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# Ecology and Management of *Pemphigus betae* (Hemiptera: Aphididae) in Sugar Beet

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## Abstract

*Pemphigus betae* Doane (Hemiptera: Aphididae), is a sporadic pest of sugar beet (*Beta vulgaris* L. var. *vulgaris*) in all major sugar beet production regions of North America. These oval-shaped, pale-yellowish insects, with a body length ranging from 1.9–2.4 mm, secrete a waxy material, giving their subterranean colonies a moldy appearance. Poplars in the genus *Populus* L. are the preferred primary hosts, while sugar beet and certain weed species, such as common lambsquarters (*Chenopodium album* L.) and kochia (*Kochia scoparia* (L.)), are among the secondary hosts. *Pemphigus betae* has a complex and varied life cycle and is usually heteroecious and holocyclic, although anholocyclic apterae are known to overwinter in the soil. Heavy infestations of this aphid can induce significant reductions in yield, sugar content, and recoverable sugar. Under conditions of extreme stress and heavy infestations, the alienicolae can induce stunting, chlorosis, wilting, and even death of sugar beet plants. Accurately establishing population densities for sugarbeet root aphids presents a challenge, because the economic important stage of this insect is subterranean. However, use of a fall root rating index aids in estimating relative population densities. Furthermore, root aphids are especially difficult to control by means of conventional insecticides. For this reason, integrated pest management tactics, including the use of host plant resistance, cultural control techniques, and the use of natural enemies, should take precedence.

**Key words**: *Pemphigus betae*, sugar beet, sugarbeet root aphid, management

Aphids of the genus *Pemphigus* Hartig (Hemiptera: Aphididae: Eriosomatinae) form galls on the leaves of their primary host, *Populus* spp. L. (Salicaceae), but the summer morphs are mostly restricted to the roots of various secondary hosts (Cranshaw 2004, Blackman and Eastop 2006, Foottit et al. 2010). This genus contains >70 named species, and 21 are known from North America (Blackman and Eastop 2006). Despite several species having been formally described, there still exists a degree of uncertainty over the true identity of the various *Pemphigus* spp. (Foottit et al. 2010). The difficulty in differentiating between *Pemphigus* spp. based on morphological characters alone was elucidated by Harper (1963). Blackman and Eastop (2006) stated that the identification of apterous aphids found on the roots of their secondary hosts is very difficult, if not impossible, when only morphological characters are used. The most recent molecular analysis conducted on the sugarbeet root aphid was done by Foottit et al. (2010). Using mitochondrial DNA cytochrome *c* oxidase subunit 1 and nuclear microsatellite flanking region sequences, the authors found that different *Pemphigus* spp. (three in this case) might coexist on the same primary host with no visible distinction between the galls they form.

However, despite the apparent difficulty in separating these species on a morphological basis, certain crops, serving as secondary hosts, are known to harbor specific species, and have been the focus of extensive research due to the economic damage they inflict. One such species, the sugarbeet root aphid, *Pemphigus betae* Doane (Hemiptera: Aphididae)[5], is a regular pest of sugar beet (*Beta vulgaris* L. var. *vulgaris*) in some beet-growing regions but can be a

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[5] The root aphid on sugar beet is commonly referred to as the "sugarbeet root aphid"; however, *Pemphagus populivanae* has also been recognized by some authors as a synonym of *P. betae*. Taxonomic confusion exists over the species in this genus, particularly of populations found on their primary host. The authors choose to use "sugarbeet root aphid" in association with *P. betae* even though its synonym, *P. populivenae*, is listed in association in the *Common Names of Insects Database*. See discussion and Foottit et al. (2010) for further discussion on this taxonomic confusion.

serious sporadic pest in the remaining regions (Harper 1963, Hutchison and Campbell 1994, Campbell and Hutchison 1995a,b).

*Pemphigus betae* was originally described from sugar beet by Doane (1900) in Washington in the United States, and it was later found to be synonymous with *Pemphigus balsamiferae*, which was described from its primary host gall (Maxson 1916). Naming confusion has continued with Grigarick and Lange (1962) considering *P. betae* and *Pemphigus populivenae* Fitch synonymous, but Foottit et al. (2010) established consistent genetic differences between these two, along with a third unrecognized group. In addition to Foottit et al. (2010) finding genetic variation within primary host galls of similar shape, Serikawa (2007) through AFLP assay found higher genetic variability within populations than between populations and relatively high, but variable, levels of gene flow among populations collected from sugar beet from Montana, Colorado, Idaho, Nebraska, and Alberta, Canada. However, *P. betae* populations collected from sugar beet in Michigan were genetically distinct from the other *P. betae* populations, demonstrating either regional isolation or a divergent primary host association. It is apparent that much is left to be determined on the identification of this species, and it is clear that primary host and regional differences need to be better defined. This paper describes the biology, economic significance, and management strategies of *P. betae* as a pest of sugar beet.

## Description of The Sugarbeet Root Aphid

Sugarbeet root aphids are small oval-shaped, pale-yellow insects, with a body length ranging from 1.9–2.4 mm (Blackman and Eastop 2006). In contrast to most other aphid species found above-soil level, soil dwelling morphs of *P. betae* have reduced appendages (siphunculi, legs, antennae, and cauda) as an adaptation to their subterranean existence (Dewar and Cooke 2006). Individual aphids secrete a waxy material, giving their subterranean colonies a moldy appearance (Blackman and Eastop 2006, Dewar and Cooke 2006, Hein et al. 2009, Natwick 2010; Fig. 1a and b) . It is thought that this waxy substance plays a role in repelling moisture from the aphid colony (Hein et al. 2009). Additionally, the wax may protect the aphids from their own honeydew, because ant attendance has never been documented, and their cauda, used by other aphids for flicking away honeydew, are reduced. As further evidence, Harper (1963) noted that these aphids cover their honeydew with wax while still enclosed in a gall on the primary host. The amount of wax present on a sugar beet root is useful for rating sugarbeet root aphid infestation levels in the field (Hutchison and Campbell 1994).

