The Basis for Cutworm (Lepidoptera: Noctuidae) Integrated Pest Management: Understanding Crop-Pest Interaction and Moth Community Structure in Prairie Agroecosystems

by

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Abstract

Cutworms and armyworms (Lepidoptera: Noctuidae) are part of a pest complex, native to North America, that causes sporadic economic damage to multiple annual crops grown across the Canadian Prairies. Both larvae and adults are generalist herbivores on a wide range of hosts from different plant families. Cutworm and armyworm life history and phenology has been well studied but the effects of agricultural practices on larval performance are unknown. Adults can disperse over long distances. There are no reliable monitoring tools developed to detect temporal or spatial changes in population density for most cutworm species. In order to develop an effective monitoring program, it is important to understand cutworm-crop interactions from both the individual and population levels. In this thesis, I take an Integrated Pest Management (IPM) approach to identify knowledge gaps on crop-cutworm interactions.

The first component of this thesis focused on crop-cutworm interaction at the individual level. The influence of cereal crop variety (Poaceae) and fertilization regime were evaluated on the relationship between oviposition preference and larval performance of the true armyworm, *Mythimna unipuncta* (Haworth). Females prefer the lowest quality host, feed barley (Xena), that supported the lowest larval performance. The addition of fertilizer increased the nutrition quality of the host plants and enhanced the larval performance, however, females failed to assess the nutritional quality of the host and equally accepted fertilized and unfertilized hosts. The true armyworm does not exhibit the 'mother know best' principle on the tested hosts and potentially employs a bet-hedging strategy instead.

The effect of crop species and fertilization regime on the larval performance and larval feeding preference were evaluated on the redbacked cutworm, *Euxoa ochrogaster* (Guenée), and pale western cutworm, *Agrotis orthogonia* (Morrison). Larval performance and preference were evaluated on three hosts: canola (*Brassica napus* L.) (Brassicaceae), field peas (*Pisum sativum* L.) (Fabaceae) and spring wheat (*Triticum aestivum* L.) (Poaceae). The redbacked cutworm has higher performance on canola and field peas, while pale western cutworm has higher performance on wheat. In multiple-choice feeding experiments, redbacked cutworm prefers canola over peas and wheat, while pale western cutworm prefers spring wheat over canola and peas. The effect of plant fertilization was tested using two plant hosts (canola and spring wheat) exposed to two fertilization regimes (unfertilized and fertilized). When fed unfertilized seedlings, redbacked cutworm has better performance on canola, whereas pale western cutworm has better performance on spring wheat. Fertilizer application enhanced the performance of both cutworms regardless of the crop species. Despite their generalist feeding behaviour, both cutworm species have larval feeding preferences that match the host plant with high performance. Canola-cereal crop is a common crop rotation schedule in the region, however, this tactic will not negatively impact cutworm performance.

The second component of this thesis focused on crop-cutworm interactions at the population level, specifically on the adult stage of cutworms and the chemical ecology of feeding attractant volatiles. A series of field experiments were conducted to develop a food-based semiochemical to monitor the cutworm and armyworm pest complex with a single lure in Canadian Prairie agroecosystems. The combination of acetic acid and 3-methyl-1-butanol (AAMB) attracts noctuid pest moths. My approach was to enhance the attractiveness of the AAMB lure to monitor the redbacked cutworm moth in canola and wheat fields in central Alberta. I tested: 1) different release rates of AAMB released from different devices; and 2) the addition of other food-based semiochemicals to the AAMB lures. I also evaluated the attractiveness of volatile compounds released from Canada thistle as a potential lure to monitor noctuid pests; and 4) the influence of moth physiological state on the response to food-based semiochemicals. Results focus on food bait lure development to efficiently monitor multiple cutworm moth species with a single lure and reduced pollinator by-catch. Finally, I report on the diversity and abundance of noctuid moths trapped with food bait lures based on the volatile by-products of fermented sugar baits.

Preface

A version of Chapter 2 of this thesis is intended for publication as: Ronald E. Batallas, Jessica J. Kwon, José Rosato, Boyd A. Mori, Brian Beres and Maya L. Evenden. Influence of crop variety and fertilization on oviposition preference and larval performance of the generalist herbivore, the true armyworm, *Mythimna unipuncta* (Lepidoptera: Noctuidae). I contributed to the experimental design, data collection, data analysis and manuscript composition. Maya Evenden was the supervising author and was involved in the concept formation and manuscript editing.

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Dedication

This thesis is dedicated

To my mother, Gloria Huacon de Batallas, who fought every obstacle in life to give me the opportunities to follow my dreams

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List of Abbreviations

TAW – True armyworm

RBC – Redbacked cutworm

PWC – Pale western cutworm

BAW – Bertha armyworm

ACW – Army cutworm

MVOC – Microbial volatile organic compound

AAMB – Acetic acid + 3-methyl-1-butanol

MP – 2-methyl-1-propanol

PAA – Phenylacetaldehyde

CT – Canada thistle

Chapter 1: General Introduction

Agriculture in the Canadian Prairies

The Prairie Ecozone, which constitutes the northern region of the Central Plains of Western Canada that covers most of Alberta, the lower half of Saskatchewan and the western portion of southern Manitoba (Shorthouse, 2010). The Prairie Ecozone is characterized by grassland habitats, typically consisting of low-lying valleys and plains (Shorthouse, 2010). At least 75% of the Canadian Prairie landscape, originally dominated by native grasses, has been highly modified by humans to support crop cultivation and livestock production over the past century (Vankosky et al., 2017). Fragmentation of the landscape through intensive monoculture is one of the major drivers of reduced arthropod diversity in the prairie grassland ecosystem (Meehan et al., 2013). Agroecosystems in the Canadian Prairies are dominated by spring-sown annual cereals, oilseeds, pulses and perennial forages maintained under intensive farming practices, and therefore, are in a constant state of disturbance on an annual basis (Martens et al., 2015). Agronomic activities like monoculture, crop rotation, varying levels of soil disturbance (i.e. tillage and harvest), chemical and organic inputs to manage soil fertility and pests have a strong impact on insect community structure and population densities that may increase crop vulnerability to pest outbreaks (Shennan, 2008).

The order Lepidoptera is one of the most diverse insect taxa in the Prairie Ecozone, with 2,232 species recorded in 61 families (Pohl et al., 2014). Noctuid moths (Lepidoptera: Noctuidae) alone, with 693 reported species, make up 28% of the entire Lepidoptera fauna in the Canadian Prairies (Pohl et al., 2014). The majority of noctuid species in the Canadian Prairies have a benign effect on agriculture or provide valuable ecosystem services, while only a small number of noctuid species are considered to be pests (Vankosky et al., 2017). These noctuid pest species comprise the cutworm and armyworm (Lepidoptera: Noctuidae) complex that cause economic damage to multiple annual crops grown across the Canadian Prairies (Beirne, 1971, Floate, 2017). Sporadic outbreaks have occurred since the introduction of extensive agriculture in the Prairies in the early 20th century (King and Atkinson, 1926).

Crop-Cutworm Interactions

Individual level

A major feature of insect-plant interactions is the degree of host specialization (Schoonhoven et al., 2005). Insects that feed on one or a few closely related hosts species within the same plant genus are categorized as monophagous, while insects that feed on a few numbers of host species within the same plant family are called oligophagous, and lastly, insects that feed on many host species from different plant family are called polyphagous (Schoonhoven et al., 2005). This classification is arbitrary because it is difficult to delimit difference between monophagy and oligophagy, and therefore, insects that feed on one or a few host species from the same plant family are regarded as ‘specialist herbivores’, whereas insects that feed on multiple host species from different plant families are considered ‘generalist herbivores’ (Schoonhoven et al., 2005). Host plant specialization is a common feature among insect herbivores, while less than 10% of insect herbivore species are generalists (Bernays and Graham, 1988). One aspect that favours generalist over specialist herbivores is their ability to use different host plants, and thus, have greater resource availability in the habitat (Bernays and Minkenberg, 1997). Cutworm and armyworm moths are generalist pests on a wide range of hosts from different plant families (Lafontaine, 2004).

The ‘naïve adaptation’ hypothesis, or ‘mother knows best’ principle, predicts that that natural selection favours females with an oviposition preference for host plants on which offspring will have the highest performance (Levins and MacArthur, 1969, Courtney and Kibota, 1990). Generalist herbivores have a disadvantage over specialists, however, as generalist females must discriminate among many options to select an optimal host plant species for offspring development (Bernays, 2001). Insect diet breadth is a factor that highly influences female oviposition preference for suitable hosts, in which specialist herbivores have a stronger preference for suitable hosts plants compared to generalist herbivores (Gripenberg et al., 2010). The ‘neural limitation’ hypothesis states that due to inherent limitations of the insect nervous system, specialist females process a limited set of information and make them more efficient and accurate in selecting host plants for offspring development than generalist herbivores (Bernays and Funk, 1999, Bernays, 2001). Despite the overall support for ‘mother knows best' principle, there are numerous studies for which preference and performance are not strongly coupled (Gripenberg et al., 2010). Many generalist pest species, like cutworm and armyworms, do not oviposit on host plants or have highly mobile larvae (Bernays and Minkenberg, 1997). These life history traits may result in a mismatch between female oviposition preference and larval performance.

Crop rotation is a common agricultural practice that aims to exploit the feeding habits of specialist herbivores with limited dispersal ability to prevent pest density buildup through substitution with non-host crops (Bullock, 1992). Crop rotation can cause larvae to feed on less than optimal host plants, which can affect the performance and adult fitness of the target pest. The overwintered insect stage is restricted to feed, at least initially, on the current crop after diapause, which may differ from that selected by the adult female. Although generalist herbivores are able to complete their life cycle on different host plant species, many generalists can discriminate among host plant species within the accepted host-range and show some degree of preference (Schoonhoven et al., 2005). Cutworm and armyworm female moths may demonstrate a hierarchical host plant selection for offspring development among crops grown in the Canadian Prairies.

Host nutritional quality strongly influences herbivore performance at the larval stage; this influence can carry forward to the adult stage, and affect fecundity or longevity (Slansky and Scriber, 1985). Agronomic activities, like fertilizer input, increases the nutritional quality of the host plant, and therefore, could enhance the performance of the herbivore to an upper limit (Slansky and Scriber, 1985). These bottom-up effects on herbivore growth and reproduction can, in turn, impact population density and contribute to outbreaks of cutworm and armyworms.

Population level

Dispersal allows pests to escape disturbances and locate suitable habitats for mating and offspring development. The dispersal ability of pests influences their spatial and temporal distribution and abundance, and this influence in turn may lead to an increase in pest population densities (Mazzi and Dorn, 2012). Adult cutworms and armyworms are large, robust-bodied moths that can disperse over long distances (McNeil, 1987, Showers et al., 1989, Hendrix III and Showers, 1992). High dispersal capability and polyphagy in these noctuid pests allow them to escape disturbances and locate suitable habitat for mating and offspring development.

Pest population densities are often reduced in landscapes with diverse vegetation (Mazzi and Dorn, 2012). Two hypotheses have been proposed to explain the reduced abundance of pests in heterogenous habitats. The 'resource concentration' hypothesis states that heterogeneous habitats negatively affect the ability of insect pests to locate suitable host plants, while the ‘enemy’ hypothesis states that pest density is reduced by the activity of natural enemies, which is enhanced in diverse ecosystems (Root, 1973). Simplification of grassland habitats with extensive monoculture crop production and disturbance allows cutworms and armyworms to locate suitable host plants in a concentrated space, which could potentially increase pest density to outbreak levels.

Cutworm and Armyworm Pest Complex

Cutworms and armyworms (Lepidoptera: Noctuidae) are part of a pest complex that causes sporadic economic damage to multiple annual crops grown across the Canadian Prairies (Floate, 2017). These pests are native to North America, and they are associated mostly with grassland habitats rather than with specific larval host plants (Lafontaine, 1987). The life-history traits and phenology of cutworms and armyworms vary considerably between species (Byers and Struble, 1987, Ayre and Lamb, 1990). Cutworm damage generally occurs in early summer when annual crops are at the seedling stage. Early instars feed on seedling foliage, whereas late instars display the characteristic cutworm feeding behaviour and cut seedling stems to feed on the stem and foliage that ultimately kill the seedling (Strickland, 1923). Conversely, crop injury by armyworm generally occurs in mid to late summer when annual crops are at the reproductive stage. Early instars feed gregariously on host plant foliage, whereas late instars can disperse *en masse* across the landscape in search of host plants when food sources are depleted (Breeland, 1958, Mason et al., 1998). Larval feeding at low population densities results in crop thinning, however, outbreaks can cause complete destruction of fields and yield loss (Beirne, 1971).

Sporadic outbreaks have been reported for several species. For example, an army cutworm, *Euxoa auxiliaris* Grote, outbreak in 1990 affected over 10,000 ha in southern Alberta, of which 6,000 ha were sprayed with insecticide while the remaining affected area was reseeded without spraying (Byers et al., 1993). Similarly, outbreaks of the bertha armyworm, *Mamestra configurata* Walker, in canola (*Brassica napus* L.) (Brassicaceae) in 1994 and 1995 caused yield losses of CAN$30 million and spraying costs of approximately CAN$16.5 million in western Canada (Mason et al., 1998). In Alberta, more than 45,000 ha were sprayed to control bertha armyworm outbreaks in 2012 and 2013 (Evenden et al., 2017). An outbreak of the glassy cutworm, *Apamea devastator* (Brace), in 2000 affected approximately 3,500 ha of fescue (*Festuca* sp. L.) (Poaceae) seed fields and pastures in northern Alberta, which caused economic losses of approximately CAN$ 5 million (Dosdall et al., 2000). The redbacked cutworm, *Euxoa ochrogaster* (Guenée), and the pale western cutworm, *Agrotis orthogonia* (Morrison), are the most common cutworm species with localized outbreaks across the Prairie Provinces affecting canola and cereal crops in 2015 and 2016 (W.C.C.P., 2015, W.C.C.P., 2016). Infestation of two or more species may co-occur in the same field if conditions are favourable (Ayre and Lamb, 1990). Outbreaks appear to be cyclical and persist for two to four years for most cutworm species, followed by two years or more of relatively scarcity (Beirne, 1971). Unless cutworm and armyworm populations are monitored systematically in high and low population phases, population surges will not be detected or predicted.

