egg to adult can occur in as little as just over 2 wk or can take >4 wk, depending on temperatures, which gives rise to three to five overlapping generations during summer months in the northern United States (Delong 1938, Hogg and Hoffman 1989).

In late summer, potato leafhoppers begin abandoning crop hosts for wild host plants along crop borders and woodlots, enter reproductive diapause, and then return to their overwintering habitat via northerly winds on a southward migration (Taylor 1989, Taylor and Shields 1995a). About 2 mo after first frost, they are completely absent from northern habitats (Decker and Cunningham 1968) owing to their southward migration and the fact that they cannot survive the low temperatures in northern winters (Specker et al. 1990).

Injury from Feeding

Hopperburn is the term used to describe symptoms associated with potato leafhopper feeding injury to host plants. Hopperburn symptoms (Fig. 4) always include stunted plant growth. In addition, various leaf symptoms include tip-wilting and chlorosis in alfalfa, but leaf curling and marginal necrosis in other host plants, ultimately leading to

Fig. 3. Adult potato leafhopper; note the six white spots located on top of the head behind the eyes.

Fig. 4. Characteristic triangular, v-shaped yellowing hopperburn damage to alfalfa. Older damage turns brown.

premature leaf-drop (Backus et al. 2005). Theories regarding toxins in saliva have been proposed since the earliest years of potato leafhopper research. However, more recent research has shown that feeding injury is actually caused by varying plant responses to the complicated feeding behaviors of the potato leafhopper (as well as its relatives in the *E. fabae* complex).

The potato leafhopper feeds by inserting its piercing-sucking mouth parts (stylets; Fig. 5) into host plant tissues, rupturing and ingesting nutrients from all types of mesophyll, parenchyma, and phloem cells, depending on the host plant (Backus et al. 2005). Unlike other leafhoppers, potato leafhoppers do not produce a true salivary sheath that encases the stylets during feeding. Instead, the naked stylets repeatedly probe plant tissues, mechanically lacerating cells and simultaneously injecting watery saliva into the tissues. The watery saliva is composed of digestive, hydrolyzing, and cell wall-degrading enzymes, and to date, has not been found to contain any nonenzymatic "toxin." Instead, hopperburn is caused by a combination of mechanical and salivary mechanisms (Ecale and Backus 1995a), so it is termed a "saliva-enhanced wound response." Unique to this species of leafhopper, the symptoms of feeding injury on different host plants are related to three different tactics of potato leafhopper stylet probing (Backus et al. 2005).

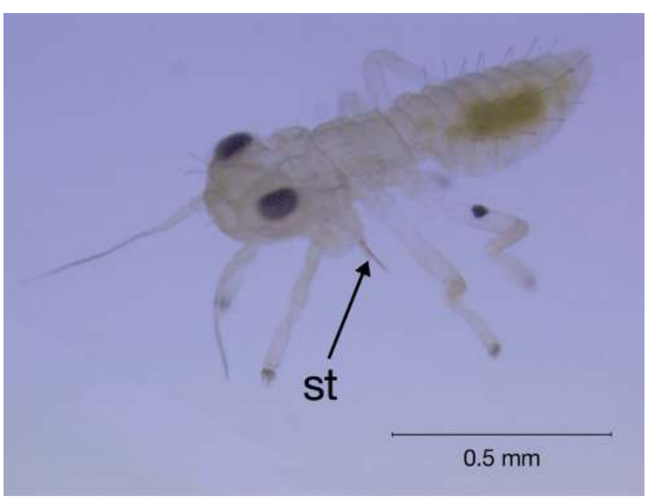

Fig. 5. Early-instar potato leafhopper with piercing-sucking mouthpart, or stylet (st).