## Primary and Secondary Host Plants

As with most host-alternating aphid species, the sugarbeet root aphid is restricted in its primary host range, but the secondary host range is more diverse. *Pemphigus* spp. prefer poplars in the genus *Populus* (Fig. 2) as their primary hosts (Blackman and Eastop 2006). Over the years, *P. betae* primary hosts have been identified as species within the *Populus* section *Tacamahaca*, including narrowleaf cottonwood (*P. angustifolia* James), balsam poplar (*P. basamifera* L.), and black cottonwood (*P. trichocarpa* Torr. & A. Gray) in North America (Parker 1915, Harper 1963, Whitham 1978, Floate et al. 1997, Dewar and Cooke 2006, Hein et al. 2009). Although there is some overlap in their geographical distribution, these primary hosts occupy relatively distinct regions in North America. For example, narrowleaf cottonwood is found primarily in the central and southern Rocky Mountain regions, the balsam poplar is found in the northern Rockies into Canada and extending east to the Great Lakes region, and the black cottonwood has a range stretching from Alaska, through western Canada, and primarily into the northwestern United States, but also sporadically down as far south as Baja, CA (U.S. Department of Agriculture [USDA] 2014). Additional ecological complexity of these aphid–primary host relationships was demonstrated by Floate et al. (1997) who found a dramatic increase in *P. betae* host acceptability for hybrids between the aphid's primary hosts and other *Populus* spp.

The roots of the secondary hosts serve as the site of summer colonization. Secondary hosts for *P. betae* include sugar beet, common lambsquarters (*Chenopodium album* L.), kochia (*Kochia scoparia* (L.)), *Rumex* L. spp., and pigweed (*Amaranthus* L. spp.) (Blackman and Eastop 2006, Hein et al. 2009). In addition to these, Harper (1963) reported that laboratory-reared *P. betae* established colonies on Swiss chard and red beets, spinach (*Spinacia oleracea* L.), and alfalfa (*Medicago sativa* L.). However, alfalfa proved to be a poor host for this aphid species.

**Fig. 1.** Waxy filaments secreted by individual aphids (**a**) gives the colony a moldy appearance (**b**).
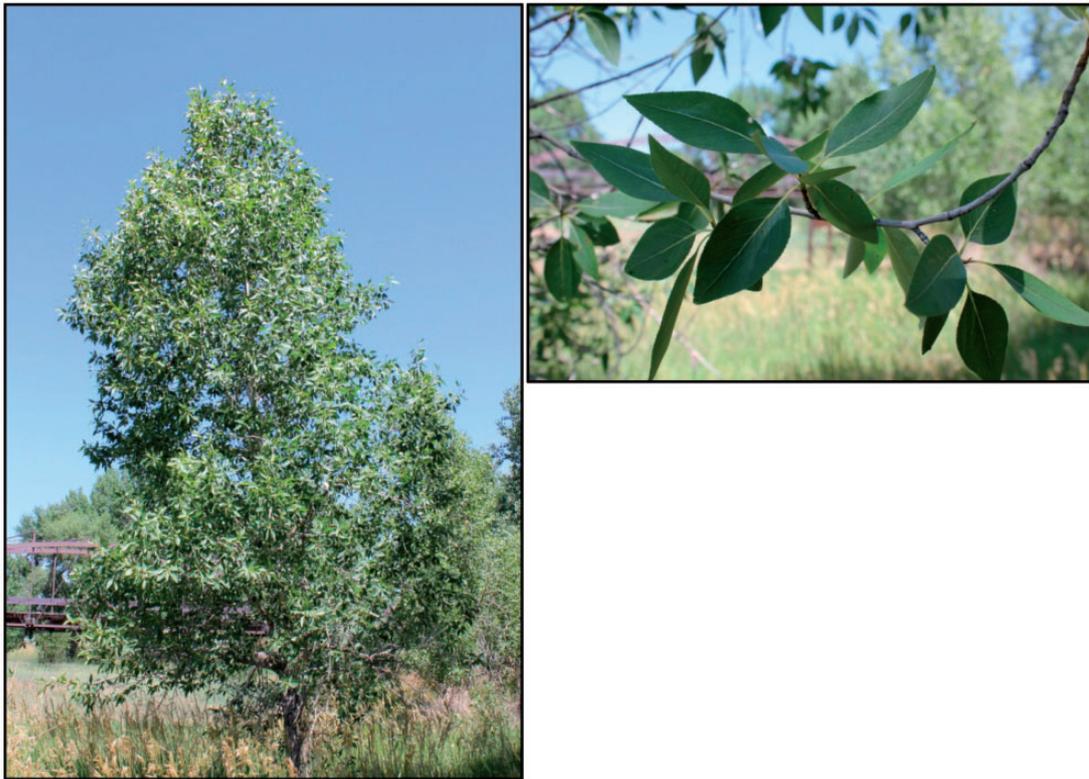
Fig. 2. *Pemphigus* spp. prefer poplars in the genus *Populus*, such as this narrowleaf cottonwood (*P. balsamifera*) as their primary host.
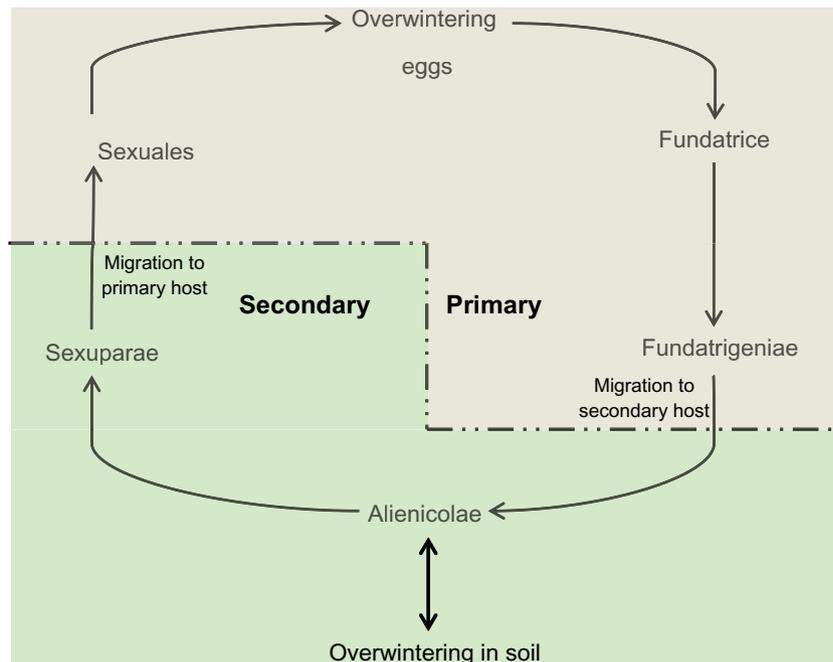


Fig. 3. Graphical representation of the life cycle of the sugarbeet root aphid, *P. betae*. (Redrawn from Harper 1963).