Target species

Redbacked cutworm

Euxoa ochrogaster, commonly known as the redbacked cutworm, is the most economically important and common cutworm pest that affects multiple annual crops across the Prairie Provinces (Gavloski and Meers, 2011). This cutworm species is widely distributed in Canada and the northern United States (Lafontaine, 1987). It occurs from Newfoundland westward to western Alaska, and southward to the northern tier states of the United States, at least as far south as Colorado (Hardwick, 1965).

Euxoa ochrogaster is univoltine and overwinters as fully developed first instar larvae within the egg (Jacobson, 1970, Philip and Mengersen, 1989). Larvae eclose from eggs in April, in the Prairie Provinces, and develop through six larval instars (King, 1926, Jacobson, 1970). Larvae feed above and below the ground surface at night, however, this cutworm species is also frequently active throughout the day (Strickland, 1923). Larval development is completed in mid-June and the pupal stage lasts for three to four weeks in an earthen cell in the soil prior to moth emergence in late summer (Jacobson, 1970, Beirne, 1971). The adult flight ranges from late-June to early-October in the Prairie Provinces, with peak flight activity from mid-August to mid-September (Byers and Struble, 1987, Gerber and Walkof, 1992). Females mate multiple times as early as two days after emergence, however, ovaries are not filled with eggs for eight days after moth emergence, also known as preoviposition period. (Jacobson, 1970, Berry, 1975). The maximum adult lifespan is 20 days for both sexes under laboratory conditions (Jacobson, 1970).

Euxoa ochrogaster is a generalist herbivore. Moths have been recorded to forage on flowers of goldenrod (*Solidago* spp. L) (Asteraceae) and may be pollinators of sunflowers (*Helianthus* spp. L) (Asteraceae) (Beirne, 1971). Larvae feed on a wide range of host plants from different families, however, there is some evidence that larvae prefer canola and mustard to cereals crops (Beirne, 1971, Willenborg and Dosdall, 2011). Females do not oviposit directly on larval host plants but lay eggs in loose-dry soil under crop stubble or in fallow fields (Beirne, 1971). There is no preference for oviposition in the proximity of certain larval host plants (Ayre et al., 1982).

Pale western cutworm

Agrotis orthogonia, commonly known as the pale western cutworm, is an economically important cutworm pest mainly of cereal crops in the Prairie Provinces (Gavloski and Meers, 2011). This cutworm species occurs in dryland areas of the northern Great Plains, particularly in the southern regions of the Prairie Provinces (Lafontaine, 2004).

Agrotis orthogonia is univoltine and overwinters as fully developed first instar larvae within the egg (Jacobson, 1962). Larvae eclose from eggs in April, in the Prairie Provinces, and develop through six or seven larval instars (Jacobson, 1971). In contrast to the redbacked cutworm, *A. orthogonia* larvae are subterranean in habit and all instars feed below the ground surface at night (Jacobson et al., 1950). Larval development is completed in June and the pupal stage lasts for three to four weeks in an earthen cell in the soil prior to moth emergence. The adult flight period ranges from early-August to mid-September in the Prairie Provinces, with peak flight activity in mid-August (Jacobson, 1971). Females mate once after emergence and oviposition begins one or two days after mating (Jacobson, 1965). The maximum adult lifespan is 12 days for both sexes under laboratory conditions (Jacobson, 1965)

Agrotis orthogonia is a generalist herbivore. Moths forage on flowers of the Asteraceae plant family, including goldenrod, sunflowers, thistles and gumweed (Beirne, 1971). Larvae feed on a wide range of host plants from different families, however, most outbreaks in the Prairie Provinces are associated with cereal crops (Jacobson, 1971). Similar to the redbacked cutworm, *A. orthogonia* females do not oviposit directly on larval host plants but lay eggs in loose-dry soil (Beirne, 1971). There is no evidence of oviposition preference among larval host plants to date.

True armyworm

Mythimna unipuncta (Haworth), commonly known as the true armyworm, is a sporadic pest mostly of cereal crops and alfalfa (*Medicago sativa* L.) (Fabaceae) across southern Canada to the southern United States (Breeland, 1958, Guppy, 1961). Infestations in Canada occur in most agricultural landscapes east of the Rocky Mountains (Beirne, 1971).

Mythimna unipuncta does not tolerate freezing temperatures, and therefore, it is unable to overwinter in northern latitudes (Fields and McNeil, 1984). Infestations in Canada occur from moths that migrate from the south (Fields and McNeil, 1984). Moths can travel at least 1,300 km during their northward migration in the spring to avoid high temperatures in the southern United States (Gavloski and Meers, 2011, McNeil, 1987). Immigrating moths appear in light and pheromone-baited traps from mid-May through July (spring flight) (McNeil, 1987). Immigrating-moths mate and produce a summer-generation in Canada. Summer-generation moths appear only in light traps from late-August through September (fall flight) (McNeil, 1987). Summer-generation moths undertake a southern migration, in response to short days and low temperatures in the fall, to escape the deteriorating conditions in the northern latitudes (McNeil, 1987).

Females search for suitable host plants in the spring and oviposits a group of eggs at the base of plant shoots (Guppy, 1961). Larvae develop through six to seven larval instars from June through July. Early instar larvae skeletonize foliage while late instars consume entire leaf blades and gradually feed on the influorescence and developing kernels when foliage is depleted (Guppy, 1961). Larvae feed at night, from dusk until dawn, and rest on the lower parts of the plant during the day (Guppy, 1961). Larval development is completed in July and pupation lasts for three to four weeks in an earthen cell in the soil prior to moth emergence (Guppy, 1969).

Females mate multiple times, however, females show an average preoviposition period of seven days in laboratory experiments and field surveys (Guppy, 1961). The average adult lifespan is 19 days for males and 17 days for females under laboratory conditions (Guppy, 1961).

Although *M. unipuncta* is considered a generalist herbivore, larvae feed primarily on hosts within the Poaceae family (Breeland, 1958). There is no evidence, however, of female oviposition preference for host plant species within the Poaceae family to date. Guppy (1961) suggested that the maturity of the host plant, density of stands and the presence of stubble are more important for attraction of ovipositing *M. unipuncta* females than host plant species.

Integrated Pest Management Approach

Integrated Pest Management (IPM) theory brings an applied ecological approach to understand crop-pest interactions from the individual, population, and community levels. In an IPM framework, "integration" implies the use of numerous tactics in harmony to provide economic control of the pest complex that affects a given crop (Kogan, 1998). The main objective in IPM theory is to prevent fluctuating pest populations from reaching a pre-defined economic injury level (Kogan, 1988). To develop successful IPM programs, it is important to investigate the biology of the pest complex (life history, phenology and feeding preference) and their population dynamics. Community ecology knowledge is important to develop IPM programs because it helps interpret habitat complexity (Kogan, 1988). Knowledge on community structure makes it possible to anticipate pest problems and to design control strategies (Kogan, 1988). The foundation of any IPM program is the implementation of efficient sampling tools to detect multiple pest and beneficial insects in the managed ecosystem.

To develop a successful IPM program for cutworms in the Canadian Prairies, it is critical to investigate the biology of the target pests. Life history and phenology have been studied in detail for several cutworm species (Jacobson, 1970, Jacobson, 1971, Ayre, 1990, Byers and Struble, 1987) however; there is no information on the effect of host plant species and plant fertilization on larval performance and fitness.

Female-produced sex pheromones have been identified for most cutworm and armyworm pest species (Steck et al., 1982b). Monitoring programs using synthetic pheromone-baited traps were implemented across the Prairie Provinces in the 1980s; however, these programs were not widely adopted because moth trap catch did not reflect crop damage (Byers and Struble, 1987, Ayre and Lamb, 1990). Furthermore, pheromone-based monitoring programs require individual traps for each species, which makes monitoring several pests costly. Lastly, there is evidence for pollinator by-catch in lepidopteran sex-pheromone baited traps (Gross and Carpenter, 1991, Mori and Evenden, 2013, Spears et al., 2016). There are no reliable tools to monitor variation in density of the cutworm pest species in the Prairie Provinces.

Food-based semiochemicals could be exploited for monitoring multiple cutworm species using a single lure and trap. As these cues attract both sexes of moths, capture of females may provide information on the reproductive status of the females and egg load (Joyce and Lingren, 1998, Lingren et al., 1998). Research on food-based semiochemicals can provide knowledge on the type of volatile cues cutworm and armyworm moths rely on.

Food-based semiochemicals

Although multiple cues mediate plant-insect interactions, olfaction is perhaps the primary mechanism moths employ for oviposition and host selection (Visser, 1988, Davis and Landolt, 2013). Cutworm and armyworm moths, like many lepidopterans, use plant volatile organic compounds for orientation towards adult food sources, and females may also use plant volatiles to select oviposition sites (Schoonhoven et al., 2005). Furthermore, insects may be sensitive to cues produced by microbes associated with food sources and oviposition sites, referred to as microbial volatile organic compounds (MVOC) (Davis et al., 2013). Microbes present in floral nectars and fruits produce MVOCs, which in combination with floral volatiles, can attract lepidopteran herbivores to hosts (Herrera et al., 2008). For example, the chemical mixture of acetic acid, a by-product from fermented sugar, and phenylacetaldehyde, a floral volatile, attract two noctuid moths (Lepidoptera: Noctuidae), the alfalfa looper, *Autographa californica* (Speyer), and the armyworm *Spodoptera albula* (Walker) to baited traps (Landolt et al., 2013). The MVOC hypothesis states that microbial emissions serve as semiochemicals that provide cues regarding suitability and nutritional quality of hosts (Davis et al., 2013).

Overall, food-based semiochemicals are classified into three groups: host plant volatiles, floral volatiles and MVOCs. Few host plant volatile lures are commercially available to monitor moth pest flight activity or for pest control in attract-and-kill formulations (Light et al., 2001, Gregg et al., 2010). Host plant volatiles may not be important cues for generalist pests like the redbacked cutworm or the pale western cutworm, as females of both species oviposit in loose-dry soil under crop stubble or in fallow fields rather than on live plant material (Beirne, 1971). Floral volatiles from several plants visited by noctuid moths as adult food sources have been used to monitor populations in field experiments (Cantelo and Jacobson, 1979, Landolt and Smithhisler, 2003). For instance, traps baited with phenylacetaldehyde captured soybean looper moths, *Chrysodeixis includens* (Walker) (Lepidoptera: Noctuidae), in cotton fields (Meagher Jr, 2001a). Likewise, traps baited with the floral blend of the butterfly bush (*Buddleja davidii*

Franch) (Loganiaceae) captured high numbers of the cabbage looper, *Trichoplusia ni* (Hübner) (Lepidoptera: Noctuidae), and alfalfa looper moths (Guédot et al., 2008). Floral volatile baited traps, however, result in high pollinator by-catch and have not been adopted commercially to monitor noctuid moths (Meagher Jr and Mitchell, 1999, Landolt et al., 2007).

Fermented sugar baits were some of the first food-based semiochemicals used to monitor diversity of Lepidoptera (Utrio and Eriksson, 1977). Noctuidae, Geometridae, Tortricidae and Pyralidae are the major lepidopteran families attracted to these types of baits (El-Sayed et al., 2005). The most common MVOCs produced from fermented sugar baits are acetic acid, isoamyl alcohol (3-methyl-1-butanol) and isobutanol (2-methyl-1-propanol) (El-Sayed et al., 2005, Davis et al., 2013). Food-based semiochemical lures that release these volatile compounds attract both sexes of many species of noctuid moths (Tóth et al., 2010).

The chemical mixture of acetic acid and 3-methyl-1-butanol (AAMB) is attractive to several noctuid pests in multiple cropping systems, including the bertha armyworm (Landolt, 2000), the true armyworm (Landolt and Higbee, 2002) and the redbacked cutworm (Landolt et al., 2007). Preliminary field experiments with AAMB lures in Alberta, however, had low trap catch of target noctuid pests (unpublished data). Further research is required to enhance the attractiveness of AAMB lures to monitor cutworm moths in Prairie agroecosystems.

Thesis objectives

In this thesis, I take an IPM approach to identify knowledge gaps on crop-cutworm interactions. I assess the influence of agricultural practices on the performance and fitness of target cutworms; and develop tools to monitor cutworm and noctuid moth diversity in agroecosystems. In Chapter 2, a series of experiments assess the relationship between oviposition preference and larval performance of the true armyworm, *M. unipuncta,* for hosts within the Poaceae family, particularly cereal crops grown in the Prairie Provinces of Canada. In Chapter 3, I evaluate the influence of host species and plant nutrition on the larval performance and larval feeding preference of the redbacked cutworm, *E. ochrogaster*, and the pale western cutworm, *A. orthogonia*. Chapter 4 focuses on development of a food-based semiochemical lure to monitor the cutworm and armyworm pest complex in Canadian Prairie agroecosystems. My approach was to enhance the attractiveness of the AAMB lures to the most common cutworm species across the prairies, the redbacked cutworm, in canola (*Brassica napus* L.) (Brassicaceae) and wheat (*Triticum aestivum* L.) (Poaceae) fields in Alberta. First, I determine the attractiveness of AAMB baited traps compared to unbaited traps and sex pheromone-baited traps. Second, I test the attractiveness of different AAMB lures with varying release rates. Third, I measure the attraction of the AAMB lure in combination with additional food-based semiochemicals. Fourth, I evaluate the potential of the floral blend released by Canada thistle (*Cirsium arvense* L.) (Asteraceae) at different doses to attract the redbacked cutworm. Lastly, electrophysiological studies were conducted on the redbacked cutworm moth to understand how moth physiological state influences the response to food-based semiochemicals. In Chapter 5, I report on the diversity and abundance of noctuid moths trapped with food bait lures based on volatiles from fermented sugar baits by-products.

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Chapter 2: Influence of crop variety and fertilization on oviposition preference and larval performance of the generalist herbivore, the true armyworm, *Mythimna unipuncta* (Lepidoptera: Noctuidae)

Abstract

The relationship between oviposition preference and offspring performance of herbivores is a vital question in the field of plant-insect interactions and important to understand for integrated pest management. I investigated the preference-performance relationship of the generalist herbivore *Mythimna unipuncta* (Haworth) (Lepidoptera: Noctuidae: Leucaniini). I evaluated the effect of cereal crop varieties and fertilization on the carbon:nitrogen ratio of plant foliage and host use by adult and larval *M. unipuncta* in both lab and field experiments. Two wheat (*Triticum aestivum* L.) and two barley (*Hordeum vulgare* L.) varieties were tested for host suitability to *M. unipuncta*. The C:N ratio varied among crops and varieties tested. The feed barley variety (Xena) had the lowest C:N ratio of all tested plants, supported larvae the best, and resulted in the heaviest pupae. Xena, however, was the least preferred plant by female moths, suggesting that females lack preference for the host on which their offspring perform the best. The addition of fertilizer to host plants did not influence adult female host preference for oviposition. Larvae reared on unfertilized plants had lower pupal weight than those reared on plants treated with fertilizer at the half (70 mg of N) or full (140 mg N) dose in a laboratory setting, regardless of the crop variety. Fertilization did not impact larval performance on Xena plants under field conditions. In the field, Xena had similar yield and grain protein content regardless of the defoliation damage or fertilizer application. The generalist herbivore, the true armyworm *M. unipuncta,* does not exhibit the 'mother knows best' principle on the tested hosts and potentially employs a bet-hedging strategy instead.

