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Wireworm and Flea Beetle IPM in Potatoes in Canada: Implications for Managing Emergent Problems in Europe

R. Vernon[1] **· W. van Herk**[1]

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Abstract Three species of wireworms (Coleoptera: Elateridae) known to cause severe damage to potatoes in Europe and Asia have been introduced to Canada and are now well established as pests in the westernmost province of British Columbia (BC) (*Agriotes obscurus* and *A. lineatus*) and the eastern provinces of Nova Scotia and Prince Edward Island (*A. obscurus*, *A. lineatus* and *A. sputator*). Conventional insecticide-based efforts to control these invasive pests have had serious environmental impacts, or are failing to prevent severe economic damage from occurring to potatoes in some key potato production areas. Research toward developing an IPM programme for these exotic species has been completed or is underway in Canada, including the following: biological and ecological studies, development of monitoring and risk assessment programmes, and development of insecticidal and alternative control strategies. This research is summarized and implications for wireworm management in Europe are discussed. In addition to wireworms, one of the primary economic insect pests of potatoes in BC is the tuber flea beetle, *Epitrix tuberis* (Coleoptera: Chrysomelidae). The larvae of this beetle feed on developing or mature daughter tubers, producing surface channels or tracks and holes directly into the tuber. In the past, growers would apply 7–10 foliar sprays of broad-spectrum insecticides per growing season, which was not always successful in controlling this pest. In the EU, a newly identified flea beetle, *Epitrix papa* sp. n., as well as the North American species, *E. cucumeris*, have been identified as attacking potatoes initially in Portugal (2004) and later also in Spain. The potential spread of these emergent pests to various EU and non-EU countries is of concern, and if established would require the development of management strategies. The former development of a highly effective IPM programme developed in BC for *E. tuberis* is discussed, as is its potential for *E. papa* and *E. cucumeris* management in Europe.

✉ R. Vernon
Bob.vernon@agr.gc.ca

[1] Agriculture and Agri-Food Canada, 6947 #7 Hwy, Agassiz, BC V0M 1A0, Canada

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Introduction

The accidental introduction of insect pests of potato from Europe to North America, and vice versa, has had significant economic impacts on potato production in both continents. A good example was the emergence and spread of the Colorado potato beetle (*Leptinotarsa decemlineata*) (Coleoptera: Chrysomelidae) from the USA to Europe, which, after several failed invasions, eventually took hold in France in 1922 and rapidly spread throughout most of mainland Europe (Gianessi and Williams 2011). Wherever established, this beetle has generally become a dominant and chronic pest, requiring aggressive and often costly pest management practices. In more recent years, the emergence of two flea beetle species (Coleoptera: Chrysomelidae) as pests of potato has been recorded in Europe. The potato flea beetle, *Epitrix cucumeris*, native to North America, first became established in the Azores Islands of Portugal around 1979 (Boavida and Germain 2009), and was later found on mainland Portugal in 2004 (Oliviera et al. 2008). Coincident with the *E. cucumeris* finding, an additional flea beetle was found on potatoes in Portugal in 2004. Initially misidentified as the North American species, *E. similaris*, this beetle is actually new to science and has recently been named *E. papa* (Orlova-Bienkowskaja 2015). Both species have since been found in Spain and are under phytosanitary regulation to retard further spread in the EU (EPPO 2017; EPPO A2, EU Commission decision 2016/1359/EU). Of these two species, *E. papa* is most significant in that it causes severe cosmetic damage to tubers at harvest, much like the western North American species, *E. tuberis* (Neilson and Finlayson 1953).

Insect introductions from Europe to North America have also been commonplace, but of greatest significance to the potato industry in Canada has been the arrival of three species of wireworms (Coleoptera: Elateridae), notably *Agriotes lineatus*, *A. obscurus* and *A. sputator*, to the western and easternmost provinces (Vernon and van Herk 2013). These species are gradually spreading geographically and have become the leading insect pests of concern to key potato-growing areas over the past decade. Although their European origins are not known, they are all common pests of potato throughout temperate Europe and Asia.