On alfalfa, adult potato leafhoppers use the *lacerate-and-sip* tactic, which is also thought to be the most injurious, mostly on stems and petioles. Adults insert their stylets perpendicular to the stem and proceed to arc the stylets back and forth, essentially cutting multiple channels through the vascular bundle (all types of phloem cells) for 1–2 min before removing the stylets, taking a couple of steps forward and repeating the action. The wounded but still living vascular cells then undergo saliva-enhanced wound responses over the next several days that result in temporary blockage of nutrient movement up the phloem (Nielsen et al. 1990) that is ultimately healed, but permanent blockage of xylem cells (Ecale and Backus 1995b). Both types of blockage cause systemic decreases in photosynthesis and decreased transport of sugars to growing areas of the plant, leading to both leaf chlorosis and plant stunting in all host plants (Backus et al. 2005). Potato leafhopper nymphs on alfalfa feed on both stems and leaves; on leaves, their feeding is similar to adult feeding on nonalfalfa host plants (see later text).

On most host plants (e.g., snap and fava bean, soybean, and potato) that show leaf shriveling, curling, and necrosis, *E. fabae* adults prefer to feed on leaves, not stems, and add two more tactics to their feeding style, *lacerate-and-flush* and *lance-and-ingest*. In lacerate-and-flush, the stylets are inserted into individual mesophyll/parenchyma cells between veins on leaves, and the cells are partially to wholly emptied. When large numbers of such cells are emptied, the leaf surface collapses. If the feeding has occurred mostly on the lower surface, cell collapse causes leaf curling (e.g., in snap bean); if both surfaces, collapse causes leaf shriveling (e.g., fava bean). In lance-and-ingest, phloem sieve element cells are lanced during stylet laceration and fluid contents are briefly sucked up. When combined with lacerate-and-sip performed on leaf veins, the three tactics together lead to leaf curling, chlorosis, and then, ultimately, necrosis and leaf drop (Backus et al. 2005).

Interestingly, the three feeding tactics of *E. fabae*-complex species are mixed-and-matched on different host plants in relation to the degree of susceptibility or resistance of the plant. Some genotypes of resistant snap bean cause less of the most-damaging tactics of feeding (lacerate-and-flush and lacerate-and-flush) to be performed, while more of the less-damaging tactic, lance-and-ingest (Serrano et al. 2000, Backus et al. 2005). In addition to genetic mechanisms of resistance or susceptibility, drought or desiccation can enhance hopperburn symptoms because water and carbon transport are impaired after potato leafhopper feeding.

Hosts

Potato leafhoppers have an extensive host plant range including 220 plant species in 26 families; both cultivated crops and noncultivated or weed plant species, the majority of which (62%) are in the legume family, Fabaceae (Lamp et al. 1994). Most host plants are non-native species, herbaceous, and in human-modified landscapes (Lamp et al. 1994). Host plants of economic importance include cultivated plants from the legume family (Fabaceae) such as alfalfa, soybean, and other bean plants, as well as apples (*Malus domestica* Burkh), potatoes, eggplant (*Solaum melongena* L.), cotton (*Gossypium spp.*), rhubarb (*Rheum rhabarbarum* L.), and ornamentals such as dahlias (*Dahlia spp.*; Delong 1938). Economic thresholds have been established for alfalfa (Cuperus et al. 1983), soybean (Ogunlana and Pedigo 1974), and potato (Cancelado and Radcliffe 1979).

Alfalfa. Potato leafhopper is the most economically damaging pest of alfalfa in the North Central and Northeast United States. Characteristic hopperburn damage is expressed as triangular v-shaped yellowing at the leaflet tips (Fig. 4). Seasonally, first cuttings typically escape potato leafhopper damage owing to the timing of spring migration (first cutting is harvested before significant potato leafhopper population buildup); however, mid- and late-season cuttings are at risk of intensive potato leafhopper pressure and damage. Damage to alfalfa is most severe for young plants, either in the seeding year or just after a harvest during initial regrowth (Kouskolekas and Decker 1968, Cuperus et al. 1983, Hower 1989). Severe feeding can decrease yields in subsequent cuttings or year (Hower 1989, Vough et al. 1992) due to disruption in photoassimilate translocation to the roots and crown tissues (Lamp et al. 2001). Potato leafhopper feeding decreases yield through reductions in internodal length and stem height (Lamp et al. 1985, Lefko et al. 2000a). Potato leafhoppers also decrease alfalfa crude protein content (Hower and Flinn 1986, Hutchins et al. 1989, Sulc et al. 2004), which is an important nutritional component that alfalfa provides for dairy cows. Hutchins and Pedigo (1990) determined that that this trend is mediated through the effect that potato leafhoppers have on alfalfa maturation; alfalfa that is infested early in the regrowth cycle matures roughly 30% slower than uninfested alfalfa, resulting in decreased daily accumulation of dry matter and nutrients. However, Wilson et al. (1989) discuss alfalfa's ability to better tolerate leafhopper populations when harvests are appropriately timed and the stand is not otherwise stressed by factors such as disease or drought.