Introduction

Insect herbivores have evolved sophisticated peripheral and central nervous systems that allow females to search and assess the quality of a host plant for oviposition. Female herbivores generally use olfactory and visual cues to search for host plants and contact cues for host assessment after landing (Visser, 1988). Host selection by females is critical for the survival and fitness of offspring, which could influence population density and lead to outbreaks of pest species.

The relationship between female oviposition preference and offspring performance in phytophagous insects has been, and continues to be, a vital question in the field of plant-insect interactions: do gravid females select optimal host plants for offspring development? Theory predicts that natural selection favours females with an oviposition preference for host plants on which offspring will have the highest performance. This hypothesis is known as the 'naïve adaptation hypothesis' or 'mother knows best' principle (Levins and MacArthur, 1969, Courtney and Kibota, 1990). A meta-analysis testing the evidence for this hypothesis found overall support for the 'mother knows best' principle at a large scale (Gripenberg et al., 2010). The analysis indicated insect diet breadth as a robust factor that influences the preference-performance relationship. Oligophagous insect herbivores have a stronger coupling between oviposition preference and larval performance than polyphagous herbivores (Gripenberg et al., 2010). Insects with a narrow diet breadth process limited information, and can be more efficient at host selection than generalist insect herbivores, which face complex choices (Bernays, 1998, 2001). Despite the overall support for 'mother knows best' principle, there are numerous studies for which preference and performance are not strongly coupled (Berdegue et al., 1998, Jallow and Zalucki, 2003, Wist and Evenden, 2016, Hufnagel et al., 2017).

Several other ecological hypotheses attempt to explain a mismatch between female preference and larval performance in phytophagous insects. Some of these explanations include: (1) females may become conditioned to a suboptimal host plant during larval development and select the natal plant species for oviposition and offspring development, also known as 'Hopkins' host selection principle' (Hopkins, 1917, Jaenike, 1983). (2) A conflict of interest in adults between foraging behaviour and searching for host plants for oviposition. The ability to feed in the adult stage may weaken preference-performance relationships because females invest time in foraging instead of searching for the most suitable host for their offspring (Gripenberg et al., 2010). (3) Females could select a suboptimal host that provides a potential refuge against natural enemies. This is known as the 'enemy-free space hypothesis', as a reduction in offspring predation increases the overall fitness of the female (Bernays and Graham, 1988, Murphy and Loewy, 2015). (4) Some larvae are capable of dispersing within and among plants during development (Cunningham et al., 2011, Rivera and Burrack, 2012, Moreira et al., 2016, Rosenwald et al., 2017). Weak selection for a preference-performance relationship would be expected in species with highly mobile larvae (Thompson, 1988, Craig and Itami, 2008). Overall, all aspects of the herbivore life history are important to understand the potential for a preference-performance relationship.

Adult females may weakly discriminate plant hosts of similar suitability present in the same area (Jaenike, 1978). It is more likely for females to evolve the ability to select suitable hosts if there is a large difference in offspring performance among host species (Gripenberg et al., 2010). For instance, two polyphagous noctuid moths (Lepidoptera: Noctuidae), the beet armyworm *Spodoptera exigua* (Hübner) and the cabbage looper *Trichoplusia ni* (Hübner), do not differ in developmental time and pupal weight when reared on two cultivars of *Apium graveolens*

(Meade and Hare, 1991). Larvae that feed on different varieties or cultivars of the same plant species may have similar performance. Thus, selection on adult females for discrimination between varieties can be low.

Environmental factors can also affect host plant quality and suitability for insect herbivores, which, in turn, can influence preference-performance coupling. Water stress or nutrient deficiency of a host plant may alter larval performance and benefit adult females to differentiate plants grown under varying environmental conditions (Thompson, 1988, Weeraddana and Evenden, 2018). Augmentation of plant nutrition through fertilization results in host plants with a higher nitrogen content and biomass. Correspondingly, herbivores that feed on host plants with higher nutrient content generally have higher growth rates and shorter developmental time (Slansky and Scriber, 1985, Chen et al., 2004). For instance, female moths of the generalist herbivore, *S. exigua*, and the specialist red postman butterfly *Heliconius erato* (Frabicius) (Lepidoptera: Nymphalidae), select host plants with high nitrogen content for oviposition. This preference is matched by the performance of the larvae, which develop faster when feeding on fertilized plants (Kerpel et al., 2006, Chen et al., 2008).

The true armyworm, *Mythimna* (*Pseudaletia*) *unipuncta* (Haworth) (Lepidoptera: Noctuidae), is a cosmopolitan insect pest known for its sporadic outbreak populations that cause economic damage on cereal crops, forage grasses and alfalfa in North America (Goble, 1965, Letendre and Muelier, 1980, Mulder and Showers, 1986, Steinkraus and Mueller, 2003). The true armyworm does not overwinter in northern latitudes, and thus infestations in Canada occur from moths that migrate from the south in spring (Fields and McNeil, 1984). Females locate a suitable host plant and lay eggs in clusters underneath the leaf sheath or in folds of the leaf blades (Guppy, 1961). Upon egg eclosion, early instar larvae skeletonize foliage while late instars consume entire leaf blades and gradually feed on the influorescence and developing kernels when foliage is depleted (Guppy, 1961). Although *M. unipuncta* is considered a generalist herbivore, larvae feed primarily on hosts within the Poaceae family (Breeland, 1958). There is no evidence of female oviposition preference for host plant species within the Poaceae family. Guppy (1961) suggested that maturity of the host plant, density of stands and stubble are more important for attraction of ovipositing *M. unipuncta* females than host plant species. This pest is commonly known as an 'armyworm' because larvae march *en masse* across the landscape in search of host plants when food sources are depleted (Breeland, 1958). The pupal stage lasts for three to four weeks in an earthen cell in the soil prior to moth eclosion. *Mythimna unipuncta* has two generations throughout the summer in Canada (Pond, 1960).

In this study, I investigate the relationship between oviposition preference and larval performance of *M. unipuncta* for hosts within the Poaceae family, particularly cereal crops grown in the Prairie Provinces of Canada. Specifically, I asked:

(i) Is oviposition preference coupled with larval performance in the generalist *M. unipuncta*?

(ii) Do *M. unipuncta* females show a hierarchical host selection within the Poaceae, and is this selection based on host plant nutrient content?

(iii) Does fertilizer input influence female oviposition behaviour and larval performance relationship?

(iv) Do experiments under field conditions reflect larval performance results from experiments under controlled conditions in the laboratory?

First, I evaluate the effect of cereal crop varieties on oviposition behaviour and larval performance under controlled conditions in the laboratory. Two wheat (*Triticum aestivum* L.) and two barley (*Hordeum vulgare* L.) varieties grown in the Prairie Provinces are tested: Go and

Buteo (wheat); Copeland and Xena (barley). All crop varieties were developed through traditional breeding crosses. Go (Crop Development Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada) is a hard-red spring wheat variety seeded in early spring, while Buteo (Crop Development Centre) is a hard-red winter wheat variety planted in late summer. Copeland (Crop Development Centre) is a malt barley variety, while Xena (Monsanto Technology, LLC, St. Louis, Missouri) is a feed barley variety, both seeded in early spring. Secondly, I assessed the effect of fertilization regime on oviposition behaviour and larval performance under controlled conditions in the laboratory. Lastly, I conducted a field experiment to determine the impact of fertilizer rates on larval development of *M. unipuncta* feeding on Xena under field conditions.

This study provides insights on oviposition preference and larval performance of a generalist insect herbivore in a managed ecosystem and how agricultural practices, like crop variety selection or fertilization regime, affect female oviposition behaviour that could potentially influence subsequent population densities that lead to outbreaks. Understanding plant-insect interactions is not only essential to further knowledge from ecological and evolutionary perspectives, but also for the development of novel crop protection practices (Bruce et al., 2005).

Materials and Methods

Insects and Plants

A laboratory colony of *M. unipuncta* was started in 2012 from eggs obtained from an established colony at the Western University. The colony was maintained under controlled conditions (Conviron CMP 3023, Controlled Environments Ltd.) at 24 °C, photoperiod of 16:8

(L:D) and 70% RH. Larvae were reared on a pinto bean-based meridic diet that was modified from Shorey and Hale (1965). Neonate larvae were reared gregariously until the moult to the second-instar, after which they were reared individually by placing one larva in fresh 30 mL plastic diet cups (Solo Cup, Mason, Michigan, USA) until pupation. Pupae were placed in 500 mL plastic containers with moist, fine vermiculite (Specialty Vermiculite Canada Corp, Alberta, Canada). Newly emerged moths (20-30 individuals, 1:1 male: female) were placed in mating chambers (40 cm × 30 cm diam.) with access to 10% sucrose solution (w:v) *ad libitum* and folded strips of wax paper that served as an oviposition substrate.

Plant seeds of four crop varieties were obtained from Lethbridge Research Centre, Agriculture and Agri-Food Canada, Alberta, Canada: spring wheat “Go”, winter wheat “Buteo”, malt barley “Copeland” and feed barley “Xena”. Plants were grown in 12.7 cm diam. pots in soilless media (Sunshine mix #2, SunGro Horticulture Canada Ltd, Seba Beach, AB) under controlled conditions, as described above. Fertilization rate was adopted from industry recommendations for cereal production from Alberta Agriculture and Forestry, Canada (Kryzanowski, 2002). Each plant received 125 mL of a mixed fertilizer solution (100 ppm of 10-52-10 [N-P-K] [Plant-prod Ultimate, Sure-Gro IP Inc, Brantford, ON]; 275 ppm of 20-8-20 [Direct Solutions, Agrium Advanced Technologies, Delta, BC]) seven days after sowing, followed by subsequent application of 125 mL (275 ppm of 20-8-20) at 25, 32 and 39 days after sowing. Each plant received in total 140 mg of nitrogen, 86 mg of phosphorus and 140 mg of potassium. Plants used for all experiments were six weeks old (42 days after sowing).

Host Plants Nutrient Analyses

In each experiment, the carbon and nitrogen (C:N) ratio of treated plants was measured to determine if nutrient availability to the larvae varied with plant treatment. Above-ground plant biomass (n=5, from each plant treatment) was collected at 42 days after sowing and oven dried at 65 °C for 48 hours. Dried plant material was finely ground and placed in tin capsules (2-3 mg) for analysis using a CE400 Elemental Analyzer (Exeter Analytical Inc., North Chelmsford, MA). Samples were combusted at 975 °C in a combustion tube that contained reagents to ensure complete oxidation of the sample. The combustion products passed through a reduction tube where the oxides of nitrogen were converted to molecular nitrogen. Thermal conductivity detectors measured the CO_2 and N_2 to quantify the amount of carbon and nitrogen in the samples.

Oviposition Preference Experiments

Two experiments tested the effect of crop variety and fertilization rate on oviposition preference of *M. unipuncta*. In the first experiment, response to four crop varieties was compared. One plant of each crop variety was placed within a single oviposition cage (39 × 39 × 80 cm) (n=15). Two pairs were introduced into each oviposition cage and provided with a 10% sucrose solution. Moths remained in the cage for one week, at which time the eggs on each plant were counted using a stereomicroscope (magnification 1.6×) (Leica MZ95, Concord, ON).

In the second experiment, two crop varieties were grown under three fertilization levels: the full dose as described above, a half dose (half fertilizer concentration of the full dose) and no fertilizer application. Fifteen cages housed three spring wheat (Go) plants, one from each fertilization level. An additional fifteen cages housed three feed barley (Xena) plants, one from each fertilization level. The total number of tillers per pot was recorded from each cage. Two mating pairs of *M. unipuncta* were introduced into each cage as described for the first experiment. Eggs were counted after one week.

Larval Performance Experiments

Two experiments measured larval performance of *M. unipuncta* on the same crop varieties and fertilization regimes tested in the oviposition experiments. In the first experiment, five second-instar larvae were introduced to plants of each of the four crop varieties tested (n=20). Plants were covered with a nylon mesh sleeve (50 cm × 30 cm) to prevent larvae from escaping and were monitored once per week until pupation. Sex was determined upon pupation (Cheng, 1970). Pupae were separated by sex and weighed to the nearest 0.01 g (Balance model: XS105 DualRange, Mettler Toledo).

In the second experiment, larval performance was evaluated on differently fertilized spring wheat (Go) and feed barley (Xena) plants. Three levels of fertilization were tested, as described for the oviposition experiment above, the full dose, half dose and no fertilizer application. Two second-instar larvae were introduced to plants of each treatment (n=20). Plants were covered with a nylon mesh sleeve (50 cm × 30 cm) and monitored three times per week until pupation. Larval developmental time was recorded from second larval instar to pupation. Sex was determined upon pupation (Cheng, 1970). Pupae were separated by sex and weighed to the nearest 0.01 g (Balance model: XS105 DualRange, Mettler Toledo). An additional set of plants from each fertilization level (n=5) was grown as a control to estimate the effect of fertilizer treatment on plant dry mass. Above-ground plant biomass was collected at 42 days after sowing and oven dried at 65 °C for 48 hours.

Larval Development Field Study

In 2014, a field experiment tested the impact of fertilizer rate on larval development of *M. unipuncta* on feed barley (Xena) grown in small plots (0.92 × 3 m) at the Lethbridge Research Centre, Agriculture and Agri-Food Canada, Alberta, Canada. Plots were seeded on 15

May 2014 using a self-propelled plot seeder equipped with a cone splitter and zero-tillage double disc openers (Agriculture and Agri-Food Canada Design and Engineering Lab, Swift Current, SK). The seedbed utilization for this seeder configuration is narrow and would be approximately 10%. Plots were arranged in a block factorial design with two levels of fertilization rate (full fertilizer dose and no fertilizer), and three levels of exclusion/herbivory with plots receiving either a cage (1.5 × 1.5 × 1.5 m) with or without insects, or no cage with no insects. Plot with full fertilizer dose received a single application of urea ammonium phosphate (112.3 kg/ha. of 34-17-0 [N-P-K]). Each possible combination of factors was replicated in three different blocks.