## Sugarbeet Root Aphid Life Cycle

For the pest manager and producer alike, a basic understanding of the life cycle of the sugarbeet root aphid is essential in considering management options (Fig. 3). *Pemphigus betae* has a complex and varied life cycle, as observed by Parker (1914) and Harper (1963)

(see glossary for an explanation of sugarbeet root aphid life cycle terms). This aphid is usually heteroecious and holocyclic (Blackman and Eastop 2006), but anholocyclic apterae are known to overwinter in the soil and initiate new colonies with the development of favorable weather conditions (Moran and Whitham 1988). This also

appears to be the case in Minnesota where most new infestations are reportedly initiated by these morphs (Hutchison and Campbell 1994).

Harper (1963) observed that an overwintering egg (Fig. 4a) hatches into an apterous, viviparous, parthenogenetic fundatrix (Fig. 4b) during spring (late April to early May in southern Alberta). Her initial feeding on the dorsal surface of a leaf from the primary host causes the leaf tissue to form a protective gall along the mid-rib (Fig. 5a and b). Enclosed within her gall, the fundatrix subsequently produce female alate, viviparous, parthenogenetic fundatrigeniae (Fig. 4c) that, when mature, migrate from the primary to the secondary host during early to midsummer (late June to mid-August in southern Alberta). Harper (1963) reported the average reproductive capacity of a fundatrix at 163 offspring, and Parker (1914) estimated it to be 75. After locating a suitable secondary host, the fundatrigeniae subsequently give birth to apterous, viviparous, parthenogenetic alienicolae (Fig. 4d). By dissecting 10 fundatrigeniae, Harper (1963) found that the average reproductive potential for each female was 13.3 aphids. This stage in the life cycle of the sugarbeet root aphid reproduces on sugar beet roots; therefore, they are responsible for economic damage observed in the crop. Harper (1963) established the optimum soil temperature for reproduction by alienicolae to be 25–27°C.

Several generations of alienicolae are produced before they eventually produce alate, viviparous, parthenogenetic sexuparae (Fig. 4e) that migrate back to the primary *Populus* host beginning in late August and into fall. Moran et al. (1993) were able to determine that low temperatures in the range of 17–20°C were the primary determinant in the production of sexuparae, but in this temperature range crowding also contributed to this process. These sexuparae, in contrast to most other aphid species, can only produce apterous males and the larger ovipare females, also known as sexuales. The average reproductive capacity of the sexupara is estimated at six individuals per female (Harper 1963). After mating with the apterous males, sexuales produce a single overwintering egg on the primary host. This is the only sexual generation in the life cycle of *P. betae*. Eggs are deposited in crevices of the bark where they are protected from ambient conditions throughout winter. Harper (1963) reported that the egg is deposited in a white waxy secretion and initially appears white, but it turns darker as it ages. Often, however, the female dies with the egg still inside her body (Parker 1914, Harper 1963). The eggs undergo an obligatory diapause before hatching the following spring.

## Economic Importance

Economically damaging infestations of this pest have been reported from several locations in North America. Aliencolae are reported to prefer feeding on the hosts' secondary roots (Harper 1963, Summers and Newton 1989, Hein et al. 2009, Natwick 2010), but heavy infestations may spread to the tap root. Heavy feeding will give the root a rubbery and flaccid appearance under conditions of extreme stress and inadequate moisture levels (Harper 1963, Winter 1999, Hein et al. 2009). Root aphid damage is often most severe under drier conditions (Summers and Newton 1989, Hutchison and Campbell 1994, Winter 1999). Harper (1963) also noticed that damage from early frost might be more severe for root aphid-infested beets.

Heavy infestations of *P. betae* can induce significant reductions in yield (Harper 1963, Summers and Newton 1989, Hutchison and Campbell 1991, Hein et al. 2009), sugar content (Harper 1963;

Hutchison and Campbell 1991, 1994; Winter 1999; Hein and Thomas 2003; Hein et al. 2009), and recoverable sugar (Summers and Newton 1989; Hutchison and Campbell 1991, 1994; Hein and Thomas 2003; O'Boyle et al. 2015). Late summer or fall *P. betae* infestation levels exceeding a value of "2" on the 0–5 root rating index (see scouting procedures below) are reportedly required to cause consistent loss in recoverable sugar, although precipitation levels can also influence this (Hutchison and Campbell 1994). Under conditions of extreme stress, heavy infestations of alienicolae can induce stunting, chlorosis, wilting, and even death of sugar beet plants (Harper 1963, Summers and Newton 1989, Dewar and Cooke 2006, Natwick 2010). This can be ascribed to the interference with moisture and nutrient uptake (Summers and Newton 1989, Hein et al. 2009). No economic threshold levels have been established for sugarbeet root aphid on sugar beet, and Hutchison and Campbell (1994) mention that the sporadic nature of this pest, coupled with its cryptic biology, has hindered extensive research on its economic significance as a pest of sugar beet. However, it is known that moderate infestation levels can induce sugar loss of up to 30%, even when above-soil symptoms are absent (Summers and Newton 1989, Harveson et al. 2002, Hein et al. 2009). Yield loss of 36–60%, depending on the level of root aphid infestation, have been reported by Summers and Newton (1989) in California, while Hutchison and Campbell (1994) reported yield losses of 32%. Furthermore, Hutchison and Campbell (1994) also recorded losses of 31 and 54% in sugar content and recoverable sugar, respectively, as a result of root aphid infestations. Hutchinson and Campbell (1991) reported that in 1984 and 1989 sugarbeet root aphids infested 10% of 33,000-ha sugar beets in southern Minnesota, leading to losses of US$3 million. In addition to the aforementioned preharvest losses, recent evidence suggests that postharvest losses can also be induced by sugarbeet root aphid infestations. Boetel et al. (2014) reported that sugar beets infested with root aphids in the field continue to loose sugar through increased respiration, and that this increased respiration rate can carry over to adjacent beets in a storage pile that were not infested with root aphids.