Wireworms in Canada (exotic as well as endemic species) as well as additional *Agriotes* species endemic to Europe can be considered ‘emerging problems’ to potato production, since their incidence, associated damage and geographical range are generally increasing. As such, contemporary research efforts to manage wireworm problems on both continents are yielding mutually beneficial results. With respect to the flea beetles, *E. cucumeris* and *E. papa* as ‘emergent threats’ to potato production in Western Europe (Suffert and Ward 2014), the development of a successful integrated pest management (IPM) programme for the previously ‘emergent pest’ *E. tuberis* in western Canada provides a framework for the development of IPM programmes, in Europe. The remainder of this paper describes research completed or underway in Canada for management of wireworms (*Agriotes* spp.) and flea beetles that may have implications for the development of IPM programmes, for these pests in Europe and elsewhere.

European *Agriotes* Wireworms in Canada: IPM Programme Development for *A. obscurus*, *A. lineatus* and *A. sputator*

In British Columbia (BC), Canada, *A. obscurus* and *A. lineatus* were first discovered in localized areas near Vancouver in 1949 (King et al. 1952), and both have gradually spread into new cropping areas as far as 317 km inland (Vernon et al. 2001; W. van Herk, personal observation). To the south of BC, both species have been found in the states of Washington (Vernon and Päts 1997; Vernon et al. 2001) and Oregon in the USA (LaGasa et al. 2006). In Eastern Canada, these species are known to occur in the Atlantic provinces of Nova Scotia, New Brunswick, Newfoundland and Prince Edward Island (PEI), with the additional species, *A. sputator*, occurring in Nova Scotia and PEI (Vernon and van Herk 2013).

In the lower Fraser Valley of BC, *A. obscurus* and *A. lineatus* emerged as serious agricultural pests in the 1990s, causing blemishes to potatoes destined for fresh market and damaging other crops (i.e. strawberries, corn, vegetables, etc.). As a result, the use of granular organophosphate (e.g. phorate) and carbamate (e.g. fonofos) insecticides increased in potato production in BC and was subsequently linked to the poisoning of a number of avian species including the bald eagle (Wilson et al. 2001; Elliott et al. 2011). By the turn of the century, phorate (Thimet 15G) had been removed from use in BC, and the production of fonofos (Dyfonate 10G) had ceased globally, leaving BC growers without access to effective wireworm control products. Wireworm damage to potatoes in Atlantic Canada began to increase in early 2000, first in Nova Scotia, primarily due to *A. obscurus*, followed by increasing reports of wireworm damage in PEI, the main potato production region in Canada. In PEI, *A. sputator* has been identified as the primary wireworm of concern, where populations are spreading rapidly throughout the island and potato production has ceased in some areas due to the high numbers occurring (R. Vernon, personal observation).

To address the threats to agriculture and associative threats to the environment posed by these exotic wireworms, an IPM approach has been under development by the Canadian government (Agriculture and Agri-Food Canada, AAFC) since the mid-1990s. This research has focussed on developing tools and knowledge related to the following: (a) the basic biology and ecology of these *Agriotes* species; (b) monitoring, forecasting and risk assessment; (c) building a diverse arsenal of control methods; and (d) consolidation of this research into management programmes, specific to species and key production areas in Canada. The activities and progress in achieving these IPM objectives are discussed below. It must be noted that this work augments or targets gaps in our knowledge related to wireworm IPM that have not been previously addressed by other wireworm researchers to this point. For a summary of previous IPM-related work conducted on wireworms specific to the global potato crop, the reader is directed to reviews by Parker and Howard (2001) and Vernon and van Herk (2013).

Basic Biology and Ecology of Exotic *Agriotes* spp. in Canada

Surveys Since 2000, local and national surveys have been undertaken to delimit the individual and overlapping ranges of exotic *Agriotes* spp. and endemic species of wireworms occurring in all 10 Canadian provinces (Vernon et al. 2001; Vernon and Tóth 2007; Vernon and van Herk 2013; van Herk and Vernon 2014), and this work is ongoing. In BC, where *A. obscurus* and *A. lineatus* have become well established, they have almost completely replaced the former endemic pest species (R. Vernon, personal observation) and are often found concurrently in fields (Blackshaw and Vernon 2008). The domination of these *Agriotes* species in BC is not evident in Europe and the UK, where other cohabitating wireworm genera commonly occur (Benefer et al. 2012; Blot et al. 1999; Broadbent 1946; Staudacher et al. 2013; Traugott et al. 2015). In PEI, although *A. obscurus* and *A. lineatus* do occur, *A. sputator* has become the dominant and most damaging species and is often found alongside the endemic species *Hypnoidus abbreviatus* (R. Vernon and W. van Herk, unpublished data). The relative occurrence of these *Agriotes* species and other endemic species in BC and especially PEI is of importance in that the effectiveness of certain control strategies (e.g. insecticides) can vary dramatically between certain species (van Herk et al. 2007; Vernon and van Herk 2013).