Insects were introduced into the cages assigned to the insect treatment on 14 July 2014. Each cage received six *M. unipuncta* egg masses evenly distributed throughout the plot at the whorl of the leaves on the main stem of a barley plant. Eggs were left to hatch and larvae to develop until 07 August 2014 at which time 50 larvae were randomly sampled from each cage containing insects. Larvae were transported back to the laboratory where they were weighed to the nearest 0.01g (Balance model: XS105 DualRange, Mettler Toledo), and head capsules were measured using a micrometer attached to the stereo microscope (magnification 1.6×) (Leica MS5, Concord, ON) to determine larval instar following the head capsule width range per instar by Guppy (1969).

Plots were harvested on 27 August 2014 at crop maturity using a Wintersteiger Expert (Wintersteiger AG, Salt Lake City, UT, USA) plot combine equipped with a straight-cut header, pickup reel and crop lifters. Grain yield was calculated from grain harvested from the entire plot area and corrected to 140 g kg-1 grain moisture. All grain collected from plots was retained post-harvest to characterize grain test weight (kg hL-1), seed mass (g 1000-1) and grain protein concentrations as per industry standards (Canadian Grain Commision, 2011). Grain protein concentration was determined from whole grain using near infrared reflectance spectroscopy technology (Foss Decater GrainSpec, Foss Food Technology Inc, Eden Prairie, MN).

Statistical Analysis

Data were tested for normality and heteroscedasticity using visual techniques and Shapiro-Wilks test. Plant dry mass and nutrient concentration were analyzed using a linear model with crop variety and fertilization regime as explanatory variables (Table 2-1) in R package ‘MASS’ v.7.3-33 (Venables and Ripley, 2002). The proportion of eggs laid on each plant treatment out of the total numbers of eggs within the cage was square root transformed for normality and analyzed using a linear mixed model in R package ‘nlme' v.3.1-117 (Pinheiro et al., 2014). Plant treatment (crop variety or fertilization rate) was specified as the explanatory variable, and cage was treated as a blocking random factor (Table 2-1). For the oviposition experiment with varying fertilization levels, the number of tillers per plant was analyzed using a generalized linear mixed model with Poisson family distribution in R package ‘lme4’ v.1.1-17 (Bates et al., 2015), with crop variety and fertilizer regime as explanatory variables and cage as a random factor (Table 2-1). For the larval performance experiments, pupal weight data were analyzed using a linear mixed model in R package ‘nlme' v.3.1-117 (Pinheiro et al., 2014), with crop variety or fertilizer regime and sex as explanatory variables and plant as a random factor (Table 2-1). Larval developmental time was analyzed using a generalized linear mixed model with Poisson family distribution in R package ‘lme4’ v.1.1-17, with crop variety, fertilizer regime and sex as explanatory variables and plant as a random factor (Table 2-1). For the larval development field study, larvae were grouped by instar, and independent analyses were performed for each instar group. Head capsule width and larval weight were transformed to the 1/4 power for normality. (Table 2-1). Means separation for all experiments was performed using the Tukey method (α = 0.05) with package 'lsmeans' v.2.17 (Lenth and Hervé, 2015). All statistical tests were conducted using the freely available statistical package 'R v3.1.0' (R Core Team, 2014) in 'RStudio v0.98.' (http://www.rstudio.com).

Results

Effect of Crop Variety on M. unipuncta

Nutrients available to larvae differed among crop varieties ($F_{3,18} = 4.533$, $p = 0.015$). Spring wheat (Go) and malt barley (Copeland) had the highest C:N ratio (7.72 ± 0.32 SE and 7.44 ± 0.65, respectively), followed by winter wheat (Buteo) (7.04 ± 0.19). The feed barley variety (Xena) had the lowest C:N ratio (5.679 ± 0.19), which was significantly different from spring wheat (Go) ($t = 3.49$, $p = 0.013$) and malt barley (Copeland) ($t = 2.97$, $p = 0.037$) varieties (Figure 2-1).

Mythimna unipuncta showed oviposition preference for different crop varieties ($F_{3,36} = 2.94$, $p = 0.045$). A higher percent of eggs were laid on winter wheat (Buteo) (37% ± 0.05 SE), followed by malt barley (Copeland) (24% ± 0.05) and spring wheat (Go) (20% ± 0.03 SE). The feed barley variety (Xena) had the lowest percent of eggs (18% ± 0.04 SE). After pairwise means comparison, only the proportion of eggs found on winter wheat (Buteo) was significantly different from feed barley (Xena) ($t = 2.84$, $p = 0.007$).

Crop species and variety had a strong influence on pupal weight ($F_{3,112} = 7.818$, $p < 0.001$) (Figure 2-2). Larvae reared on both barley varieties had the highest pupal weights, followed by those reared on winter wheat (Buteo). Larvae reared on the spring wheat variety (Go) had the lowest pupal weights. Overall, *M. unipuncta* larvae reared on barley had higher performance than larvae reared on wheat based on pupal weights (332.14 ± 4.33 SE and 301.83

± 5.32, respectively) ($F_{1,114} = 18.985$, $p < 0.001$). There was no difference in weight between female and male pupae ($F_{1,112} = 0.693$, $p = 0.406$).

Effect of Fertilization Regime on M. unipuncta

Plant dry mass differed with crop variety tested ($F_{1,26} = 18.99$, $p < 0.001$) and fertilization level ($F_{1,26} = 49.29$, $p < 0.001$). Feed barley (Xena) had heavier plant dry mass (700.00 ± 125.36 mg SE) than spring wheat (Go) (478.66 ± 120.55 mg), regardless of the fertilizer treatment. Plants in full and half fertilizer dose had similar plant dry mass (76.00 ± 103.71 and 76.00 ± 67.33, respectively), while unfertilized plants had the lowest plant dry mass (260.00 ± 48.07 mg), regardless of the crop variety tested. Furthermore, nutrients available to the larvae were influenced by the interaction between fertilizer level and crop variety ($F_{2,24}$=5.12, p=0.014) (Figure 2-3). Feed barley (Xena) at full and half fertilizer doses had the lowest C:N ratio (6.15 ± 0.05 and 6.42 ± 0.11, respectively), although they were not different from each other. Spring wheat (Go) at full and half fertilizer doses had equal intermediate levels of C:N ratios (6.73 ± 0.05 and 6.63 ± 0.05, respectively). Both feed barley (Xena) and spring wheat (Go) without fertilizer had the highest C:N ratio (14.84 ± 1.15 and 19.12 ± 0.91, respectively), and were significantly different from each other.

The number of tillers differed between crop variety tested (Wald χ^2=49.43, df=1, p<0.001) and fertilization level (Wald χ^2=39.39, df=2, p<0.001). Feed barley (Xena) had more tillers than spring wheat (Go), regardless of the fertilizer treatment. Plants treated with the full and half fertilizer doses had a similar high number of tillers while unfertilized plants had the lowest number of tillers, regardless of the crop variety tested. *Mythimna unipuncta* did not exhibit an oviposition preference for the differently fertilized host plants. A similar proportion of eggs was laid on plants that received either half or full fertilizer treatments and unfertilized plants. This result occurred in both feed barley (Xena) ($F_{2,20}$ = 1.01, p = 0.3705) and spring wheat (Go) ($F_{2,22}$ = 0.11, p = 0.892) cages that were tested independently in this experiment. Conversely, fertilization regime had a significant effect on *M. unipuncta* pupal weight ($F_{2,32}$=4.25, p=0.023) and larval developmental time (Wald $\chi 2$=9.17, df=2, p=0.010). Larvae reared on unfertilized plants had lower pupal weight (252.25 ± 6.75 mg SE) than larvae reared on plants treated with the half or full fertilizer concentrations (305.61 ± 9.70 and 316.40 ± 14.27 mg, respectively) (Figure 2-4). There was no effect of crop type ($F_{1,32}$=2.58, p = 0.117) or sex ($F_{1,32}$=1.59, p = 0.215) on pupal weight. Larvae reared on unfertilized plants had a longer larval developmental time (29.71 ± 2.54 days SE) than larvae reared on plants treated with the half or full fertilizer concentrations (23.04 ± 0.36 and 24.89 ± 0.62 days, respectively) (Figure 2-5). Crop type did not influence larval developmental time (Wald $\chi 2$=0.76, df=1, p=0.382). Larvae reared on feed barley (Xena) had a similar developmental time to those reared on spring wheat (Go), regardless of the fertilization regime. Female and male individuals reached the pupal stage at the same time (Wald $\chi 2$=0.36, df=2, p=0.546).

Larval Development Field Study

Larvae sampled from the variously treated feed barley (Xena) plots were in the fourth and fifth larval instar at the time of collection. Fertilization regime did not influence larval weight for fourth ($F_{1,2}$ = 3.41, p = 0.206) and fifth ($F_{1,2}$ = 0.66, p = 0.501) instar larvae.

There was no effect of fertilization regime on plot yield ($F_{1,12}$ = 1.12, p = 0.309) (Table 2-2). Plots without cages had a higher yield than plots with cages but there was no difference in yield in caged plots with or without insects (t = 0.38, df=12, p = 0.710). There was no significant effect of fertilization regime ($F_{1,12}$ = 0.002, p = 0.835) or insect treatment ($F_{2,12}$ = 1.15, p = 0.271) on grain protein content (Table 2-2).

Discussion

This study assessed the effect of cereal crop variety on adult female preference and larval performance of the generalist herbivore, the true armyworm *M. unipuncta*. Many generalist insect herbivores can discriminate between hosts within their accepted host-range and exercise some degree of preference at host selection for oviposition (Schoonhoven et al., 2005). I observed an inverse relationship between oviposition preference and larval performance in *M. unipuncta*. Spring wheat (Go) received a higher number of eggs but did not support larval performance, whereas feed barley (Xena) received the fewest eggs but supported the highest larval performance. Differences in larval performance can be attributed to nutrient availability in the different crop varieties.

Weak or no coupling between oviposition preference and larval performance occurs in several lepidopteran pests. For instance, the bertha armyworm *Mamestra configurata* Walker (Lepidoptera: Noctuidae) has an inverse preference-performance relationship for hosts within the Brassicaceae family. *Sinapis alba* L receives more eggs than other *Brassica* spp hosts, however, *M. configurata* larvae fed *S. alba* have slower development and lower survival (Ulmer et al., 2001, 2002). Likewise, *S. exigua* females oviposit more frequently on *Chenopodium murale* L (Chenopodiaceae) than *Apium graveolens* L (Umbelliferae), although larvae reared on *A. graveolens* develop into heavier pupae faster than larvae reared on *C. murale* (Berdegue et al., 1998). Similarly, host selection by females of the generalist fall armyworm, *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae), is independent from the performance of the offspring, as larvae that fed on a commercial landrace maize var. Tuxpeño (*Zea mays* ssp. *mays* L) (Poaceae) grew faster than larvae that feed on the ancestral variety, Balsas teosinte (*Zea mays* ssp. *parviglumis* Itlis & Doebly), although females lay an equal proportion of eggs on both host plants (Bernal et al., 2015). Pest species in the armyworm guild have highly mobile larvae that are capable of dispersing among plants when food resources are depleted. The larval mobility may weaken natural selection for oviposition preference on female moths. For example, larvae of the generalist African cotton leafworm, *Spodoptera littoralis* (Boisduval) (Lepidoptera: Noctuidae), feed *in situ* for about five days on the young leaves of cotton (*Gossypim arboretum* L.) (Malvaceae) selected by female moths for oviposition. As larvae grow, they gradually move to feed on mature leaves of the same plant or neighbouring plants (Sadek, 2011). Thus, female choice may not be under strong selective pressure in *M. unipuncta* because larvae can disperse from the host plant selected by their mother.

Alternatively, weak preference-performance coupling in *M. unipuncta* can also be explained by the parasite/grazer hypothesis (Thompson, 1988), which categorizes herbivores as parasites or grazers. Parasites are herbivores that complete their development on a single host plant, whereas grazers can move between plants throughout larval development. The hypothesis predicts that natural selection should favour oviposition on host plants that provide higher survival rates of eggs and early larval instars, although survival and development of later instars is better on alternate hosts (Thompson, 1988). Spring wheat (Go) may provide higher offspring survival during early development of *M. unipuncta*, while later instar larvae disperse to hosts with higher nutritional quality. To determine if the inverse preference-performance relationship in *M. unipuncta* provides support for the parasite/grazer hypothesis, future studies should address feeding preference in early and late instar larvae under controlled experiments.

Contrary to suggestions by Guppy (1961), our results demonstrate that *M. unipuncta* has a hierarchical selection of host plants within the cereal crops tested, however, female host selection is not based on the nutritional quality of the host. The most preferred host for oviposition, spring wheat (Go), had the lowest nitrogen content whereas the least preferred oviposition host, feed barley (Xena), had the highest nitrogen content. There is evidence for herbivorous insects to select host plants with low nutritional quality for oviposition sites and subsequent offspring development. For instance, *T. ni* females prefer to oviposit on cabbage *Brassica oleracea* L var. capitata (Brassicaceae) that is nutritionally inferior to the other tested hosts (Coapio et al., 2018). In a similar pattern, larvae of the specialist herbivore, the diamondback moth (*Plutela xylostella* L) (Lepidoptera: Plutellidae), have higher performance on young leaves located at the top of plants in three *B. oleracea* varieties that contain higher protein and glucosinolate concentrations than older leaves. Female moths, however, prefer to lay eggs on mature and senescing leaves with less nutrition in order to reduce egg mortality associated with the adverse microclimatic conditions in the upper plant stratus (Moreira et al., 2016). Plant morphological characters or plant defense metabolites may play a more critical role in female oviposition behaviour in *M. unipuncta* than the nutritional quality of the host.