A study conducted in Minnesota by Hutchison and Campbell (1994) found that field infestations of *P. betae* tend to occur in elliptical foci within fields. A similar phenomenon was observed by Summers and Newton (1989) in California. However, much more uniform infestations occur in growing regions near the Rocky Mountains (G.L.Hein, personal communication). These foci likely develop as a consequence of sparse initial infestations which subsequently establish well in the field. Hutchison and Campbell (1994) mentioned that severe infestations could result in individual foci merging with each other, leading to heavier infestations. The formation of these foci could be ascribed to the tendency of these aphids to move down rows, rather than across them (Summers and Newton 1989). Sugarbeet root aphids are known to use cracks in the soil to migrate between individual hosts (Harper 1963. Hein and Yonts 2005), but they can also be dispersed via precipitation, irrigation water, wind, and field equipment (Harper 1963, Summers and Newton 1989, Hutchison and Campbell 1994). Therefore, variability in soil type might play a role in infestation patterns.

## Sugarbeet Root Aphid Monitoring

Accurately establishing population densities for sugarbeet root aphids presents a challenge, because the economic important stage of this insect is subterranean. Because root aphid feeding does not always produce above-soil symptoms (e.g., Winter 1999), and because
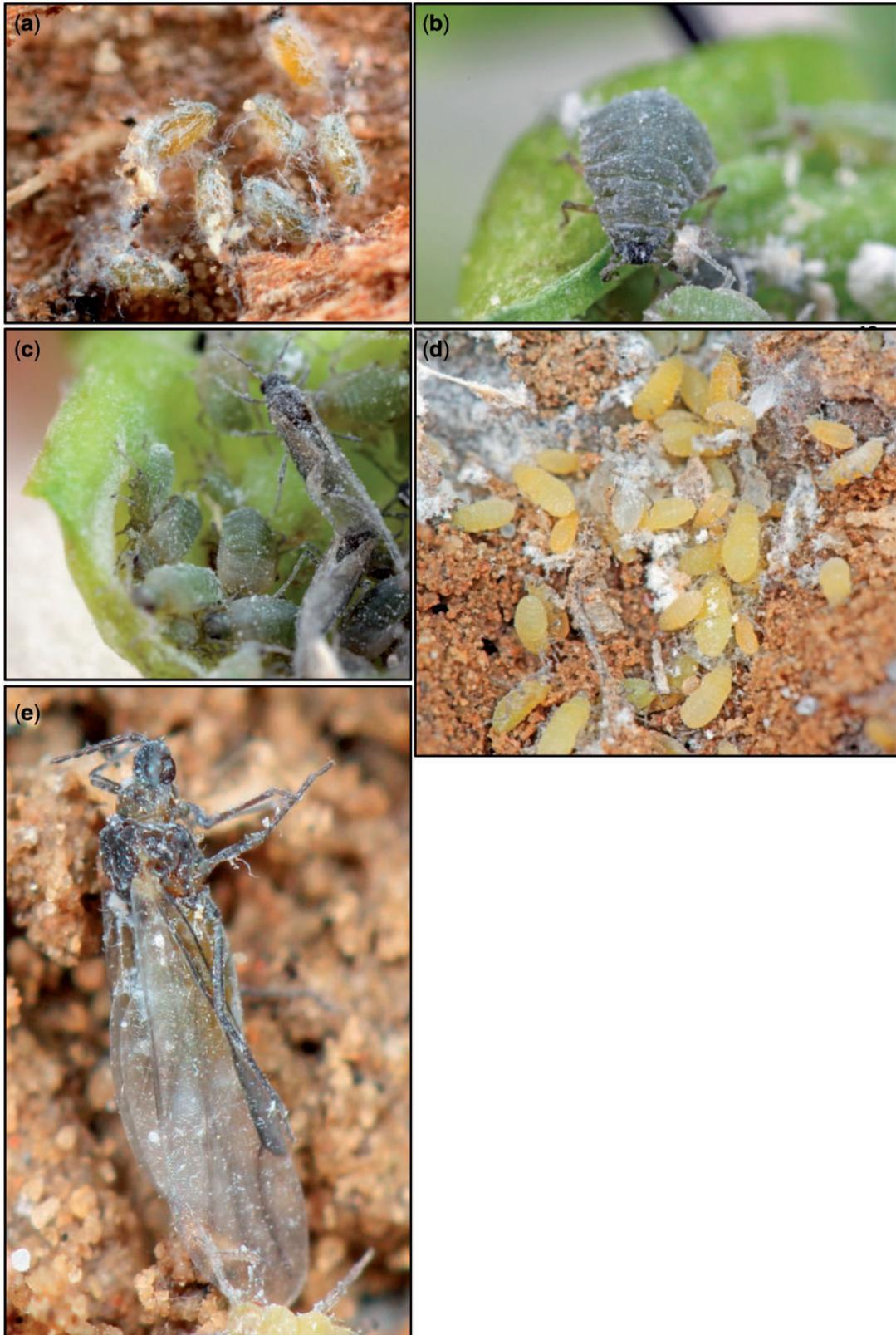
**Fig. 4.** Different life stages and morphs found in the life cycle of *P. betae*. Pictured are eggs (**a**), a fundatrix in a gall (**b**), fundatrigeniae in various stages of development in a gall (**c**), alienicolae on sugar beet roots (**d**), and sexupara amongst aliencolae on a sugar beet root (**e**). The eggs could not be confirmed with certainty as belonging to *P. betae*, but dead bodies of both sexuparae and sexuales were observed on the bark of the trees from which the eggs were collected. Furthermore, an aphid hatched from one of these eggs, but died in the absence of its host. The white filamentous material surrounding the eggs also conforms to the description given by Harper (1963).
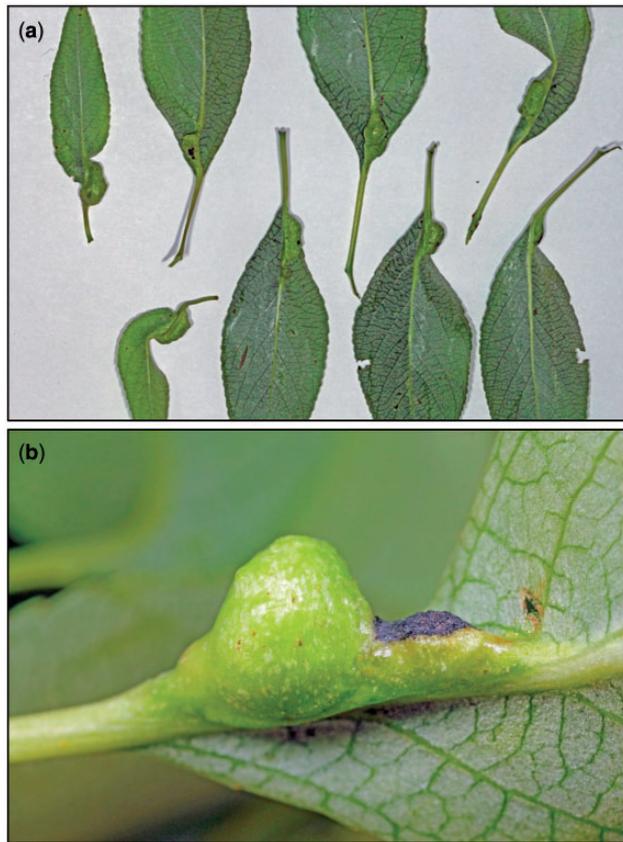
**Fig. 5.** Narrowleaf cottonwood leaves with galls formed by the fundatrix of the root aphid, _P. betae_ (**a**). A close-up of root aphid gall; usually located near the midrib of the leaf (**b**).