Life History In Canada, the development of IPM programmes, for *Agriotes* spp. wireworms in certain high-risk areas such as BC and PEI is now compelled to include management options for the adult click beetle stage. However, little information is available on the general life history of endemic or exotic click beetles in Canada, which is required for development of the various control strategies under consideration (i.e. mass trapping, field sprays, biological controls, cultural controls, etc.). As such, studies to determine the relative time of initial and peak emergence of male and female *A. obscurus* and *A. lineatus* have been conducted in potato-growing regions in southwestern BC (Vernon et al. 2001; Vernon and Tóth 2007; Vernon et al. 2014a), and the temporal development of eggs and oviposition periods have recently been completed (W. van Herk and R. Vernon, unpublished data). Similar studies are also underway in PEI related to male and female initial and peak emergence, egg development and onset of oviposition in *A. sputator* and the endemic species *H. abbreviatus* (R. Vernon and W. van Herk; C. Noronha and S. Liu, unpublished data).

Field Ecology The spatial and temporal relationships of *A. lineatus* and *A. obscurus* in farmed fields and their surrounding non-farmed grassy habitats have been studied in BC (Blackshaw and Vernon 2008; Blackshaw et al. 2017) and are currently being studied for *A. sputator* and *H. abbreviatus* in PEI (R. Vernon and W. van Herk, unpublished data). These studies so far indicate that the relative numbers and spatial presence of these *Agriotes* species in the grassy habitats surrounding arable fields are relatively stable from year to year, which has positive implications for targeting these areas for yearly adult monitoring programmes, and field risk assessments, as well as for control (see below). The movement of these *Agriotes* species adults within arable fields or between fields and grassy headlands has also been studied for *A. lineatus* and *A. obscurus* in BC (Blackshaw et al. 2017) and for *A. sputator* in PEI.

Development of Monitoring Programmes

Wireworm Sampling Although several ‘absolute’ (e.g. Yates and Finney 1942) and ‘relative’ (e.g. Chabert and Blot 1992) sampling methods (Southwood 1978) have been designed for wireworms, it is a general consensus that they are time consuming, often variable or unpredictable, require identification in fields with multiple species and are therefore of questionable practicality in IPM programmes, where reasonable cost and high accuracy are essential (Parker and Howard 2001; Vernon and van Herk 2013). To address these concerns, efforts are underway in BC and PEI to develop new wireworm traps and field sampling protocols to more rapidly and accurately determine the risk of tuber damage by *Agriotes* spp. and other endemic species.

Click Beetle Sampling In contrast to wireworm sampling, several effective trapping methods for detecting and quantifying adult click beetles have been developed and are more likely to play a significant role in IPM programmes, under development for *Agriotes* spp. in Canada. Various pheromone-based traps have been used for collecting *Agriotes* spp. click beetles in Europe and Canada for research, survey and management purposes (Ritter and Richter 2013; Vernon and van Herk 2013). Pheromones for *A. obscurus*, *A. lineatus* and *A. sputator* were initially described and used for survey purposes in the former USSR (e.g. Yatsynin et al. 1996), followed by the identification and commercialization of pheromones (Tóth et al. 2003; Tóth 2013) and an effective trap (Yatlor Funnel trap: Furlan et al. 2001; Furlan and Toth 2007) for all economic *Agriotes* species occurring in Europe.

In Canada, an alternative pheromone trap, the ‘Vernon Beetle Trap’ (VBT), was developed in 1999 (Vernon 2004; Vernon and Tóth 2007) specifically to aid in delimitation surveys of *A. obscurus*, *A. lineatus* and *A. sputator* in Canada and the USA (Vernon et al. 2001; LaGasa et al. 2006; Vernon et al. 2014a). In 2014, this trap was replaced by the ‘Vernon Pitfall Trap™’ (VPT), which was designed for lower cost, simplified and effective use in general surveys, research and IPM programmes, and is also being evaluated for mass trapping of *Agriotes* spp. in BC and PEI (R. Vernon and W. van Herk, unpublished data). The VPT is currently being used by potato growers, private consultants and researchers in BC and PEI to determine the presence and abundance of *Agriotes* spp. in general-growing areas (termed ‘sentinel trapping’) as well as in grassy headlands surrounding individual fields (termed ‘IPM Trapping’) to determine spatial sources of infestation and relative species abundance, and for targeting locations and the effectiveness of adult controls under development (see below). For research purposes, the VPT is also effective without pheromones in trapping both male and female *Agriotes* spp. as well as other species of click beetles, and has facilitated much of the life history and field ecology work described above (i.e. initial and peak emergence, egg development, etc.).