Although not tested in the current study, the selection of the low quality host, spring wheat (Go), by female *M. unipuncta* for oviposition can be explained by the “enemy-free space hypothesis” (Bernays and Graham, 1988). Evidence in favour and against the enemy-free space hypothesis occurs in the armyworm guild. For example, *S. littoralis* females prefer the inferior larval host plant alfalfa (*Medicago sativa* L) (Fabaceae) over cotton for oviposition. This preference may be driven by greater parasitoid pressure by *Chelonus inanitus* L. (Hymenoptera: Braconidae) in cotton than in alfalfa plants (Sadek et al., 2010). In contrast, *S. frugiperda* females show no oviposition preference for hybrid maize varieties despite the lower egg predation risk in these hosts compared to the ancestral variety, *Balsas teosinte* (Bernal et al., 2015). If predation risk is unpredictable, the generalist herbivore is more likely to employ a bet-hedging strategy to spread the risk among offspring by dispersing eggs over multiple plants within the accepted host-range (Singer, 2008). To determine if *M. unipuncta* female oviposition behaviour supports the enemy-free space hypothesis, future studies should determine if Spring wheat (Go) provides a safer microhabitat during early larval development. Field surveys in different cereal crops should be conducted to estimate egg hatch and early instar survival.

The current study also evaluated the effect of fertilization on the preference-performance coupling of *M. unipuncta*. As expected, fertilizer application increased nitrogen concentration in host plant leaves and plant dry biomass, and therefore, the nutritional quality for the herbivore. Insects benefit from increased nitrogen in plant foliage in a number of systems (Mattson, 1980, Chen et al., 2004, Hwang et al., 2008). For *M. unipuncta*, larvae reared on fertilized plants develop faster and have a greater pupal mass than larvae fed unfertilized plants. Fertilizer dose, however, did not enhance larval performance. Larvae reared on fertilized plants fertilized at the full dose had similar larval developmental time and pupal mass to those reared on plants fertilized at the half dose. Although each plant of the crop varieties tested received 140 mg of N in the full dose and 70 mg of N in the half dose, there were no differences in foliar nitrogen concentration between fertilized plants at full dose or half dose. Fertilizer application to cotton of 24 to 158 mg of nitrogen per plant increased larval weight and reduced developmental time in *S. exigua*, but did not generate individuals with a heavier pupal mass (Chen et al., 2008). Higher amounts of fertilizer may be necessary to observe differences in larval performance in *M. unipuncta*. For example, *M. configurata* larvae fed canola plants treated with 3.0 g of fertilizer per plant produced heavier pupae than those reared on canola plants at 1.0 g per plant (Weeraddana and Evenden, 2018). Fertilization rates used in the current study were adopted from industry recommendations for cereal production in Canada (Kryzanowski, 2002), and thus, *M. unipuncta* larvae are not exposed to higher fertilizer rates that may maximize the performance of this pest.

Nitrogen fertilization not only increases the nutritional quality of host plants for larval development but also enhances the host plant volatile profile (Chen et al., 2010, Veromann et al., 2013) and chlorophyll concentration in leaves (Fox et al., 1994, Garratt et al., 2010), and thus, can augment host plant attractiveness to insects. Many female herbivores can assess the nutritional quality of host plants and preferentially oviposit on plants with higher nitrogen levels than unfertilized plants (Jauset et al., 1998, Jiang and Cheng, 2003, Prudic et al., 2005), including other armyworm pests like bertha armyworm (Weeraddana and Evenden, 2018) and beet armyworm (Chen et al., 2008). Fertilizer input supported tiller growth in the cereal crop varieties tested, and therefore, increased potential oviposition sites for *M. unipuncta*. Females failed to discriminate higher quality plants, however, when presented hosts grown under different fertilization regimes.

Contrary to the results of the larval performance study on differently fertilized plants under controlled conditions in the laboratory, I found no effect of fertilization of feed barley (Xena) on larval performance in the field study. Fourth and fifth instar larvae sampled from caged plots with fertilized plants had similar head capsule widths and mass to larvae sampled from caged plots with unfertilized plants. Furthermore, plots with fertilizer treatment had similar yield and grain protein content compared to plots without any fertilizer. It is possible that the initial soil fertility provided minerals to plants in the field experiment regardless of the fertilizer treatment (Ortiz-Monasterio et al., 1997, Havlin et al., 2005). Crop plants in the unfertilized treatment may have obtained available nutrients from the soil and produced similar yield to the plants in the fertilizer treatments. Feed barley (Xena) plants in the field experiment may have been vigorous regardless of the fertilizer treatment, and therefore, larvae reared on either fertilized or unfertilized plots had similar performance. The herbivory treatment did not reduce yield or grain protein content.

Insect density may not have reached thresholds to reduce yield, or plants were vigorous enough to compensate for herbivory damage. *Mythimna unipuncta* economic threshold for cereals crops is 20 larvae per m^2 at the heading stage in the Canada Prairies (Floate, 2017), however, cereal crops can sustain up to 75 % defoliation damage with little loss in yield (Steinkraus and Mueller, 2003). Similarly, crop yield was not impacted in plots of conventionally tilled corn that was manually infested with late instar *M. unipuncta* larvae at one to three larvae per plant, despite the presence of defoliation damage (Mulder and Showers, 1987). Similarly, total seed number and seed weight were not reduced in *Brassica nigra* L (Brassicaceae) plants damaged by *Pieris rapae* L (Lepidoptera: Pieridae) larvae compared to undamaged plants at both low and high soil fertility (Meyer, 2000).

Although *M. unipuncta* has lower performance when fed unfertilized plants under laboratory conditions, it is possible that local true armyworm populations will not encounter hosts plants with low nutritional quality under field conditions in managed ecosystems. Fertilizer amendment at seeding is a common agricultural practice to increase soil fertility and maximize cereal crop yield, and thus, *M. unipuncta* will encounter vigorous cereal crops that will enhance their larval performance to some extent. In the Canadian Prairies Provinces, the current wheat and barley fertilizer recommendations have a positive effect on *M. unipuncta* performance, and potentially could increase adult fitness. Research on the preference-performance hypothesis, should be conducted in both the laboratory and field settings so that findings from experiments under controlled conditions can be compared to natural conditions.

In conclusion, the generalist herbivore *M. unipuncta* does not follow the ‘mother knows best’ principle. Components of the herbivore life history of *M. unipuncta* may weaken the coupling between adult preference and larval performance. True armyworm larvae are highly mobile, and therefore, female oviposition behaviour may not be under strong selection pressure. Furthermore, wheat and barley are self-pollinating crops and do not provide a nectar reward for noctuid moths (Okada et al., 2018). *Mythimna unipuncta* female moths may benefit from increased foraging behaviour over oviposition host location in order to increase their fitness at the expense of the performance of their offspring. I suggest that *M. unipuncta* potentially employs a bet-hedging strategy instead to spread predation risk among offspring by dispersing eggs over multiple plants within the accepted host-range. I cannot rule out the parasite/grazer hypothesis or the enemy-free space hypothesis as underlying mechanisms for the host selection by *M. unipuncta* for plants with low nutritional quality, however, further field survey should determine if lower quality hosts result in higher survival rates in early larval development.

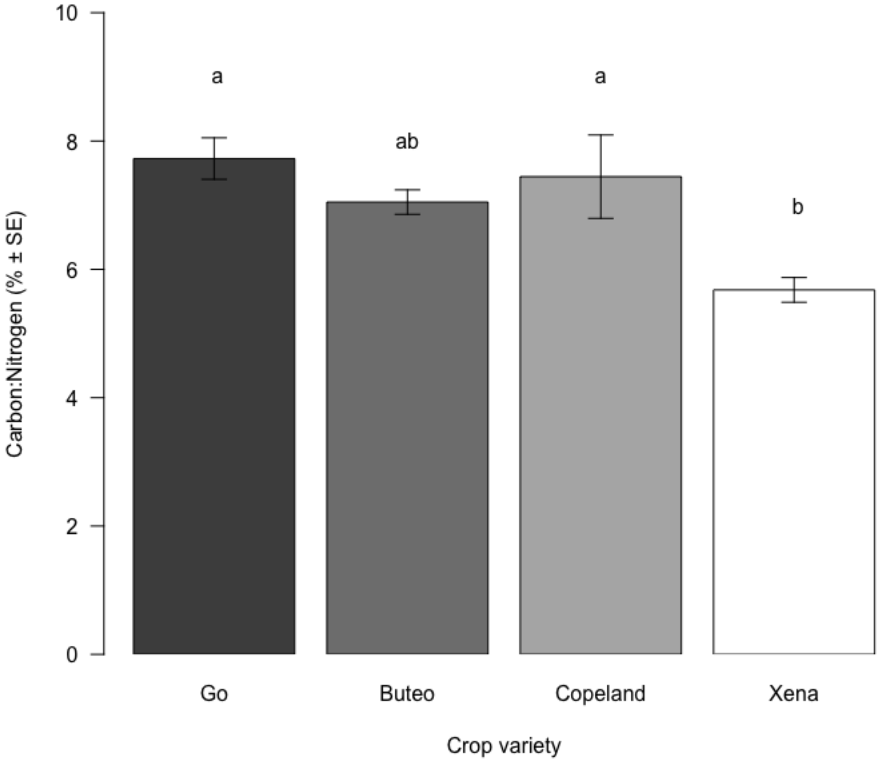

Figure 2-1. Mean carbon: nitrogen (C:N) ratio (% ± SE) of aboveground biomass of four crop varieties: two wheat varieties – “Go” (spring wheat) and “Buteo” (winter wheat) – and two barley varieties – “Copeland” (malt variety) and “Xena” (feed variety) (n = 5 per crop variety). Bars marked with different letters are statistically different (Tukey method, α = 0.05).

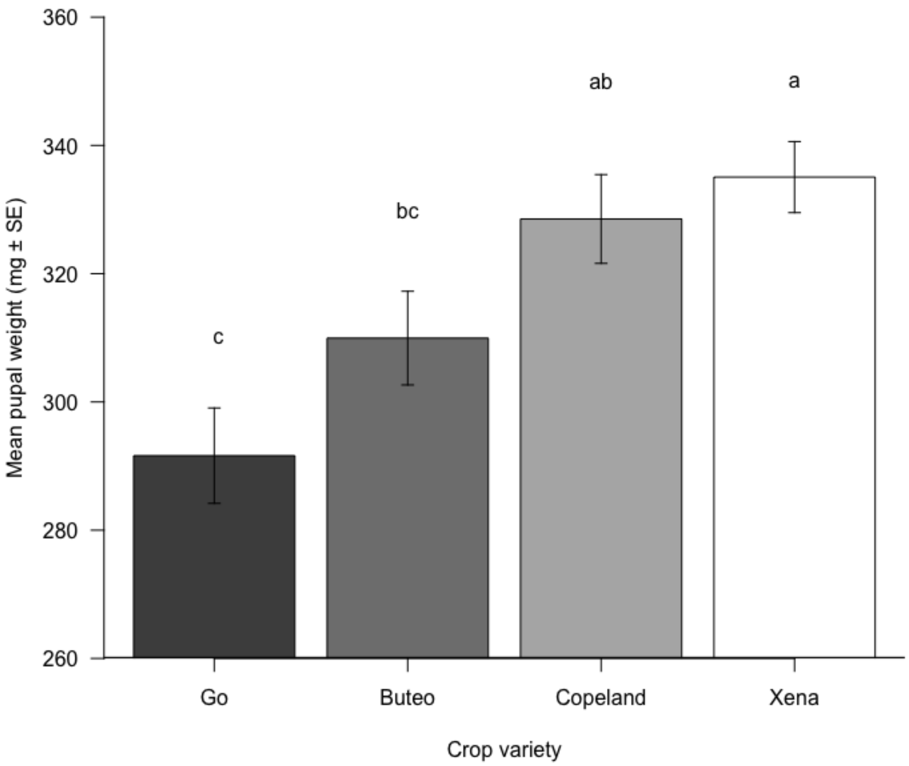

Figure 2-2. Effect of crop variety on *Mythimna unipuncta* performance. Mean pupal weight (mg ± SE) of individuals reared on two wheat varieties – "Go" (spring wheat) (n = 27) and "Buteo" (winter wheat) (n = 34) – and two barley varieties – "Copeland" (malt variety) (n = 25) and "Xena" (feed variety) (n = 31). Male and female pupae are pooled in each crop variety. Bars marked with different letters are statistically different (Tukey method, α = 0.05).

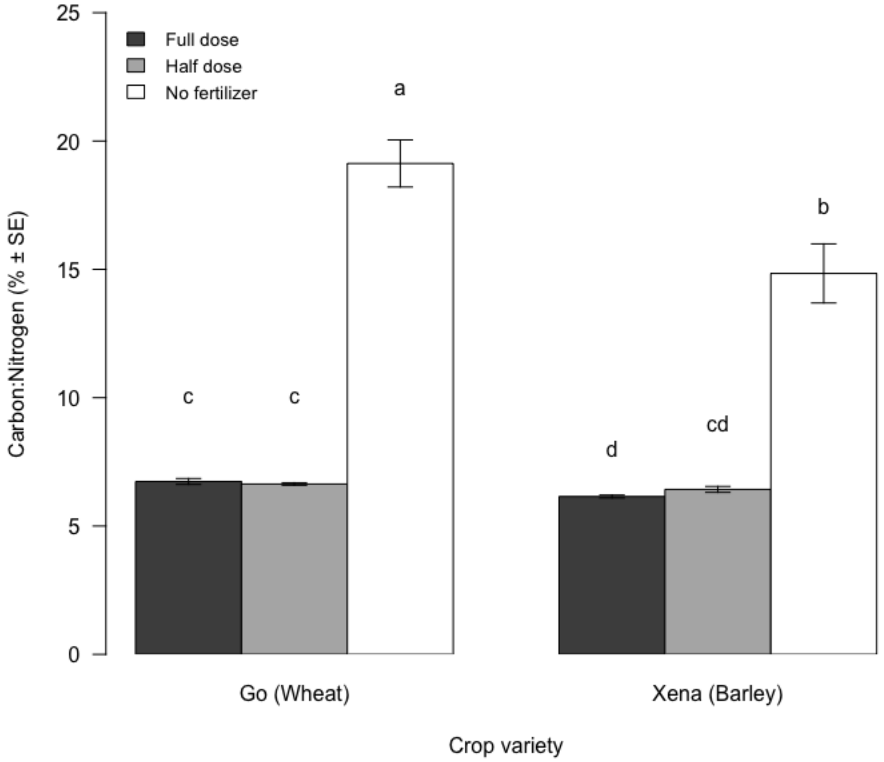

Figure 2-3. Mean carbon: nitrogen (C:N) ratio (% ± SE) of aboveground biomass of feed barley variety "Xena" and spring wheat variety "Go" grown under one of three fertilization regimes: full dose, half dose and unfertilized (n =5 per treatment combination). Bars marked with different letters are statistically different (Tukey method, α = 0.05).