individual aphids are small, it is important to dig up roots and examine them for aphids and the presence of the characteristic waxy material. For this reason, Hutchison and Campbell (1994) developed a root rating index during 1990 in Minnesota. The index ranges in scale from 0–5, with "0" signifying no infestation and a "5" indicating the highest level of infestation achievable where multiple colonies or wax [or both] covers >95% of the root surface. This scale relies largely on quantifying the amount of aphid-secreted wax present on the root, rather than making direct aphid counts. Apart from its usefulness in rating root aphid infestation levels, this rating scale is also helpful when evaluating cultivars for sugarbeet root aphid resistance (Hutchison and Campbell 1994, Harveson et al. 2002). However, despite the development of the fall root rating index, there still exists the need to effectively monitor sugarbeet root aphid migration into sugar beet fields and their subsequent population growth (Hutchison and Campbell 1994). The reason for this is so that producers can be aware of significant infestations that might develop during the course of the growing season so that management decisions, e.g., water management where sugar beet are grown under irrigation (Hein and Yonts 2005), can be implemented In an attempt to investigate population growth and age-specific life tables of _P. betae_, Campbell and Hutchison (1995a) used hydroponic growth pouches to rear these aphids. Their method allowed the authors to determine the fecundity of individual root aphids, something that would be challenging under field conditions. This method proved successful judging by the fact that the authors could maintain a culture for over three years.

## Management Practices

Root aphids are especially difficult to control by means of conventional insecticides (Winter and Patrick 1997, Dewar 2007) due to their cryptic biology. Most systemic insecticides cannot be transported downward toward the root system of the host plant (Dewar 2007), and early-season chemical control (such as seed treatments) are reported to be inconsistent against aphids moving into fields later in the season (Dewar 2007, Hein et al. 2009). However, some chemicals, such as triazamate (no longer registered in the United States), were used to control root aphids (_Pemphigus bursarius_ (L.)) on lettuce (Parker et al. 2002) and was also very effective against the sugarbeet root aphid (G.L.H., personal communication). Results from chemicals tested in the United States, such as terbufos (Counter 15 granules), were inconsistent (Campbell and Hutchison 1991), while others, such as chlorpyrifos (Lorsban 4 Emulsifiable concentrate, 15 G), and several foliar insecticides led to increased root aphid numbers (Campbell and Hutchison 1991, Wenninger 2011). Harper (1961) also found that the use of insecticides reduced predator numbers significantly, leading to a loss of biological control, which was equally effective in reducing root aphid numbers compared with the insecticides. In 1989, Summers and Newton reported that there are no effective chemicals for use against this aphid, and this situation has not changed (Hein et al. 2009, O'Boyle et al. 2015). Seed treatments with neonicotinoids (seed-applied Poncho Beta and Cruiser Tef) have also been tested against these insects, but results have shown inconsistent suppression of root aphid infestations (Strausbaugh et al. 2010, Pretorius 2014). Wenninger (2011) mentions that the neonicotinoid seed treatments imidacloprid (under the trade names: Agrisolutions Nitro Shield, Agristar Macho 600 ST, Attendant 480 FS, Axcess Insecticide Seed Treatment, Dyna-Shield Imidacloprid 5, Gaucho 480 Flowable, Gaucho 600 Flowable, Imida E-AG 5 F ST, and Senator 600FS) and thiamethoxam (trade name: Cruiser 5 FS) could provide limited control of sugarbeet root aphids, but suppression would also likely be inconsistent due to heavy infestations developing later in the season when the impact of the seed treatments have diminished. Terbufos (several Counter formulations) is registered against the sugarbeet root aphid in Idaho, but field trials (conducted in Minnesota) showed limited impact on these insects (Wenninger 2011). Another option for chemical control of this pest might be the use of soil drenches (Winter 1999).

Due to the importance of sugar beet as a source of sucrose, and the absence of reliable chemical control measures, there is a need for alternative control measures of sugarbeet root aphid to curb economic losses. Integrated pest management is an important approach for sugarbeet root aphid management and incorporates biological control, cultural control, and host plant resistance. Interest in the integrated use of these management strategies in other crops (for example in wheat) has received increasing attention in North America (Brewer and Elliot 2004), and can be implemented to the benefit of sugar beet production.

### Host Plant Resistance

Breeding sugar beet for resistance to various pests and diseases has been crucial in ensuring sustained cultivation in regions where these problems are pronounced (Bosemark 2006). The significance of using resistant or tolerant varieties for keeping pests and diseases at bay is evident when considering the possibility of increased yields with decreased chemical inputs and, hence, decreased production costs. The success rate for breeding insect-resistant varieties of sugar beet, in general, has been low compared with breeding disease-resistant varieties (Bosemark 2006). However, several sugar beet varieties have shown good resistance against the sugarbeet root aphid.