In addition to the VPT, another trap, the Noronha Elaterid Light trap (NELT™), was developed in PEI in 2015 that is also effective in attracting *A. sputator* and other click beetle species (C. Noronha, AAFC, Charlottetown) for various IPM and research purposes. The benefit of these traps over pheromone traps is their attraction to both males and females, and they are being investigated for mass trapping females in infested fields in PEI (C. Noronha, unpublished data).

Wireworm Risk Rating System In BC and PEI, where exotic *Agriotes* species are expanding geographically and emerging as serious pest problems, a means of assessing the risk of wireworm damage on a field-by-field basis would provide potato growers with an important proactive IPM tool. Although other attempts to correlate wireworm risk with certain field-specific characteristics such as soil type, moisture, topography, cropping history and grower activities have met with limited success elsewhere (Parker and Howard 2001; Parker and Seeny 1997; Thomas 1940), the availability of pheromone traps has been shown to improve the predictability of damage for certain *Agriotes* spp. In Europe for example, an effective wireworm risk assessment method for use in maize has recently been developed that combines various physical and rotational field variables with wireworm and click beetle sampling (Furlan et al. 2016), and some aspects of this system have been adopted for use in predicting *Agriotes* spp. damage to potatoes in Canada. As such, an *Agriotes* risk rating system has been developed that combines the following: (a) the cropping history of a field over the past 4 years, (b) the presence of wireworm damage at various proximities to the field, (c) optional wireworm sampling results and (d) the previous year's *Agriotes* spp. pheromone trapping results (regional 'sentinel traps' and/or field-specific 'IPM traps' using VPTs). This risk rating system is currently under evaluation in BC and PEI, concurrent with ongoing research to determine the relative favourability of common rotational crops in promoting or disfavouring wireworm population growth in fields.

Development of Control Methods

The availability of various methods for controlling wireworms and their damage to potatoes on a global scale has been reviewed (Parker and Howard 2001; Ritter and Richter 2013; Traugott et al. 2015; Vernon and van Herk 2013). In more recent years, however, a number of alternative control methods to the traditional use of chemicals, including cultural, biological, semiochemical and combined strategies, have been implemented or are under development for control of the exotic *Agriotes* species occurring in BC and Atlantic Canada.

Cultural Control Methods Where damage occurs to potato crops by wireworms, the problem is often associated with various cultural practices favouring the increase of wireworm populations in fields. For example, rotational practices that alternate various grasses or cereal crops with potatoes provide preferred oviposition habitats for click beetles and acceptable food for the development of wireworms (Landis and Onsager 1966; Vernon and van Herk 2013). In PEI, growers typically rotate potatoes with 2 years of cereals undersown to clover, and this practice is occurring in other areas of Canada. To address this concern in PEI, where *A. sputator* is reaching epidemic levels in some areas, brown mustard (*Brassica juncea*) or buckwheat (*Fagopyrum esculentum*) planted in 3-year potato rotations has been found to reduce wireworm damage to daughter tubers, relative to high levels of damage observed in traditional rotations of barley undersown to clover (Noronha 2011). Although this work is ongoing to determine the actual mechanism(s) of control involved (i.e. allelopathy, reduced oviposition, increased neonate and resident wireworm mortality, etc.), 15,000 ha of brown mustard is now grown annually in PEI in rotation with potatoes (C. Noronha, unpublished data). Another cultural approach under evaluation in PEI is to avoid the presence or planting of crops favourable for click beetle oviposition (i.e. grass, pasture, cereals) at times of *Agriotes* egg laying (Furlan 2007; Ritter and Richter 2013). This practice can be timed by growers and consultants using the VPT™ or NELT™ traps described above, and studies to determine favourable versus unfavourable rotational crops are underway.