Soybean. Heavy potato leafhopper infestations on soybean can lead to plant stunting, smaller seed size, and decreased yield (Yeargan et al. 1994). These negative impacts are more severe on seedling soybeans, whereas larger plants can better tolerate potato leafhopper feeding (Hunt et al. 2000). Yield loss from potato leafhopper damage is more severe when the plant is under moisture stress (Yeargan et al. 1994). However, heavy infestations are not common on soybeans (Ogunlana and Pedigo 1974), except when nearby alfalfa fields are harvested (Poston and Pedigo 1975). Economic thresholds for soybeans vary by plant age: early vegetative stages can be treated when there are two leafhoppers per plant, flowering fields can be treated when there is one leafhopper per trifoliate leaf, and while pods are developing, fields should be treated when there are two leafhoppers per trifoliate leaf (Krupke et al. 2013).

Potato. Potato leafhoppers are a member of the key pest complex of potatoes. Feeding causes a reduction in photosynthesis and may result in leaf necrosis. Nymphs are more damaging than adults but can be efficiently sampled to implement effective management strategies. Damage on potatoes can be predicted not only by the intensity of feeding, but also based on which leaves the feeding is occurring and the age of those leaves (Johnson and Radcliffe 1991). Economic thresholds are based on populations of nymphs and/or adults, for which there are separate scouting methods. Adults are scouted with a sweep net and nymphs are scouted by examining leaves from the mid-canopy. When one adult per sweep or 2.5 nymphs per 25 leaves are found, insecticide treatment is recommended (Sexson et al. 2005).

Snap Bean. Snap beans (*Phaseolus vulgaris* L.) are regularly infested by potato leafhoppers, and under intense feeding, this can result in complete leaf drop, whereas at moderate pressure, plant stunting and yield loss may occur (Gonzalez and Wyman 1991). Duration and timing of infestation are important when making management decisions; infestation on younger plants causes more significant yield loss than the equivalent pressure on older plants (Gonzalez and Wyman 1991). Economic thresholds for green beans vary by plant age: for seedlings, the threshold is set at 0.5 potato leafhoppers per sweep, and for the third trifoliate to bud stage, the threshold is set at one per sweep. For dry beans, the thresholds are 0.5 potato leafhoppers per plant at the unifoliate stage and one potato leafhopper per trifoliate leaf once the plants have reached the trifoliate stage (Flood and Wyman 2005). Neonicitinoid seed treatments are also commercially available and have been largely successful at controlling a suite of snap bean pests, including potato leafhoppers, especially for roughly the first 30 d of plant growth (Nault et al. 2004). However, when potato leafhopper populations are exceptionally high, growers should still be mindful of scouting for economic threshold populations later in the summer.

Ecology

Abiotic Factors. Throughout the summer, insect population growth and plant vigor are regulated by abiotic factors such as precipitation and temperature. On moisture-stressed alfalfa, development time of potato leafhopper eggs, nymphs, and adults slows, mortality increases, and fecundity decreases (Hoffman et al. 1990, 1991). However, hopperburn seems to appear more frequently during summer droughts (Hoffman et al. 1991). This may be due to an additive effect of leafhopper feeding and drought stress on alfalfa's physiological response (Schroeder et al. 1988). Moreover, drought stress interspersed with bouts of rain throughout the summer may increase potato leafhopper performance, which has been proposed as a theory that could explain discrepancies in leafhopper population growth in field observations versus laboratory studies (Huberty and Denno 2004).