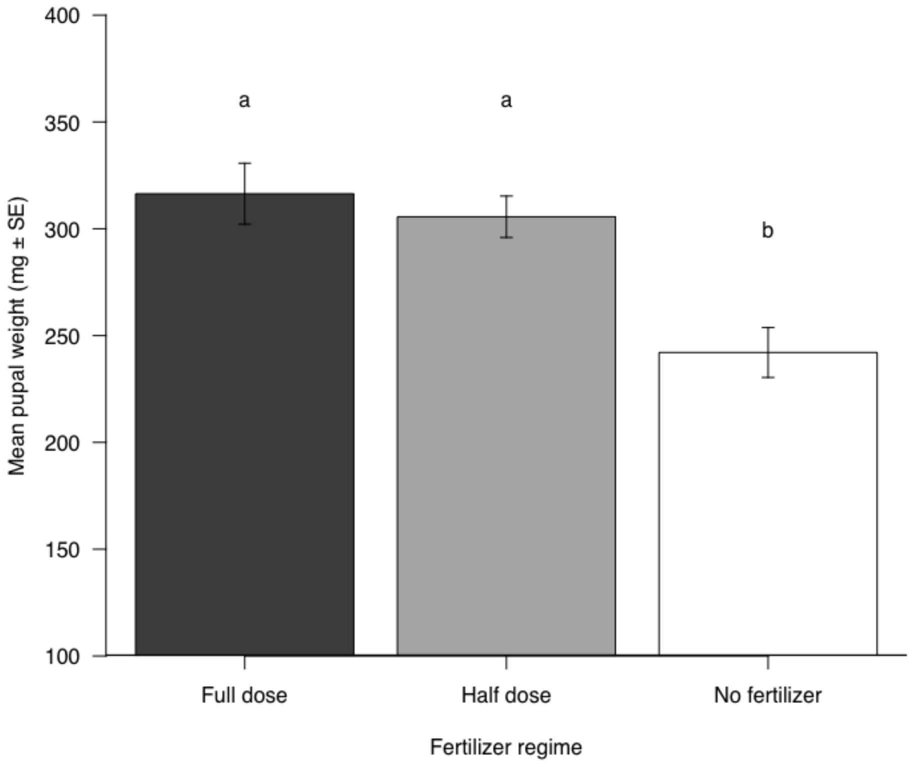

Figure 2-4. Effect of host plant fertilization on *Mythimna unipuncta* performance. Mean pupal weight (mg ± SE) of individuals reared on spring wheat “Go” and the barley feed variety “Xena” at three fertilization regimes: full dose (n = 14), half dose (n = 17) and unfertilized (n = 6). There was no effect of the sex of the individual or the crop variety on which larvae were reared on subsequent pupal weight. Pupal weight is pooled by fertilization regime. Bars marked with different letters are statistically different (Tukey method, α = 0.05).

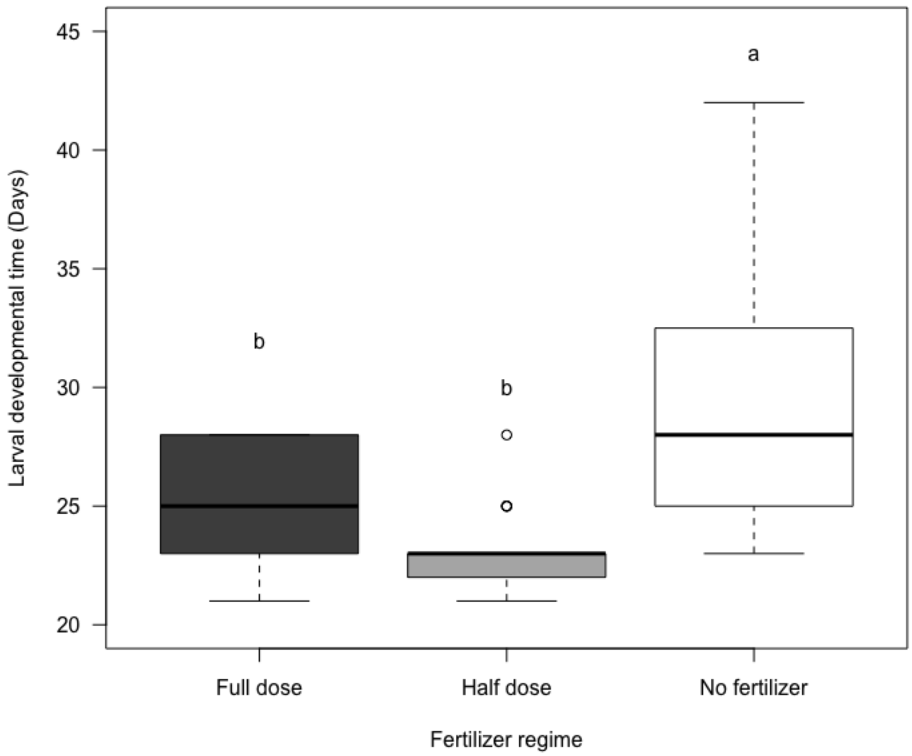

Figure 2-5. Effect of host plant fertilization on *Mythimna unipuncta* performance. Boxplots of larval developmental time (days) when reared on the spring wheat variety "Go" and the barley feed variety "Xena" at three fertilization regimes: full dose (n = 14), half dose (n = 17) and unfertilized (n = 6). Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or maximum value; open circles represent points more than 1.5 times the interquartile range. There was no effect of the sex of the individual or the crop variety on which larvae were reared on subsequent pupal weight. Larval developmental time is pooled by fertilization regime. Bars marked with different letters are statistically different (Tukey method, $\alpha = 0.05$).

Table 2-1. Results of the optimal statistical models used in the several experiments to determine the influence of crop variety and fertilization on oviposition preference and larval performance of the true armyworm, *Mythimna unipuncta* (Lepidoptera: Noctuidae)

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
1 Effect of Crop Variety											
Plant nutrient analysis	C:N	lm	C:N ~ Crop variety	Variety	F-value	4.53	3,18	0.015	67.3	67.3	73.5
Oviposition preference	Egg proportion	lmer	(Proportion)$^{1/2}$ ~ Crop variety + (1|Cage ID)	Variety	F-value	2.94	3,36	0.045	-4.9	-4.9	-2.9
Larval Performance	Pupal weight	lmer	Pupa ~ Crop variety + Sex + (1|Plant ID)	Variety Sex	F-value	7.81 0.69	3,112 1,112	< 0.001 0.406	1144.4	1127.7	1176.9
2 Effect of Fertilizer Regime											
Plant dry mass	Dry mass	lm	Dry mass ~ Crop + Fertilizer	Crop Fertilizer	F-value	18.99 49.29	1,26 2,26	< 0.001 < 0.001	-30.8	-28.1	14.08
Plant nutrient analysis	C:N	lm	C:N ~ Crop + Fertilizer + Crop:Fertilizer	Crop Fertilizer Host:Fertilizer	F-value	22.12 40.51 5.12	1,24 2,24 2,24	< 0.001 < 0.001 0.014	-516.7	-516.7	-96.98
Plant, number of tillers	Tillers	lm	Tillers ~ Crop + Fertilizer	Crop Fertilizer	Wald χ^2	49.43 39.39	1 2	< 0.001 < 0.001	290.7	292.7	387.2
Oviposition, barley	Egg proportion	lmer	(Proportion)$^{1/2}$ ~ Fertilizer + (1| Cage ID)	Fertilizer	F-value	1.01	2,20	0.3705	.	33.3	26.7
Oviposition, wheat	Egg proportion	lmer	(Proportion)$^{1/2}$ ~ Fertilizer + (1| Cage ID)	Fertilizer		0.11	2,22	0.892	.	32.7	23.9
Larval performance	Pupal weight	lmer	Pupa ~ Crop + Fertilizer + Sex + (1|Plant ID)	Crop Fertilizer Sex	F-value	2.58 4.25 1.60	2,32 2,32 2,32	0.117 0.023 0.215	132.6	140.4	141.8

Table 2-1. (Concluded).

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
2 Effect of Fertilizer Regime											
Larval performance	Larval time	glmer	Time ~ Crop + Fertilizer + Sex + (1|Plant ID)	Crop	Wald χ^2	0.76	1	0.383	269.3	281.8	271.5
				Fertilizer		9.17	2	0.010			
				Sex		0.36	1	0.546			
3 Larval Development Field Study											
Larval performance	Weight, 4th instar	lmer	$(\text{Larva})^{1/4}$ ~ Fertilizer + (1|Block/Cage)	Fertilizer	F-value	3.41	1,2	0.206	.	21.6	18.9
	Weight, 5th instar	lmer	$(\text{Larva})^{1/4}$ ~ Fertilizer + (1|Block/Cage)	Fertilizer	F-value	0.66	1,2	0.501	.	172.3	167.0
Agronomic metrics	Plot yield	lmer	Yied ~ Fertilizer + Exclusion + (1|Block)	Fertilizer	F-value	1.12	1,12	0.309	205.6	182.4	258.8
				Cage		29.28	2,12	< 0.001			
	Grain protein	lmer	$(\text{Protein})^{1/4}$ ~ Fertilizer + Cage + (1|Block)	Fertilizer	F-value	0.00	2,12	0.835	-77.5	-63.5	108.3
				Cage		1.15	2,12	0.271			

Table 2-2. Agronomic data collected for the feed barley Xena plot field study conducted in summer 2014. Plots received full fertilization dose or no fertilizer. Insect treatment was the addition of six *Mythimna unipuncta* egg masses. Different letters represent statistical significance between means (Tukey method, α = 0.05)

Fertilizer	Cage/Insects	Yield (g)		Protein
Fertilizer (full)	Cage and insect	2060.57 ± 78.23	b	13.57 ± 0.03
	Cage and no insect	2157.47 ± 132.84	b	14.00 ± 0.06
	No cage, no insect	2709.70 ± 87.63	a	13.77 ± 0.03
No fertilizer	Cage and insect	2058.50 ± 122.17	b	13.77 ± 0.19
	Cage and no insect	1884.03 ± 139.30	b	13.70 ± 0.06
	No cage, no insect	2720.03 ± 115.43	a	13.93 ± 0.19

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Chapter 3: Influence of host plant species and fertilization regime on larval performance and feeding preference of the redbacked cutworm, *Euxoa ochrogaster*, and the pale western cutworm, *Agrotis orthogonia*, (Lepidoptera: Noctuidae)

Abstract

The redbacked cutworm, *Euxoa ochrogaster* (Guenée), and the pale western cutworm, *Agrotis orthogonia* (Morrison), are generalist pests that cause sporadic economic damage to several crops grown across the Canadian Prairies. Early larval instars feed on foliage, whereas mature larvae eat into the stem and sever crop seedlings. The objective of this study was to evaluate the influence of host species and plant nutrition on larval performance of both cutworm species. For all experiments, third instar larvae were housed individually in Petri dishes with randomly assigned seedlings under controlled conditions and monitored until pupation. The first experiments evaluated larval development and preference on three hosts (canola, peas and spring wheat). *Euxoa ochrogaster* had higher performance on canola and peas, while *A. orthogonia* had a higher performance on wheat. *Euxoa ochrogaster* consumed more canola, whereas *A. orthogonia* consumed more spring wheat in multiple-choice feeding experiments. The second experiments evaluated larval development on fertilized and unfertilized seedlings on canola and spring wheat. When fed unfertilized seedlings, *E. ochrogaster* had better performance on canola than spring wheat, whereas *A. ochrogaster* had better performance on spring wheat than canola. Fertilizer application enhanced the performance of both cutworms regardless of the crop species. Despite their generalist feeding behaviour, both cutworm species have a larval feeding preference that matches the host plant with high performance. Canola-cereal cropping is a common crop rotation schedule in the region, however, this tactic will not negatively impact cutworm performance.

Introduction

Agricultural ecosystems under extensive farming are in a constant state of annual disturbance (Vankosky et al., 2017). Agronomic practices like monoculture, crop rotation, varying levels of soil disturbance (i.e. tillage and harvest), chemical and organic inputs to manage soil fertility, and pest management have a strong impact on insect community structure and population densities that may increase crop vulnerability to pest outbreaks (Shennan, 2008).

Integrated pest management (IPM) programs employ multiple tactics to prevent insect pests from reaching economic injury levels (Kogan, 1998). For instance, crop rotation is a fundamental IPM tactic to prevent pest density buildup by disruption of the life cycle of the target pest through substitution with non-host crops (Bullock, 1992). Crop rotation can result in larvae that feed on suboptimal host plants, which can affect the performance and adult fitness of the target pest. For example, the pest density of the Colorado potato beetle, *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae), is reduced by a one-year rotation with non-host cereal crops in potato (*Solanum tuberosum* L.) (Solanaceae) fields (Wright, 1984). Similarly, recommendations to rotate wheat (*Triticum aestivum* L.) (Poaceae) with non-cereal crops to reduce wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), numbers have been implemented in the Canadian Prairies for several years (Beres et al., 2011). It is essential to acquire knowledge on the biology of the pest and to understand how agricultural practices may affect pest species at the individual and population level in order to develop successful IPM programs.

Multiple factors determine the optimal performance of immature insect herbivores (Scriber and Slansky, 1981). Fluctuation in environmental factors (i.e. temperature, humidity, light, CO_2 levels) affects growth rate, as well as the quality of host plants (Rao et al., 2012, Aguilon et al., 2015). Intra- and interspecific interactions may increase competition for food resources and predation risks (Fantinou et al., 2008, Underwood, 2010). Host plant nutritional quality, such as carbon content, macro- and micronutrient content, and defensive secondary chemical compounds, can be critical biotic factors that affects herbivore performance at the larval stage; this influence can carry forward to the adult stage, and affect fecundity or longevity (Slansky and Scriber, 1985). These bottom-up effects on herbivore growth and reproduction can, in turn, influence population density and contribute to outbreaks of pest species.

Nitrogen is a critical element for growth and reproduction in plants and insect herbivores. Fertilizer input increases nitrogen content in plants, and thus, augments biomass and total protein content (Mattson, 1980, López-Bellido et al., 1996, Jackson, 2000). Respectively, insect herbivores that feed on host plants with high nitrogen content generally have high performance (Chen et al., 2004, Chen et al., 2010, Weeraddana and Evenden, 2018). In contrast, insect herbivores that feed on host plants with low nitrogen content have low growth rates and prolonged developmental time, which may increase risk to predation and parasitism (Haggstrom and Larsson, 1995, Uesugi, 2015). This is known as the 'slow-growth high-mortality' hypothesis (Feeny, 1976).