Chemical Control Methods

Wireworms Chemical controls to manage wireworms in potatoes typically involve prophylactic treatments applied at planting to control the wireworm stage in soil (Kuhar and Alvarez 2008; Parker and Howard 2001; Vernon and van Herk 2013). Insecticides can be applied in-furrow either as granular or spray formulations, as seed treatments applied to mother tubers prior to planting, or in various combinations thereof. In Canada, the number of effective insecticide registrations for wireworm control in potatoes, although formerly numerous, is now severely limited relative to those available in the USA In BC for example, the entire arsenal of effective granular insecticides was removed in the 1990s, largely due to associated avian poisonings (e.g. bald eagle) by the insecticides phorate and fonofos (Elliott et al. 2011; Wilson et al. 2001). These insecticides were replaced post 2000 by in-furrow sprays of the organophosphate chlorpyrifos, along with the neonicotinoid clothianidin applied as a seed piece treatment (Vernon et al. 2013). This combination has provided exceptional control of wireworms in BC (against *A. obscurus* and *A. lineatus*), with no associated incidents of avian poisonings being recorded. These insecticides, however, although registered, are not being used for wireworm control in the rest of Canada due to trade restrictions with the USA (chlorpyrifos) or variability in efficacy occurring among other species (clothianidin) (Vernon et al. 2013). Outside of BC, the granular insecticide phorate is the only effective product registered for wireworm control.

The lack of effective alternative insecticides for wireworm control is of major concern to the potato industry in Canada, and research by AAFC to find acceptable insecticides for wireworm control has been underway since the mid-1990s. This research has intensified over the past decade with the aim of replacing the current Canadian arsenal of chlorpyrifos, clothianidin and phorate, which are currently of public, environmental or regulatory concern.

Click Beetles Wireworm problems arise when click beetles oviposit in fields of their preferred crops (i.e. pasture, cereals and certain forages). By reducing oviposition, wireworm populations are also reduced, along with the threat of damage to potatoes in subsequent rotations. This approach was effectively demonstrated in the Netherlands, where click beetles (*A. obscurus A. lineatus* and *A. sputator*) were sprayed once or twice in fields of grass with foliar applications of pyrethroid insecticides (i.e. deltamethrin or lambda cyhalothrin), timed at peak activity using pheromone traps (Ester et al. 2004; van Rozen et al. 2007). In spray efficacy trials conducted in BC and PEI, however, population reduction was not observed with deltamethrin (against

A. obscurus) and was quite variable with lambda cyhalothrin both within and between the three *Agriotes* species (R. Vernon and W. van Herk, unpublished data). Although initial knockdown occurred with these insecticides, this was often followed by full recovery, similar to that observed with wireworm exposure to pyrethroids in the lab (van Herk and Vernon 2007, 2008; van Herk et al. 2013). Research is currently focussing on identifying alternative sprays that can be safely applied to fields containing preferred oviposition crops in rotation with potatoes.

Biological Control Methods

Wireworms Historically, attention relating to the biological control of wireworms has mostly focussed on the fungal pathogen *Metarhizium anisopliae* (now *M. brunneum*) (Parker and Howard 2001; Richter and Richter 2013; Thomas 1940; Wraight et al. 2009). With improved methods of producing and formulating fungal pathogens now available, there has been an escalation in evaluating various isolates of *M. brunneum* for wireworm biocontrol in North America and Europe (Kuhar and Doughty 2008; Richter and Richter 2013; Wraight et al. 2009). The results so far suggest that although wireworms can be infected and killed by *M. brunneum* under laboratory conditions (e.g. Ericsson et al. 2007; Kabaluk et al. 2007a), attempts to control them with inundative releases in the field are typically variable (e.g. Brandl et al. 2017; Kabaluk et al. 2005; Kuhar and Doughty 2008; Richter and Richter 2013; Tharp et al. 2007). Among the more optimistic of these field trials, Kabaluk et al. (2005, 2007b) reported a 33.3% reduction in daughter tuber blemishes by *A. obscurus* in BC trials using a pre-plant broadcast application of the *M. brunneum* isolate LRC112. In Germany, the efficacy of *M. brunneum* was recently improved using a novel attract-and-kill (A&K) strategy, whereby wireworms (*Agriotes* spp.) were attracted to an encapsulated carbon dioxide-emitting bait in combination with *M. brunneum* conidia (Brandl et al. 2017). Application of these beads in-furrow reduced damage to daughter tubers by 37–75% relative to the untreated control. This strategy has further merit in that inoculum rates per hectare can potentially be reduced, thus reducing cost, and it provides a much needed wireworm control method for organic producers. This A&K method is also under evaluation in BC against *A. obscurus* using the *M. brunneum* isolate LRC112.