As with other cold-blooded organisms, potato leafhopper development is dependent on environmental temperatures. Potato leafhopper development ceases when temperatures drop below a lower developmental threshold of 45°F (7.6°C), and the rate begins to decline when temperatures consistently exceed an upper developmental threshold of 86°F (30°C; Hogg 1985).

Natural Enemies. Under no-choice laboratory conditions, various generalist predators will feed on potato leafhopper nymphs and adults. These predators include the minute pirate bug (*Orius insidious* Say), damsel bug (*Nabis americoferus* Carayon), lacewings (*Chrysopa spp.*), and various lady beetles (Coccinellidae; Martinez and Pienkowski 1982, Erlandson and Obrycki 2010). Flinn et al. (1985) demonstrated through choice experiments with potato leafhopper nymphs and the pea aphid (*Acyrthosiphon pisum* Harris) that damsel bugs exhibit a strong preference for the pea aphid. Preference for alternative, less mobile prey could be one reason that none of the generalist predators abundant in alfalfa and other cropping systems play a crucial role in suppressing potato leafhopper populations. There are a few egg parasitoids that have been collected and reared from potato leafhopper eggs (*Anagrus* sp. and *Aphelopus* sp.; McGuire 1989). A naturally occurring entomopathogenic fungus detected in Wisconsin, *Erynia radicans*, has had some success at suppressing potato leafhopper outbreaks in Illinois (McGuire et al. 1987a). However, this method of control is generally ineffective because temperatures exceeding 86°F prohibit successful establishment of this fungus (McGuire et al. 1987b). Regardless of the presence of potential natural enemies, the efficacy of biological control agents at suppressing potato leafhopper populations in alfalfa and other cultivated crops remains limited.

Scouting and Management Options in Alfalfa

Scouting. Scouting for potato leafhoppers in alfalfa is standardized through the use of a 15-inch-diameter sweep net. University extension recommendations are to monitor alfalfa fields weekly beginning mid-June or when potato leafhopper migrants have arrived in the area by taking five sets of 20 sweeps at various locations in a W-shaped pattern throughout the alfalfa field (University of Wisconsin-Extension 2010). Adult potato leafhoppers may be found at the bottom of the sweep net, while nymphs can be found along the rim of the sweep net as well as throughout the net (University of Wisconsin-Extension 2013). Insecticide recommendations are based on the average potato leafhopper number per sweep calculated from total samples taken across the field, including nymphs and adults (Cullen et al. 2012). Because taller alfalfa can tolerate more potato leafhopper feeding, established economic thresholds depend on the average height of the alfalfa stand. When scouting for potato leafhoppers, it is important to avoid taking sweep net samples at field edges, as potato leafhopper populations are typically higher along field margins and this is not representative of population density throughout the field (Emmen et al. 2004). It is also important to avoid taking sweep samples while it is raining or when dew is present on the plants, and if possible, avoid sweeping when winds are >10 miles per hour, as this reduces the sweep net sample efficiency (Cherry et al. 1977).

Management: Economic Thresholds and Foliar Insecticides. Established economic thresholds are based on research done by Cuperus et al. (1983). They concluded that treatment was economic when 0.15 potato leafhoppers per sweep were present on 2-inch alfalfa and when 0.42 potato leafhoppers per sweep were present on 7-inch alfalfa. These conclusions have been adapted to current university recommendations of roughly one-tenth of a leafhopper per sweep per inch height of alfalfa growth (Table 1; Fick et al. 2003, Townsend 2002, University of Wisconsin-Extension 2013). Some university extension recommendations suggest a dynamic economic threshold based on varying costs of insecticide treatment (Rice et al. 1999; Table 2) or fluctuating alfalfa hay market prices (Danielson and Jarvi 2006). Under these threshold guidelines, as the treatment cost increases or the alfalfa hay market price decreases, a greater density of potato leafhoppers is required to cause economic yield loss equivalent to the treatment cost, and therefore the threshold is increased. Hutchins and Pedigo (1998) calculated economic injury levels for potato leafhopper on alfalfa, with an emphasis on management for nutritional value based on type of animal for which the feed is intended. Incorporating variables of insect injury on forage quality characteristics (Hutchins and Pedigo 1990) and different animal nutrition needs, they determined that the economic injury level is lowest for alfalfa hay intended for sheep or horses, medium for a beef or dairy cows, and highest for beef steer. However, economic thresholds were not calculated based on these economic injury levels, and thresholds based on livestock nutrient needs have not been adopted in practice.