In the past, sugar beet varieties have been successfully screened for resistance to the sugarbeet root aphid in North America (Harper 1964, Wallis and Turner 1968, Campbell and Hutchison 1995b, Winter 1999, Harveson et al. 2002, Hein and Thomas 2003, Hein and Thomas 2005). The importance of using root aphid-resistant sugar beet varieties for reducing the impact of root aphids on yield has been demonstrated by Hein and Thomas (2003). Resistance in some of the varieties tested may be so pronounced that no aphids are able to survive on them (Campbell and Hutchison 1995b). The mechanisms underlying this resistance have been ascribed to both antibiosis and antixenosis (Campbell and Hutchison 1995b), with more recent evidence that this resistance is conferred by a single gene (Leijman 2011). Currently, host plant resistance is considered the most important management strategy against the sugarbeet root aphid (Hein et al. 2009, Wenninger 2011, O'Boyle et al. 2015). Harveson et al (2002) found that in fields with significant root aphid pressure nearly all high yielding varieties were root aphid resistant. However, variety selection is often complicated due to the need for resistance to multiple disease problems in addition to the root aphid (Harveson et al. 2002). It is highly probable that host resistance will continue to play an important role in sugarbeet root aphid management with the availability of gene transfer techniques and marker-assisted selection which could contribute toward breeding disease and pest-resistant varieties with higher yield (Bosemark 2006).

## Natural Enemies

The inability to effectively control sugarbeet root aphids with conventional chemicals increases the importance of natural enemies in suppressing aphid infestations. In fact, before the use aphid-resistant varieties, Harper (1963) indicated that natural enemies were largely responsible for curtailing sugarbeet root aphid infestations. Because this is an indigenous pest to North America, native natural enemies may be more effective in suppressing their numbers. Therefore, conserving these beneficials could be important. However, with the damaging stages being subterranean, it is unlikely that parasites will play a significant role in reducing root aphid infestations (Dunn 1960).

Although there is ample information on the predatory arthropod complex that prey on aphids occurring above ground, the opposite is true for subterranean aphid populations. It is likely that these aphids have a different predatory complex than that of their above-soil counterparts (Dunn 1960). Harper (1963) reported the flies, *Syrphus bigelowi* Curran, *Leucopis pemphigae* Malloch, and *Thaumatomyia glabra* (Meigen); the anthocorid bug, *Anthocoris antevolens* White; and a coccinellid in the genus *Scymnus*, as predators of *P. betae* in Alberta. However, with the exception of *T. glabra*, these predators were all reported from the galls on the primary host, and not on subterranean aphid populations. Dunn (1960) reported syrphid fly larvae and anthocorid bugs (*Anthocoris nemorum* (L.) and *Anthocoris nemoralis* (F.)) preying on the closely related *P. bursarius* in their galls on the primary host. The coccinellids, *Coccinella transversoguttata* Faldermann, *Coccinella trifasciata* Mulsant, and *Adalia bipunctata* Say, as well as the anthocorid bug, *Anthocoris antevolens*, prey on sexual forms and fall migrants of *P. betae* occurring on the primary host (Harper 1963). Similarly, Dunn (1960) noted three coccinellid species preying on sexuparae of a related species, *P. bursarius*, arriving on poplars from their secondary host, lettuce.

In contrast to these, *T. glabra* prey on *P. betae* colonies in the soil, as reported in Alberta, CA, and elsewhere (Dunn 1960, Harper 1963, Summers and Newton 1989, Hein et al. 2009). Other predators observed preying on subterranean sugarbeet aphids include *Metasyrphus pauxillus* (Williston), *Hippodamia convergens* Guerin, *Scymnus collaris* Meish, and *Scymnus appaculus* Horn (Maxson 1916). Both Dunn (1960) and Rivard (1964) mention that there are many carabids and staphylinids associated with *P. bursarius* colonies below soil, and that these likely prey on the summer morphs. However, very few studies have been conducted to determine the importance of these generalist predators on sugarbeet root aphid infestations, despite much emphasis given on the value of carabid beetles as generalist predators in other cropping systems (Eitzinger and Traugott 2011). Recent studies by Pretorius (2014) in western Nebraska found several aphidophagous epigeal arthropod taxa associated with sugarbeet root aphid-infested sugar beets, of which carabids formed a speciose and abundant component. Furthermore, it was found that 10 of the most abundant carabid species in these sugar beet agroecosystems readily fed on root aphids under controlled conditions. However, more work is needed to quantify the contribution of these arthropods to sugarbeet root aphid management under natural field conditions.

## Cultural Practices

Alternative management strategies that have been suggested to lower root aphid infestations include sanitation, crop rotation, managing alternate hosts, and maintaining adequate soil moisture regimes (e.g., Summers and Newton 1989, Hein and Yonts 2005, Wenninger 2011). Crop rotation can decrease the survival of alienicolae overwintering in the field, provided adequate weed control can be achieved. Weed species, such as common lambsquarters and redroot pigweed, are abundant in sugar beet agroecosystems and field margins and can act as secondary hosts for the aphid. Thus, these alternate hosts need to be managed vigorously in the sugar beet and nonbeet crops. Unfortunately, herbicide-resistant weed populations can pose a problem in this regard, especially with the increased prevalence of glyphosate-tolerant weed populations identified recently (Sandell et al. 2012, Heap 2014).

It is also suggested that these aphids can be spread between fields on contaminated equipment (Summers and Newton 1989, Wenninger 2011), highlighting the importance of practicing good sanitation. The use of frequent and early irrigation, coupled with optimum levels of soil fertility, has been suggested to keep sugarbeet root aphid damage to subeconomic levels (Parker 1915, Harper 1964). Summers and Newton (1989) also suggest that tail water from fields infested with these aphids should not be applied to uninfested fields, because these aphids are readily transported by irrigation water. Dry soil conditions should be minimized where irrigation is available, because root aphid populations build up rapidly under these conditions on susceptible varieties (Hutchison and Campbell 1991, Hein and Yonts 2005), and because it reduces water stress and aphid impact on the sugar beet crop. Hein and Yonts (2005) found that late summer irrigation is especially important for reducing sugarbeet root aphid impact on yield. These authors also found that soil compaction (which results in increased soil cracking), as well as lower midseason irrigation, leads to increased sugarbeet root aphid numbers. In addition to these, cultivation might also reduce sugarbeet root aphid numbers. Thorough cultivation following harvest will destroy overwintering aliencolae in field soils (Summers and Newton 1989).