Click Beetles Biological control using various formulations and isolates of *M. brunneum* is currently under investigation as a management option against the click beetle stage of *Agriotes* species in BC and PEI (Kabaluk 2014; Kabaluk et al. 2015). Efficacy studies have tested *M. brunneum* applied as inundative sprays (Kabaluk 2014) or as granular formulations in combination with pheromones (A&K strategies) in rotational fields of grass or cereals (Kabaluk et al. 2015). If effective and economically practical, these techniques would be useful for use in potato production areas at high risk of damage, and particularly in organic production systems. They could also be used to reduce reservoir *Agriotes* spp. populations occurring in the permanent grassy headland areas surrounding arable fields, which cannot currently be targeted with conventional insecticides.

Semiochemical Control Methods

Where pheromones have been developed for wireworm pests, such as various *Melanotus* spp. in Japan and *Agriotes* spp. in Europe and Asia, their potential for reducing wireworm populations by mass trapping adults or disrupting mating to reduce oviposition has been investigated (Reddy and Tangtrakulwanich 2014; Vernon and van Herk 2013). Although some success in reducing wireworm populations using various semiochemical control strategies has been reported in Russia against *A. sputator* (e.g. Balkov 1991) and Japan against *M. okinawensis* (e.g. Arakaki et al. 2008), research into semiochemical control methods has not been as aggressive as with other alternative controls, and this can be attributed to several factors. The biggest obstacle to mass trapping, for example, is the cost and inconvenience of deploying and maintaining a large number of pheromone traps/hectare within arable fields during mixed crop rotations (i.e. 30–120 traps/ha over 4 years using Balkov's 1991 study). Also, since multiple species of wireworms often cohabitate in fields, the cost of trapping increases proportionately with the number of economic species present.

To circumvent the obstacles associated with field-scale implementation, an alternative approach would be to target the permanent wireworm population reservoirs (i.e. grassy headlands, ditch banks, dykes, etc.) surrounding arable fields in the general agricultural landscape. These permanent reservoirs occupy only a small fraction of land in intensively farmed areas, making semiochemical controls more affordable, less labour intensive and less disruptive to farming activities. In addition, once wireworm populations are removed from permanent reservoirs, control efforts in those areas could be abandoned for several years until new click beetle population build-ups warrant renewed control efforts (Vernon and van Herk 2013). To investigate this option, studies have been completed or are underway in BC to determine the optimal number and spacing of pheromone traps (Vernon Beetle Traps or Vernon Pitfall Traps™) for mass trapping *A. obscurus* and *A. lineatus* in grassy habitats (Vernon et al. 2014b, 2014c). Trials are also underway to determine if pheromones formulated as granules can be used for mating disruption and male disorientation for use in farmed and non-farmed habitats (Kabaluk et al. 2015).

Combined Control Methods

A number of 'integrated' control methods are already available for the 'management' of wireworms in potato production, some of which have been discussed herein. For example, the selection of specific crops during rotations (e.g. brown mustard) or cultivation procedures (e.g. field fallowing during the *Agriotes* egg laying period) known to be unfavourable for the establishment of wireworms can reduce populations sufficiently to improve the success of insecticides applied to subsequent potato crops. Another integrated method under development in Canada involves the companion planting of wheat seed either between or alongside crops to attract and/or kill wireworms. Planting rows of lindane-treated wheat seed between rows of later-planted strawberry seedlings, for example, was shown to attract and kill the majority of wireworms present in the field (*A. obscurus*) (Vernon et al. 2000; Vernon 2005). This has also been demonstrated in potatoes, where wheat seed treated with fipronil, with or without a neonicotinoid, and planted in-furrow with untreated mother tubers at planting, provided equal blemish protection and superior wireworm reduction to the Canadian industry standard phorate (Vernon et al. 2015). Although fipronil is unlikely to be registered in Canada, the attract-and-kill methodology has been fully developed and alternative insecticides with similar efficacy to fipronil are under evaluation in Canada and elsewhere. In addition, with the ongoing development of new and effective insecticides to control wireworms in wheat, options for managing wireworm populations in rotational cereal crops can be considered in the future. Such a strategy was formerly available in Canada with the availability of lindane (banned in Canada in 2004) as a cereal seed treatment.