Foliar insecticides registered for potato leafhopper control on alfalfa are effective against nymphs and adults. Pyrethroids are the most commonly recommended and used insecticides for control of potato leafhopper. There are a limited number of insecticide active ingredients in the organophospate chemical class registered for potato leafhopper control in alfalfa. In addition, insecticide premix products are registered that combine two insecticide classes (e.g., organophosphate + pyrethroid; chlorantraniliprole + pyrethroid; neonicotinoid + pyrethroid). Because potato leafhopper populations vary from year to year, and field to field, populations within a given year cannot be predicted, and fields must be monitored weekly to accurately determine damage potential before insecticides are applied. Other pests and beneficial insects in the alfalfa field should also be considered before application of these broad-spectrum insecticides. For example, insecticides that control potato leafhopper at economic thresholds can also kill beneficial insects such as honey bees. To reduce hazards to honey bees in alfalfa, applicators can notify beekeepers before using insecticides, apply between 4 p.m. and nightfall, when bees are least likely to be foraging, and refrain from spraying alfalfa when in bloom (Cullen et al. 2012).

Management: Cultural Control. *Harvest Timing.* If economic thresholds are reached within 7 d of a planned harvest, early harvest is advised, rather than an insecticide spray (Undersander et al. 2004). Early harvest helps alfalfa stands to avoid further potato leafhopper feeding damage. In addition, potato leafhopper population dynamics can be influenced by harvest operations (Pienkowski and Medler 1962, Simonet and Pienkowski 1979, Cuperus et al. 1986). Cuperus et al. (1986) showed that greater populations of nymphs and adults were correlated with taller stubble or lodged growth left behind after harvest. Cuttings at stubble height of 2–5 cm (1–2 inches) with no remaining leaves or succulent stems can reduce populations up to 95% in the next growth cycle (Simonet and Pienkowski 1979). These effects are due to high nymph and egg mortality from their lack of mobility and exposure to hot, drying conditions (Simonet and Pienkowski 1979) and adult dispersal post harvest to neighboring fields (Poston and Pedigo 1975).

Table 1. Economic thresholds for potato leafhoppers in alfalfa (adapted from University of Wisconsin – 2013)

Alfalfa ht (inches)	Leafhoppers per sweep
Stubble–3	0.2
4–6	0.5
8–11	1.0
>12	2.0

Table 2. Dynamic economic thresholds for potato leafhoppers in alfalfa (potato leafhoppers per sweep) considering a range of insecticide treatment costs (adapted from Rice et al. 1999)

Alfalfa ht (inches)	Cost of insecticide treatment ($)				
	10	12	14	16	18
4	0.2	0.3	0.4	0.5	0.6
6	0.3	0.5	0.6	0.8	0.9
8	0.4	0.6	0.8	1.0	1.2
10	0.5	0.8	1.0	1.3	1.5
>10	1.0	1.6	2.0	2.6	3.0

Grass Intercrop. Lamp (1991) showed that alfalfa–oat mixtures have fewer potato leafhopper adults, both per area as well as per alfalfa stem. Several forage grass–alfalfa mixtures have had similar effects on potato leafhopper density. Alfalfa stands containing 9% forage grass, either smooth bromegrass (*Bromus inermis* Leyss) or orchardgrass (*Dactylis glomerata* L.), had 4–37% reduction in potato leafhopper densities compared with alfalfa monocultures (Roda et al. 1997). DeGooyer et al. (1999) similarly observed significantly fewer leafhoppers in alfalfa stands intercropped with smooth bromegrass or orchardgrass compared with alfalfa monocultures. These patterns may be due to higher leafhopper emigration out of plots containing grass (Roda et al. 1997), as well as inability of potato leafhoppers to reproduce on monocots such as grass (Lamp et al. 1994).