In conclusion, the sugarbeet root aphid poses a serious threat to sugar beet production in the many sugar beet production regions of North America due to its ability to reduce sugar content and yield. Control and detection of this aphid pest is not easily attained, owing

to the subterranean summer morphs occurring on the roots of the crop. Unlike most aphid pest species, chemical control of the sugarbeet root aphid is not a viable option at present, and attention to integrated pest management strategies should take precedence. In this regard, host plant resistance, cultural techniques, and likely biological control, play a pivotal role.

## GLOSSARY OF SUGARBEET ROOT APHID LIFECYCLE TERMS

**Alate:** Having wings.

**Alienicolae:** Aphids developing on the secondary host plant (e.g., sugar beet), and which produce young asexually (parthenogenetically).

**Anholocyclic:** A situation in which aphids continually reproduce asexually without sexual reproduction and subsequent egg-laying taking place.

**Apterous:** Having no wings.

**Fundatrigeniae:** Asexually producing female aphids produced by the fundatrix (stem mother) which migrate from the primary host (e.g., narrowleaf cottonwood) to the secondary host(s) (e.g., sugar beet) where they produce alienicolae.

**Fundatrix (stem mother):** An asexual foundress female aphid which hatches from an overwintering egg produced by sexuales during the previous season.

**Heteroecious:** Alternating between primary and secondary hosts (usually unrelated host plant species).

**Holocyclic:** A situation in which aphids possess a sexual stage in the life cycle where they reproduce sexually with subsequent egg-laying taking place (the eggs facilitate in overwintering).

**Parthenonogenetic:** A form of asexual reproduction in which young are produced by female aphids without fertilization taking place.

**Sexuales:** The sexual reproducing form of aphids which includes both males and oviparae (egg-producing) females.

**Sexuparae:** Winged (alate) female aphids produced on the secondary host by the alienicolae, and which are responsible for migrating back to the primary host (e.g. narrowleaf cottonwood) toward the end of the season. Here they produce sexuales in an asexually.

**Viviparous:** Giving birth to live young.

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## References Cited

Blackman, R. L., and V. F. Eastop. 2006. Aphids of the world's herbaceous plants and shrubs, Volume 2: the aphids. John Wiley & Sons, West Sussex, United Kingdom.

Boetel, M. A., L. G. Campbell, A. J. Schroeder, and R. J. Dregseth. 2014. Root aphid impacts on stored roots and an outlook for 2014. 2013 Sugarbeet Research and Extension Reports, Cooperative Extension Service, North Dakota State University, Fargo, ND 44.

Bosemark, N. O. 2006. Genetics and breeding, pp. 50–88. *In* A. P. Draycott (ed.), Sugar beet. Blackwell Publishing, Oxford, United Kingdom.

Brewer, M. J., and N. C. Elliot. 2004. Biological control of cereal aphids in North America and mediating effects of host plant and habitat manipulations. Annu. Rev. Entomol. 49: 219–242.

Campbell, C. D., and W. D. Hutchison. 1991. Sugarbeet root aphid control in southern Minnesota, 1990. Insecticide and Acaricide Tests 16: 231–232.

Campbell, C. D., and W. D. Hutchison. 1995a. Rearing methods and demographic statistics for a subterranean morph of the Sugarbeet root aphid (Homoptera: Aphididae). Can. Entomol. 127: 65–77.

Campbell, C. D., and W. D. Hutchison. 1995b. Sugarbeet resistance to Minnesota populations of Sugarbeet root aphid (Homoptera: Aphididae). J. Sugar Beet Res. 32: 37–45.

Cranshaw, W. 2004. Garden insects of North America: The ultimate guide to backyard bugs. Princeton University Press, Princeton, NJ.

Dewar, A. M. 2007. Chemical control, pp. 391–422. *In* H. F. Van Emden and R. Harrington (eds.), Aphids as crop pests. Cromwell Press, Trowbridge, United Kingdom.

Dewar, A. M., and D. A. Cooke. 2006. Pests, pp. 316–358. *In* A. P. Draycott (ed.), Sugar beet. Blackwell Publishing, Oxford, United Kingdom.

Doane, R. W. 1900. Notes on a new sugar-beet pest, with a description of the species. Entomol. News 11: 390–391.

Dunn, J. A. 1960. The natural enemies of the lettuce root aphid, *Pemphigus bursarius* (L.). Bull. Entomol. Res. 51: 271–278.

Eitzinger, B., and M. Traugott. 2011. Which prey sustains cold-adapted invertebrate generalist predators in arable land? Examining prey choices by molecular gut-content analysis. J. Appl. Ecol. 48: 591–599.

Floate, K. D., G. D. Martinsen, and T. G. Whitham. 1997. Cottonwood hybrid zones as centres of abundance for gall aphids in western North America: importance relative to habitat size. J. Anim. Ecol. 66: 179–188.

Foottit, R. G., K. Floate, and E. Maw. 2010. Molecular evidence for sympatric taxa within *Pemphigus betae* (Hemiptera: Aphididae: Eriosomatinae). Can. Entomol. 142: 344–353.

Grigarick, A. A., and W. H. Lange. 1962. Host relationships of the sugar-beet root aphid in California. J. Econ. Entomol. 55: 760–764.

Harper, A. M. 1961. Effect of insecticides on the sugar-beet root aphid, *Pemphigus betae*. J. Econ. Entomol. 54: 1151–1153.

Harper, A. M. 1963. Sugar-beet root aphid, *Pemphigus betae* Doane (Homoptera: Aphididae) in southern Alberta. Can. Entomol. 95: 863–873.

Harper, A. M. 1964. Varietal resistance of sugar beets to the sugar-beet root aphid *Pemphigus betae* Doane (Homoptera: Aphididae). Can. Entomol. 96: 520–522.