The redbacked cutworm, *Euxoa ochrogaster* (Guenée), and the pale western cutworm, *Agrotis orthogonia* (Morrison), are noctuid (Lepidoptera: Noctuidae) pests native to North America that cause sporadic economic damage to several annual crops grown across the Canadian Prairies (Beirne, 1971, W.C.C.P., 2015, 2016, Floate, 2017). The redbacked cutworm is widely distributed in the northern regions of the Canadian Prairie Provinces while the pale western cutworm is mostly present in the southern regions, however, infestations may co-occur in the same area if environmental conditions are favourable for both species (Beirne, 1971, Lafontaine, 1987, Lafontaine, 2004). Both species are univoltine and overwinter as fully developed first instar larvae within eggs (Beirne, 1971). Larvae eclose from eggs in late spring, when annual crops are at the seedling stage, and develop through six or seven larval instars (Beirne, 1971). Early instars feed on seedling foliage, whereas late instars display the behaviour characteristic of cutworms and cut seedling stems to feed on the stem and foliage that ultimately kill the seedling (Strickland, 1923). Low-density populations result in crop thinning, however, outbreak infestations can cause complete destruction of a field (Beirne, 1971). Pupation lasts for two to five weeks in an earthen cell in the soil prior to moth eclosion in late summer.

The redbacked cutworm and pale western cutworm are generalist herbivores with a wide range of host plants from different families (Beirne, 1971, Floate, 2017). Many generalist insect herbivores can discriminate hosts within their accepted host-range, and females exercise some degree of preference at host selection for oviposition and subsequent larval development (Schoonhoven et al., 2005). There is no evidence to date, however, of oviposition preference among crops for either cutworm species. Females do not oviposit directly on larval host plants but lay eggs in loose-dry soil under crop stubble or in fallow fields (Beirne, 1971). Furthermore, moths fly in late summer and early fall after crop harvest, so that assessment of the plant community available for offspring the following spring is not possible. There are suggestions that the redbacked cutworm larvae may prefer canola to cereals, whereas pale western cutworm infestations are associated with cereal crops (Beirne, 1971).

In this study, I investigated the larval performance and larval feeding preference of both cutworm species. Specifically, I asked:

(i) Do host plant species influence larval performance in both cutworm species?

(ii) Do cutworm larvae show feeding preference between host plant species? Does host selection by the larvae match the larval performance?

(iii) Does fertilizer input alter host plant species suitability for either cutworm species?

First, I evaluated the effect of host plant species on larval performance compared to an artificial diet as control. Three annual crops grown in the Canadian Prairie Provinces are tested: Canola variety 'Q2' (*Brassica napus* L.) (Brassicaceae), field peas variety 'Cutlass' (*Pisum sativum* L.) (Fabaceae) and spring wheat variety 'CDC Go' (*Triticum aestivum* L.) (Poaceae). All crop species were developed through traditional breeding crosses. 'Q2' (Faculty of Agriculture and Forestry, University of Alberta, Edmonton, Alberta, Canada) is a canola variety well-adapted for western Canada with high seed oil content and resistant to lodging and blackleg disease (Stringam et al., 1999). 'CDC Go' (Crop Development Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada) is a hard-red wheat variety seeded in early spring. 'Cutlass' (Crop Development Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada) is a field pea variety well-adapted for western Canada with high yield and resistance to powdery mildew (Blade et al., 2004). Second, I assess larval feeding preference for the tested host plant species in three-way choice assays. Lastly, I evaluate the effect of plant fertilizer input on larval performance under controlled conditions in the laboratory.

To develop a successful IPM program for cutworms in the Canadian Prairies, it is critical to investigate the biology of the pest. Life history and phenology have been studied in detail for both cutworm species (Jacobson, 1970, Jacobson, 1971, Byers and Struble, 1987, Ayre, 1990), however, there is no information on the effect of host plant species and plant fertilization on larval performance and fitness. Cutworms provide a good system to study insect nutritional ecology, and understand how agricultural practices, like crop rotation and crop fertilization, may influence generalist herbivore performance and fitness.

Materials and Methods

Insect and Plants

A laboratory colony of redbacked cutworm was started from eggs obtained from an established colony at Lethbridge Research Centre, Agriculture and Agri-Food Canada, Alberta. Pale western cutworm eggs were obtained from mated adults reared in the laboratory from field collected larvae. Colonies of both cutworm species were maintained under control conditions (Intellus Environmental Controller, Percival Scientific, Iowa, US) at 21 °C and 16:8 photoperiod (light: dark). Larvae were reared on a pinto-based meridic diet (200.0 g pinto beans, 100.0 g wheat germ, 64.0 g brewer's yeast, 4.0 g methyl parben, 6.5 g ascorbic acid, 2 g sorbic acid, 1.5 mL formaldehyde, 27.5 g agar and 1350 mL water). Larvae were reared individually in 29.6 mL plastic cups (Solo Cup, Mason, Michigan, US) with a diet cube piece (0.5 × 0.5 × 0.5 cm) and a piece of filter paper lining the bottom of the cup to reduce condensation. The size of the diet cube increased by 0.5 cm as larvae reached later instars. Diet and filter papers were replaced once a week and larvae were monitored until pupation. Pupae were placed in 500 mL plastic containers with moist, fine vermiculite (Specialty Vermiculite Canada Corp, Alberta, Canada). Newly emerged moths (20-30 individuals, 1:1 male: female) were placed in a mating chamber (40 × 40 × 80 cm) with access to 10% sucrose solution (w: v) and Petri dishes (9 cm diam.) containing fine particle sieved sand (Canadian Standard Sieve Series No. 40, St. Catherines, ON) that served as an oviposition site. Eggs were collected every two days and kept at 21 °C for 15 days to complete development of first instar larvae within the egg. Prior to diapause, eggs were pre-chilled at 10 °C for 10 days. Eggs were overwintered at 0 °C for four months. Once diapause was completed, eggs were removed from cold storage for emergence.

Seeds were obtained from Lethbridge Research Centre, Agriculture and Agri-Food Canada, Alberta. Three host plant species were used in these experiments: canola variety “Q2”, field peas variety “Cutlass” and spring wheat variety “CDC Go”. Seedlings were grown in 96-cell trays (cell dimensions: 4.0 × 3.0 cm and 5.0 cm deep) held in plastic watering trays with soilless media (Sunshine mix #2, SunGro Horticulture Canada, Ltd, Seba Beach, AB) at 21 °C and 16:8 photoperiod (light: dark). Seeds were planted in alternate cells, leaving one empty cell in between each plant, and thus, each tray held 48 seedlings. One host plant species per tray was planted every other day to maintain a constant food source for the larvae throughout the experiments. Trays were watered from below (approx. 2.0 L) every second day. For experiments evaluating the effect of host plant species on larval performance, seedling trays received water only. For experiments evaluating the effect of fertilization regime on larval performance, fertilized seedling trays received a fertilizer solution (1 g/L 20-20-20 [N-P-K] [Plant-prod Ultimate, Sure-Gro IP Inc, Brantford, ON]) from below (approx. 2.0 L) at 7, 14 and 21 days after sowing, whereas non-fertilized seedling trays received water only.

Seedlings used in all experiments were three weeks old (21 days after sowing). Intact host plants were used in all experiments to avoid bias on larval performance from feeding on excised leaf tissue, and to maintain seedling moisture. Larvae had access only to the above ground biomass as a food source and had no access to the seedling root system. Each individual seedling was kept within the plastic cell excised, and removed from the seedling trays for the experiments. The soil surface surrounding the seedling root system was covered with corrugated plastic insert (4.0 × 3.0 cm) and secured to the plastic cell with masking tape.

Host plant nutrient analyses

Nutrient content (nitrogen, phosphorus, potassium and sulphur) for each host plant species, fertilized or non-fertilized, was measured to determine if nutrient availability to the larvae varied with treatment. Above-ground plant biomass (n=5, from each plant treatment) was collected at 21 days after sowing and oven dried at 64 °C for 48 hours. Dried plant material was finely ground and nutrient content analyses were conducted at the Natural Resources Analytical Laboratory at the University of Alberta, Edmonton, CA. Total nitrogen content was measured through the Dumas combustion method (AOAC, 2000) with a Costech Model EA 4010 Elemental Analyzer (Costech International Strumatzione, Florence, Italy, 2003). Phosphorus, potassium and sulphur were measured through nitric acid digestion method and analysed using Thermo iCAP6000 Duo inductively coupled plasma-optical emission spectrometer (ICP-OES Spectrometer. Thermo Fisher Corporation, Cambridge, UK, 2012).

Larval Performance - Host Plant Species Experiments

Two experiments were conducted to test the effect of host plant species on larval performance. The first experiment evaluated redbacked cutworm larval performance (n = 16 per treatment) and a second experiment evaluated pale western cutworm larval performance (n = 32 per treatment). Larval development on three host plant species (canola, field peas and spring wheat) was compared to that on an artificial diet, which served as a positive control. A single third-instar larva was placed in a large Petri dish (14 cm diam. × 2.5 cm deep) with two strips of bleach-free paper towel (2.5 × 10 cm). The lid had a 13 cm diam. hole covered with fabric to reduce water condensation inside the Petri dish. A plant treatment was randomly assigned to each larva and seedlings were replaced prior to depletion or desiccation. Petri dishes were placed in a completely randomized design in a growth chamber under controlled conditions, as above.

Larvae were monitored every second day until pupation. Change in larval instar was determined by the presence of shed exuvia from the previous instar in the Petri dish and the increase in head capsule width. Larval weight at each instar, head capsule width at each instar, larval developmental time (from third instar to pupation) and pupal weight were recorded for each larva. Larvae were weighed to the nearest 0.01g (Balance model: XS105 DualRange, Mettler Toledo), and head capsule width was measured using a micrometer attached to the stereo microscope (magnification 1.6×) (Leica MS5, Concord, ON). Sex was determined upon pupation (Cheng, 1970). Pupae were separated by sex and weighed to the nearest 0.01 g (Balance model: XS105 DualRange, Mettler Toledo).

Larval Feeding Preference Experiments

Three-way choice experiments evaluated the larval feeding preference of both cutworm species among the three host plant species: canola, spring wheat and field peas. The first experiment assessed redbacked cutworm preference, while the second experiment assessed pale western cutworm preference. Both experiments were conducted independently under controlled conditions at 21 °C and 16:8 photoperiod (light: dark).

Seedlings from each host plant were arranged at random in 12.5 cm diam. pots with soilless media (Sunshine mix #2). Pots (n=30 for each experiment) were arranged in a grid in the experimental arena (1.7x 0.85 m). Fifth-instar larvae were starved for 24 hours and weighed prior to the experiment. At the beginning of the following scotophase, a single larva was placed in the center of the pot. Larval feeding choice was recorded at 1, 2, 3, 6, 12, 24 and 36 hours after set-up. Red incandescent lights (25 w, 125 v, Sylvania Group, Wilmington, MA, USA) were used during the scotophase to allow recording of the larval feeding choice. After 36 h, the final larval weight was recorded. Uneaten above-ground plant biomass was collected and oven dried for 48 hours at 64 °C. To estimate an average of initial plant biomass from each crop plant species, the above-ground biomass of seedlings with no larval feeding damage (n=30) was measured. Consumed plant biomass per host plant species per pot was calculated by subtracting uneaten plant dry biomass from the average initial plant dry biomass.

Larval Performance – Fertilization Regime Experiments

Two experiments evaluated the effect of fertilizer regime on larval performance. Two host plant species were used in these experiments (canola and spring wheat) at two fertilization regimes (fertilized or non-fertilized). The first experiment evaluated redbacked cutworm performance (n = 32 per treatment combination) and a second experiment evaluated pale western cutworm performance (n = 32 per treatment combination). Single third-instar larvae were placed in a large Petri dish following the experimental design as described for the larval performance – host plant species experiments. A treatment was randomly assigned to each larva and replaced prior to depletion or desiccation. Larval weight at each instar, head capsule width at each instar, larval developmental time (from third instar to pupation) and pupal weight were recorded for each larva. Larvae were weighed to the nearest 0.01g (Balance model: XS105 DualRange, Mettler Toledo), and head capsule width was measured using a micrometer attached to the stereo microscope (magnification 1.6×) (Leica MS5, Concord, ON). Sex was determined upon pupation. Pupae were separated by sex and weighed to the nearest 0.01 g (Balance model: XS105 DualRange, Mettler Toledo).

Statistical Analyses

For all statistical analyses, models were fitted as “full models” at first, in which the fixed component of the models included the main effect of all relevant explanatory variables and all possible interactions.

For host plant species experiments, data were tested for normality and heteroscedasticity using visual techniques and the Shapiro-Wilks test. Host plant nutrient concentration was analyzed using a linear model in the ‘lm’ command in the R package ‘MASS’ v.7.3-33 (Venables and Ripley, 2002), with crop plant species as the explanatory fixed variable (Table 3-1). Larval weight at each instar was normalized through natural logarithm transformation, while head capsule width at each instar was square-root transformed. Larval weight and head capsule width at each instar were analyzed with a linear mixed model with random intercept and slope to account for the repeated measures on the same individual larvae with the ‘lme’ command in the R package ‘nlme' v.3.1-117 (Pinheiro et al., 2014). Host plant species, sex and instar (and their interactions) were specified as explanatory fixed variables (Table 3-1). Instar was also specified as the random intercept and larval identification number as the random slope (~ instar | larva ID) (Table 3-1). Larval developmental time, from third larval instar to pupation, was analyzed using a generalized linear model with Poisson family distribution in the ‘glm’ command in R package ‘lme4’ v.1.1-17 (Bates et al., 2015), whit host plant species and sex (and their interactions) as explanatory fixed variables (Table 3-1). Pupal weight was transformed to the (1/4) power for normality and analyzed in a linear model in the ‘lm’ function in the R package ‘MASS’ v.7.3-33 (Venables and Ripley, 2002), with host plant species and sex (and their interactions) as explanatory fixed variables (Table 3-1). Analyses for fertilizer regime experiments used similar statistical models as described for host plant species experiments, with fertilization regime specified as the explanatory fixed variable in all models for each of the response variables (Table 3-1).

For larval feeding preference experiments, first feeding choice was analyzed using Person’s chi-squared test for count data with the ‘chisq.test’ command in the R package ‘stats’ v.3.5.0. Additionally, plant biomass consumed by larvae was analyzed using a linear mixed model with host plant species as explanatory fixed variable and pot number as random blocking factor in the 'lmer' command in R package 'lme4' v.1.1-17 (Bates et al., 2015).