The results of studies performed by Roda et al. (1997) and DeGooyer et al. (1999) show that potato leafhoppers are typically reduced in alfalfa–grass stands but that is not the case for every harvest. Moreover, even when the population is reduced, it is not always reduced below economic threshold, so it is still important to monitor the population and use other management strategies when necessary. There is a great deal of variability in the response of potato leafhopper to the presence of grass in alfalfa stands, in part owing to the relative proportion of grass to alfalfa as well as the spatial arrangement of the grass in the alfalfa stand (Roda et al. 1997).

Management: Host Plant Resistance. Observations regarding alfalfa host plant resistance to potato leafhopper date back to 1928, when Granovsky (1928) noted that "hairier" *Medicago spp.* demonstrated greater tolerance to leafhoppers before exhibiting hopperburn. Laboratory studies have shown greater potato leafhopper mortality and reduced reproduction on glandular-haired *Medicago spp.* as well as leafhopper preference for smooth-stem alfalfa varieties in choice tests (Shade et al. 1979, Brewer et al. 1986, Ranger and Hower 2002). Both physical and chemical traits associated with glandular-haired alfalfa have been reported as resistance mechanisms: entrapment of the first instars in trichome exudates (Ranger and Hower 2001) and adult settling deterred by compounds in the exudate (Ranger et al. 2004).

The wild glandular-haired *Medicago spp.* were integrated into breeding programs that eventually led to the first line of commercially available alfalfa cultivars with host plant resistance in 1997 (Miller 1998). However, in the field, glandular-haired alfalfa cultivars have had varying levels of success. Lefko et al. (2000b) found that established stands of resistant alfalfa could tolerate greater than twice the potato leafhopper pressure as established susceptible stands, but this was not the case for the first cutting of seeding-year stands. Established resistant stands also had greater yield (Sulc et al. 2001) as well as higher forage quality over susceptible cultivars when leafhopper pressure was high (Sulc et al. 2004). However, under low potato leafhopper pressure, resistant alfalfa stands have no yield benefit and sometimes express a yield drag (Hogg et al. 1998, Hansen et al. 2002).

Glandular-haired alfalfa varieties with >50% resistance offer a valuable trait to potato leafhopper IPM programs. It is important to note that although alfalfa varieties bred for resistance to the potato leafhopper no longer demonstrate visual hopperburn, this does not necessarily indicate that there is no yield or quality damage to the alfalfa (Kindler et al. 1973, Shockley et al. 2002). Under moderate to heavy potato leafhopper infestations, glandular-haired varieties still benefit from timely scouting and insecticide treatment when leafhopper populations have exceeded thresholds established for susceptible alfalfa varieties. The first crop of seeding-year stands of glandular-haired varieties should be treated for potato leafhopper using the same economic thresholds established for susceptible alfalfa (Lefko et al. 2000b; Tables 1 and 2), although Rice et al. (1999) recommend increased economic thresholds for resistant alfalfa stands in subsequent crops and years.

The potato leafhopper is a polyphagous insect herbivore that can achieve pest status in many agricultural crops throughout the United States. However, it is most frequently a pest of economic concern in alfalfa fields in the Midwest and northeast United States. Owing to the migratory nature of the potato leafhopper, intensity of infestation cannot be predicted from year to year throughout its geographic range. Although models have been developed to aid in predicting development of migrant source populations from southern states (Taylor and Shields 1995b), these have not been incorporated into management. This lack of incorporation is likely owing to the fact that timing of initial migrant arrivals is not a reliable predictor of infestation or damage severity (Maredia et al. 1998). The most valuable management recommendation is to establish a regular scouting program for the potato leafhopper and to apply foliar insecticides if and when economic threshold populations are found. In addition, in geographic regions that experience economically damaging potato leafhopper populations more consistently, farmers should consider planting leafhopper-resistant alfalfa cultivars.

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