Harveson, R. M., G. L. Hein, J. A. Smith, R. G. Wilson, and C. D. Yonts. 2002. An integrated approach to cultivar evaluation and selection for improving sugar beet profitability: A successful case study for the central high plains. Plant Dis. 68: 192–202.

Heap, I. 2014. Herbicide resistant weeds, pp. 281–301. *In* D. Pimentel and R. Peshin (eds.), Integrated pest management: Pesticide problems, Volume 3. Springer, Dordrecht, The Netherlands.

Hein, G. L., and J. A. Thomas. 2003. Impact of sugar beet root aphids on sugar beet yield and response to resistant varieties, pp. 381–386. *In* Proceedings, 32nd Biennial Meeting of the ASSBT, 16 February–1 March 2003, San Antonio, TX.

Hein, G. L., and J. Thomas. 2005. Screening for varietal resistant to sugarbeet root aphid, pp. 138–142. *In* Proceedings, 33rd Biennial Meeting of the ASSBT, 2-5 March 2005, Palm Springs, CA.

Hein, G. L., and C. D. Yonts. 2005. Soil and moisture factors affecting sugarbeet root aphid and its impact on sugarbeet yield, pp. 181–184. In Proceedings, 33rd Biennial Meeting of the ASSBT, 2–5 March 2005, Palm Springs, CA.

Hein, G. L., M. A. Boetel, and L. D. Godfrey. 2009. Part IV: major insect and arthropod pests, pp. 95–117. *In* R. M. Harveson, L. E. Hanson, and G. L. Hein (eds.), Compendium of beet diseases and pests, 2nd edn. APS Press, St. Paul, MN.

Hutchison, W. D., and C. D. Campbell. 1991. Biology, yield impact, and management of the sugarbeet root aphid in southern Minnesota: first year results. 1990 Sugarbeet Research and Extension Reports, North Dakota State University, Fargo 21: 151–159.

Hutchison, W. D., and C. D. Campbell. 1994. Economic impact of sugarbeet root aphid (Homoptera: Aphididae) on sugarbeet yield and quality in southern Minnesota. J. Econ. Entomol. 87: 465–475.

Leijman, E. 2011. Fine mapping of resistance against root aphids in sugar beet. M.S. thesis, Saint Louis University, Alnarp.

**Maxson, A. C. 1916.** Some unpublished notes on *Pemphigus betae* Doane. J. Econ. Entomol. 9: 500–504.

**Moran, N. A., and T. G. Whitham. 1988.** Evolutionary reduction of complex life cycles: loss of host-alteration in *Pemphigus* (Homoptera: Aphididae). Evolution 42: 717–728.

**Moran, N. A., J. Seminoff, and L. Johnstone. 1993.** Induction of winged sexuparae in root-inhabiting colonies of the aphid *Pemphigus betae*. Physiol. Entomol. 18: 296–302.

**Natwick, E. T. 2010.** Sugarbeet root aphid. UC IPM Pest Management Guidelines: Sugarbeet. UC ANR Publication 3469.

**O'Boyle, P. D., W. M. Beyer, J. C. Lein, and M. M. Rekoske. 2015.** Benefits of sugar beet root aphid resistance in North American sugar beet production, pp. 66–71. *In* Proceedings, 38th Biennial Meeting of the ASSBT, 23–26 February 2015, Clearwater Beach, FL.

**Parker, J. R. 1914.** The life history of the sugar-beet root-louse (*Pemphigus betae* Doane). J. Econ. Entomol. 7: 136–141.

**Parker, J. R. 1915.** Influence of soil moisture upon the rate of increase in sugar beet root-louse colonies. J. Agric. Res. 4: 241–250.

**Parker, W. E., R. H. Collier, P. R. Ellis, A. Mead, D. Chandler, J. A. Blood Smyth, and G. M. Tatchell. 2002.** Matching control options to a pest complex: The integrated pest management of aphids in sequentially-planted crops of outdoor lettuce. Crop Prot. 21: 235–248.

**Pretorius, R. J. 2014.** The effect of agricultural practices on sugar beet root aphid (*Pemphigus betae* Doane) and beneficial epigeal arthropods. Ph.D. dissertation, University of Nebraska–Lincoln, Lincoln.

**Rivard, I. 1964.** Carabid beetles (Coleoptera: Carabidae) from agricultural lands near Belleville, Ontario. Can. Entomol. 96: 517–520.

**Sandell, L., R. Wilson, and G. Kruger. 2012.** Glyphosate-resistant kochia confirmed in Nebraska. CropWatch, January 27.

**Serikawa, R. H. 2007.** Genetic variation between different populations of the sugarbeet root aphid (*Pemphigus betae* Doane) across North America. M.S. Thesis, University of Nebraska–Lincoln, Lincoln.

**Strausbaugh, C. A., I. A. Eujayl, and P. Foote. 2010.** Seed treatments for the control of insects and diseases in sugarbeet. J. Sugar Beet Res. 47: 105–125.

**Summers, C. G., and A. S. Newton. 1989.** Economic significance of sugarbeet root aphid, *Pemphigus populivenae* Fitch (Homoptera: Aphididae) in California. Appl. Agric. Res. 4: 162–167.

**(USDA) U.S. Department of Agriculture, NRCS. 2014.** The PLANTS Database. USDA, National Plant Data Team, Greensboro, NC.

**Wallis, R. L., and J. E. Turner. 1968.** Resistance of sugar beets to sugar beet root aphids, *Pemphigus populivenae* Fitch. J. Am. Soc. Sugar Beet Technol. 14: 671–673.

**Wenninger, E. J. 2011.** Sugar beet root aphids: Identification, biology, & management. University of Idaho Extension, University of Idaho, CIS 1176.

**Whitham, T. G. 1978.** Habitat selection by *Pemphigus* aphids in response to response limitation and competition. Ecology 59: 1164–1176.

**Winter, S. R. 1999.** Root aphid infestation relationship to agronomic performance and field position in furrow irrigated sugarbeet cultivar comparisons. J. Sugar Beet Res. 36: 1–13.

**Winter, S. R., and C. Patrick. 1997.** Sugar beet root aphid management in Texas, pp. 173–178. *In* Proceedings, 29th Biennial Meeting of the ASSBT, 2–5 March 1997, Phoenix, AZ.