Epitrix tuberis Flea Beetles in British Columbia: IPM Programme Development and Implications for Management of *E. cucumeris* and *A. papa* in Europe

The tuber flea beetle, *Epitrix tuberis*, is believed to be native to North Colorado (Gentner 1944), where first reports of damage to potatoes occurred in 1904 (Johnson 1904). It was later reported in BC in 1940 (Fulton et al. 1955; Neilson and Finlayson 1953), but was initially misidentified as *E. cucumeris* until Gentner (1944) described the morphological differences between *E. cucumeris* (eastern North American species) and *E. tuberis* (western North American species). In BC, *E. tuberis* is bivoltine (Finlayson 1950; Neilson and Finlayson 1953), having two complete generations per year. It overwinters as adults in soil in and around former potato fields (Vernon and Thomson 1991) and emerges in spring to produce first, or summer generation larvae which feed on roots and newly developing tubers in June and early July. Some surface channelling and tunnelling of tubers can occur at this time. The summer adult generation emerges about mid-July, producing the second generation of larvae in August and September. This is when populations of larvae are highest, and it has been estimated that a single overwintered-generation female can give rise to 2×10^4 second generation larvae (Finlayson 1950). These larvae coincide with the tuber maturation period of later-season cultivars, and damage is typically through repeated tunnelling directly into the tuber flesh. The presence of this type of damage often results in crops being rejected for fresh market or processing.

When *E. tuberis* emerged as a primary and chronic pest of potatoes in BC, growers typically applied 7–10 field sprays to achieve acceptable control. Due to the cost, toxicity and emerging environmental concerns of such prophylactic spray programmes, in BC, *E. tuberis* was targeted for IPM research by Agriculture and Agri-Food Canada in 1980. Research again focussed on developing tools and knowledge related to the following: (a) the basic biology and ecology of *E. tuberis*, (b) monitoring and development of action thresholds, (c) evaluation of lower risk insecticides and alternative control methods, (d) consolidation of this research into an IPM programme and (e) IPM programme implementation. The important aspects of these *E. tuberis* IPM research and extension activities are discussed below and can serve as a framework for the development of similar management programmes, for the emergent pests *E. papa* and *E. cucumeris* in the EU.

Basic Biology and Ecology of *Epitrix tuberis*

Life History Much of the basic life history of *E. tuberis* in BC was discussed above. Knowing when the overwintered adult generation occurs (typically mid-May in south-western BC, Vernon and Thomson 1991) is of primary importance, since the IPM of this pest relies heavily on the detection and aggressive control of this generation (Vernon et al. 1990; Vernon and Mackenzie 1991). In addition, knowing the periods of emergence and the extent of oviposition periods in both the overwintered and summer adult generations is important in constructing timely and accurate monitoring programmes, (Finlayson 1950; Neilson and Finlayson 1955).

Field Ecology Overwintered *E. tuberis* adults are usually concentrated at the very edges of potato fields (Cusson et al. 1990; Vernon and Thomson 1991), and this has also been observed for other flea beetle species, including *E. cucumeris* (Wolfenbarger 1940) and *E. hirtipennis* (Dominick 1971). This edge bias suggests *E. tuberis* overwinters in areas surrounding potato fields; however, it has been shown that some within-field overwintering does occur (Vernon and Thomson 1991). It has also been shown that this adult edge bias is most prominent in well-rotated potato fields, but deteriorates somewhat with consecutive years that potato fields are not rotated (Kabaluk and Vernon 2000). The existence of such a strong and relatively stable edge bias in overwintered *E. tuberis* populations is essentially their 'Achilles heel' and forms the basis for the highly effective *E. tuberis* IPM programme described below.

Epitrix tuberis Sampling and Action Thresholds

Monitoring Procedures Visual plant inspection is the only effective method for estimating overwintered *E. tuberis* population levels on newly emerged potatoes (< 30 cm in height), and a practical and consistent protocol for use in the field has been determined (Vernon et al. 1990). Visual samples consist of examining 10 consecutive potato plants with samples taken every 30 m. This is done at each field edge, examining plants on the outermost row, and is also done down rows located about one third and two thirds into the field. When plants exceed 30 cm in height, visual plant inspections are replaced with sweep-net samples, whereby 10 consecutive 180° sweeps are taken. The pattern of sweep-net sampling in a field is similar to that of visual sampling, whereby edge and inside field samples are taken. In addition, other monitoring procedures are conducted concurrently, including leaf sampling for aphids and associated beneficial insects, and visual observations for other problems, including lepidopteran feeding and late blight. Field sampling employs two scouts per field, begins immediately at crop emergence and ceases at top-kill. Sampling results are collated and interpreted separately for each of the four field edges, as well as for the inside of the field on a weekly basis.

Action Thresholds For visual sampling, a mean of one overwintered *E. tuberis* per 60 plants along any of the field edges or inside the field requires treatment in those specific areas (Giles 1987). Thus, if the threshold is only exceeded along one field edge, that is the only area requiring treatment. For sweep-net sampling, the threshold is a mean of one beetle per 10 sweeps (Agriculture and Agri-Food Canada 2005), once again specific to the field edges or inside rows of the field.

Epitrix tuberis Control

Cultural Control Methods *E. tuberis* populations have been shown to increase along with the number of consecutive years a field is in potatoes (Kabaluk and Vernon 2000). Where volunteer potatoes are present in poorly rotated fields, these plants can become more widely distributed sources of overwintered *E. tuberis* invasion, making sampling and control more difficult. These concerns are removed if fields are planted to potatoes once every 3 years (Kabaluk and Vernon 2000).

Chemical Control Methods The historical and contemporary use of synthetic insecticides for control of *E. tuberis* and other flea beetles in North America and Europe has recently been reviewed (Cuthbertson 2015). In BC, the most effective, least costly and most environmentally acceptable approach for managing overwintered populations of *E. tuberis* in an IPM programme is to apply pyrethroid insecticides (i.e. cypermethrin, permethrin) to field locations determined by field monitoring. Pyrethroids provide longer *E. tuberis* control (7 days) than other formerly used options such as carbaryl, methamidophos and clothianidin (4 days) (Vernon and MacKenzie 1991), and, if used in early season only along one or more field edges, pose little threat to beneficial insects.

Epitrix tuberis Management Strategy

The development of an IPM approach for *E. tuberis* in BC combines the knowledge and tools relating to the biology, sampling and control options discussed above. Growers follow a 3-year potato rotation to reduce populations and maximize the edge bias of overwintered adults in fields. In addition, growers are requested to plant outer rows of potatoes (usually equal to the number of rows covered by their sprayer), parallel to each field edge, with an unplanted gap of about 4 m between these outer rows and the main crop within. This planting strategy allows growers sprayer access to the outer rows of each field edge, which can be sprayed individually, as well as to rows within the field. At the start of crop emergence (i.e. 10% emergence), visual sampling is conducted as described above on a weekly basis until the crop is 30 cm tall. Any of the four field edges or rows inside the field that are above the action threshold is then sprayed with a pyrethroid insecticide. In general, the inside field rows are seldom sprayed, and only one to two of the field edges, if any, require spraying. When this is done in a timely fashion, oviposition by the overwintered adults is prevented, and the need for repeated spraying of *E. tuberis* summer-generation adults is seldom required. The need for subsequent *E. tuberis* sprays, if any, is determined by weekly sweep-net sampling, and sprays for other insect and disease problems (i.e. aphids, late blight, etc.) are also determined. In general, this approach is successful in achieving season-long control of *E. tuberis* with sprays applied once to only one to two field edges, in contrast to 7–10 prophylactic sprays to entire fields applied previously. In addition, the virtual elimination of broad-spectrum sprays for *E. tuberis* has facilitated the build-up of natural predators and parasites of aphids, which also seldom require spraying in this IPM programme.

Epitrix tuberis IPM Programme Implementation

The IPM programme described above was first introduced to potato growers in southwestern BC by a private consulting company (Monagro Consultants Ltd) in 1981. The programme expanded to additional growers in the late 1980s by ESCropconsult Ltd, is now provided to the majority of BC growers and is fully funded by subscribing growers. Since the programme was introduced, subscribing growers have never had reports of significant *E. tuberis* damage to their potato crops, and spraying for this pest has been reduced by > 90%.

With respect to the management of *E. papa* and *E. cucumeris*, certain elements of the *E. tuberis* IPM programme described above, including early-season spraying of potatoes with the pyrethroid bifenthrin or the neonicotinoid acetamiprid, are now being used successfully in Portugal (Boavida et al. 2013; Cuthbertson 2015). As this problem continues to spread, however, and control options become fewer and more expensive, the expansion of flea beetle management options to a more surveillance-driven, sustainable IPM approach may be necessary.

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