For all models, model simplification was performed in step-wise *a posteriori* procedure by removing non-significant interaction terms and comparing nested models through Likelihood-ratio chi-square test with the 'anova' command in R package 'car' v.3.0-0 (Fox and Weisberg, 2011). The optimal model was selected using Akaike's information criterion (AIC). Test statistic values, degree of freedom numbers and p-values were obtained from the 'Anova' function in R package 'car' v.3.0-0 (Fox and Weisberg, 2011). The 'Anova' function produces analysis of variance tables from models created by 'lm', 'lme', 'glm' or 'lme4' commands. F-tests are calculated for linear models, Wald chi-square (Wald χ^2) tests are calculated for linear mixed models and Likelihood-ratio chi-square (LR χ^2) are calculated for generalized linear models. Means comparison for all experiments was performed using Tukey method ($\alpha = 0.05$) with package 'lsmeans' v.2.17 (Lenth and Hervé, 2015). All statistical analyses were conducted using the freely available statistical package 'R v.3.5.0' in 'RStudio v0.98.' (http://www.rstudio.com).

Results

Larval Performance – Host Plant Species

Nutrient concentration varied among host plant species in nitrogen ($F_{2,12} = 36.20$, $p < 0.001$), phosphorus ($F_{2,15} = 6.96$, $p = 0.007$) and sulphur content ($F_{2,15} = 91.08$, $p < 0.001$). Field peas had the highest concentration of nitrogen and phosphorus, followed by spring wheat, while canola had the lowest concentrations for both elements (Figure 3-1). Canola and fields peas had similar sulphur content while spring wheat had significantly less sulphur than canola and field peas (Figure 3-1). There was no difference in potassium concentration among the tested host plant species ($F_{2,15} = 2.27$ $p = 0.137$).

The influence of host plant species treatment on redbacked cutworm larval weight was dependant on larval instar (host species × instar, Wald $\chi^2 = 126.39$, df = 12, $p < 0.001$) and sex (host species × sex, Wald $\chi^2 = 13.28$, df = 3, $p = 0.004$) (Figure 3-2). Male and female individuals in all host plant species treatment had similar weights only at the third larval instar, however, differences in weight by sex appeared in later instars. Fourth instar female larvae reared on artificial diet and canola had the highest weight, followed by females fed field peas. Female larvae fed spring wheat had the lowest weight. Fourth instar male larvae reared on artificial diet had a higher weight than males fed spring wheat, while male larvae reared on canola or field peas had intermediate levels. For both sexes in the fifth instar, larvae that fed on artificial diet, canola or field peas had a similar and heavier weight than larvae that fed on spring wheat. Sixth and seventh instar female larvae fed artificial diet had the highest weight, followed by those fed canola and field peas, which had a similar weight. Female larvae fed spring wheat had the lowest weight. In contrast, sixth and seventh instar male larvae fed artificial diet had the heaviest weight compared to larvae that fed on any of the crop plants.

The effect of host plant species on pale western cutworm larval weight was dependant on larval instar (host plant species × instar, Wald $\chi^2 = 150.90$, df = 12, $p < 0.001$) (Figure 3-3), however, female and male individuals had a similar performance across all larval instars regardless of the host plant species treatment (Wald $\chi^2 = 0.349$, df = 1, $p = 0.554$). Larvae that fed on artificial diet were heavier than larvae reared on any of the host plant species, regardless of the larval instar. Larval weight did not differ with the host plant species on which they were reared at any stage of larval development.

There was a significant interaction between host plant species and instar on redbacked cutworm head capsule width (host plant species × instar, Wald $\chi^2 = 71.88$, df = 12, $p < 0.001$), which indicates that host plant species influenced head capsule width within each instar (Figure 3-4A). Female and male individuals had a similar head capsule width within each larval instar, regardless of the host plant species treatment (Wald $\chi^2 = 0.00$, df = 1, $p = 0.945$). There were no differences in head capsule width between larvae on the different host plant species treatments within the third and fourth larval instar, however, the effect of host plant species treatment on head capsule width occurred in later instars. Fifth instar larvae that fed on artificial diet, canola or field peas had wider head capsules than larvae that fed on spring wheat. Sixth instar larvae that fed on artificial diet or canola had wider head capsules than larvae that fed on field peas or spring wheat.

Likewise, there was a significant interaction between host plant species and instar on pale western head capsule width (host plant species × instar, Wald $\chi^2 = 347.33$, df = 12, $p < 0.001$) which indicates that differences in head capsule within each instar were influenced by the host plant species (Figure 3-4B). There was no difference in head capsule width between male and female individuals within each larval instar, regardless of the host plant species treatment (Wald $\chi^2 = 0.331$, df = 1, $p = 0.565$). Third instar larvae had similar head capsule width on all host plant species treatments. Fourth and fifth instar larvae reared on artificial diet had wider head capsules than larvae fed on the host plant species. Sixth and seventh instar larvae reared on artificial diet had wider head capsules, followed by larvae fed on spring wheat. Sixth and seventh instar larvae reared on canola and field peas had the narrowest head capsule width.

Host plant species treatment had an effect on redbacked cutworm larval developmental time (LR $\chi^2 = 23.43$, df = 3, $p < 0.001$). Larvae that fed on artificial diet had a faster developmental time (28.0 ± 1.33 days SE) compared to larvae reared on crop plant species (canola 36.0 ± 1.13; field peas 33.35 ± 1.18; spring wheat 37.26 ± 1.16) (Figure 3-5A). Host plant species treatment also influenced larval developmental time in pale western cutworm (LR $\chi^2 = 26.22$, df = 3, $p < 0.001$). Larvae reared on artificial diet and spring wheat had faster developmental times (48.34 ± 1.34 and 50.46 ± 1.02 days, respectively) compared to larvae reared on canola (58.04 ± 1.16 days) or field peas (58.71 ± 2.36 days) (Figure 3-5A). There was no difference in larval developmental time between male and female individuals for either redbacked cutworm (LR $\chi_2 = 1.53$, df = 1, $p = 0.214$) or pale western cutworm (LR $\chi_2 = 1.16$, df = 1, $p = 0.282$).

Redbacked cutworm larvae had high survival incidence, with more than 87% of individuals reaching pupation in each of food source treatments. Pupal weight in redbacked cutworm was strongly influenced by host plant species treatment ($F_{3,49} = 57.43$ $p < 0.001$) and this effect was dependent on sex of the individual (host plant species × sex $F_{3,49} = 2.97$ $p = 0.040$) (Figure 3-6). Individuals reared on artificial diet had the heaviest pupal weight, regardless of sex (305.32 ± 6.95 mg SE). The pupal weight of females reared on canola (196.57 ± 14.07 mg) and field peas (196.98 ± 11.09 mg) was heavier than that for females reared on spring wheat (148.60 ± 9.25 mg), whereas the pupal weight in males was equal for all individuals regardless of the host plant species treatment.

Pale western cutworm survival incidence varied among food source treatments. Larvae reared on field peas had a low survival incidence (22%), followed by canola (66%); while larvae reared on spring wheat and artificial diet had high survival incidence (88% and 91%, respectively). Host plant species treatment had a strong influence on pale western cutworm pupal weight ($F_{3,80} = 122.89$, $p < 0.001$), regardless of sex ($F_{1,80} = 0.08$, $p = 0.772$) (Figure 3-7). Individuals reared on artificial diet had the heaviest pupal weight (324.89 ± 7.21 mg), followed by spring wheat (214.44 ± 6.02 mg) and peas (181.21 ± 11.11 mg). Larvae feeding on canola had the lowest pupal weight (150.01 ± 6.04 mg).

Larval Feeding Preference Experiment

The first feeding choice of cutworm larvae did not vary with host plant species for redbacked cutworm ($\chi^2 = 3.8$, df = 2, $p = 0.149$) or pale western cutworm ($\chi^2 = 1.75$, df = 2, $p = 0.416$). The consumed plant biomass, however, differed with crop species for both species. Redbacked cutworm consumed more canola, followed by spring wheat and field peas with the lowest consumed biomass (Wald $\chi^2 = 11.51$, df = 2, $p = 0.003$). Statistical differences were only detected between the consumed biomass of canola and field peas (Figure 3-8A). Conversely, pale western cutworm consumed more spring wheat compared to canola and field peas (Wald $\chi^2 = 17.65$, df = 2, $p < 0.001$) (Figure 3-8B).

Larval Performance – Fertilization regimes

Fertilizer application increased potassium content in seedlings regardless of the host plant species ($F_{1,20} = 105.02$, $p < 0.001$) (Figure 3-9). Unfertilized spring wheat and canola seedlings had similar low potassium levels (1.101 ± 0.025 and 1.446 ± 0.100 g/100 g ± SE, respectively). Fertilization increased potassium content for both wheat and canola seedlings (4.143 ± 0.370 and 3.746 ± 0.350 g/100 g, respectively). For the remainder of the macro-elements analyzed, the effect of fertilization on nutrient concentration was dependent on the host plant species for nitrogen ($F_{1,20} = 11.33$, $p = 0.003$), phosphorus ($F_{1,20} = 7.70$, $p = 0.011$) and sulphur ($F_{1,20} = 36.02$, $p < 0.001$) (Figure 3-9). Unfertilized spring wheat seedlings (1.328 ± 0.062 g/100 g) had a higher nitrogen content than unfertilized canola seedlings (1.046 ± 0.026 g/100 g). Fertilizer treatment increased nitrogen in both spring wheat and canola to a similar concentration level (3.568 ± 0.195 and 3.773 ± 0.353 g/100, respectively). For phosphorus, both unfertilized spring wheat and canola seedlings had a similar low concentration (0.192 ± 0.013 and 0.167 ± 0.12 g/100 g, respectively). Fertilization increased phosphorus concentration, as fertilized spring wheat seedlings had a higher phosphorous content than fertilized canola seedlings (1.347 ± 0.069 and 0.818 ± 0.053 g/100 g, respectively). The lowest concentration of sulphur was found in unfertilized spring wheat seedlings (0.211 ± 0.011 g/100 g). Fertilizer application increased the sulphur level in spring wheat seedlings (0.651 ± 0.026 g/100 g). Fertilizer application did not increase sulphur content in canola and both unfertilized and fertilized seedlings had a similar concentration (0.927 ± 0.054 and 0.905 ± 0.031 g/100 g, respectively).

The effect of fertilizer treatment on redbacked cutworm larval weight was dependent on an interaction with host plant species and larval instar (fertilization × host × instar, Wald χ^2 = 8.98, df = 3, p = 0.029) (Figure 3-10A). Third instar larvae reared on fertilized canola or spring wheat had higher larval weights than those reared on non-fertilized canola or spring wheat. Larvae fed non-fertilized canola had a similar weight to larvae fed fertilized spring wheat. Larval weight of larvae in instars 4-6, was highest for individuals fed either fertilized canola or spring wheat, followed by larvae fed non-fertilized canola and larvae fed non-fertilized spring wheat had the lowest weight. Redbacked cutworm larvae reared on fertilized seedlings completed development after the sixth instar, while larvae reared on non-fertilized seedlings reached the seventh instar prior to pupation.

The influence of fertilizer on pale western cutworm larval weight was dependant on crop plant species (fertilization × host, Wald χ^2 = 5.17, df = 1, p = 0.022) and on the larval instar (fertilization × instar, Wald $\chi^2 = 21.78$, df = 4, $p < 0.001$) (Figure 3-10B). Third instar larvae reared on fertilized canola or spring wheat had the highest larval weight. Third instar larvae reared on non-fertilized canola or spring wheat had the lowest larval weight, although larvae fed fertilized spring wheat had a similar weight to larvae fed non-fertilized spring wheat. Individuals fed either fertilized canola or spring wheat had the highest weight when in the fourth to sixth instar, whereas larvae fed non-fertilized canola or spring wheat had the lowest weight.

There was a significant three-way interaction among host plant species, fertilizer treatment and instar on redbacked cutworm head capsule width (host plant × fertilizer × instar, Wald $\chi^2 = 15.17$, df = 3, $p = 0.001$), which indicates that the interaction between host plant species and fertilizer treatment influenced head capsule width within each instar. (Figure 3-11A). There were no differences in head capsule width among larvae within the third and fourth larval instar, however, the effect of food source treatment on head capsule width appeared in later instars. Fifth instar larvae reared on fertilized canola or spring wheat had the widest head capsules, followed by those reared on non-fertilized canola and larvae reared on non-fertilized spring wheat, which had the narrowest head capsules. Sixth instar larvae reared on either fertilized canola or spring wheat had wider head capsules than larvae reared on the non-fertilized seedlings. Female and male larvae had similar head capsule widths within each larval instar, regardless of fertilization regime or host plant species (Wald $\chi^2 = 0.08$, df = 1, $p = 0.775$).

There was a significant three-way interaction among host plant species, fertilizer treatment and instar on pale western cutworm head capsule width (host plant × fertilizer × instar, Wald $\chi^2 = 13.09$, df = 4, $p = 0.010$) (Figure 3-11B). Third and fourth instar larvae had similar head capsule widths in all fertilizer and host plant species combinations. Sixth instar larvae fed fertilized canola or spring wheat had wider head capsules than larvae reared on non-fertilized seedlings. Fifth and seventh instar larvae reared on fertilized canola or spring wheat had the widest head capsules, followed by those fed non-fertilized spring wheat and larvae reared on non-fertilized canola, which had the narrowest head capsule widths.

Redbacked cutworm larval developmental time was not influenced by host plant species (LR $\chi^2 = 0.13$, df = 1, $p = 0.711$) or sex of the individuals (LR $\chi^2 = 2.62$, df = 1, $p = 0.105$), but was affected by fertilizer application (LR $\chi^2 = 147.24$, df = 1, $p < 0.001$). Larvae that fed on fertilized seedlings had a faster larval developmental time (24.37 days ± 0.34 SE) than larvae that fed on non-fertilized seedlings (37.85 days ± 1.17 SE) (Figure 3-12). In contrast, fertilizer application did not influence pale western cutworm larval developmental time (LR $\chi^2 = 3.12$, df = 1, $p = 0.07$). Pale western cutworm larvae that fed on spring wheat seedlings had a faster developmental time (50.92 days ± 1.34 SE) than larvae that fed on canola seedlings (54.94 days ± 1.34 SE), regardless of the fertilizer treatment or sex of the individual (LR $\chi^2 = 6.64$, df = 1, $p = 0.009$) (Figure 3-13). Males developed faster than females (LR $\chi^2 = 14.29$, df = 1, $p < 0.001$).

Redbacked cutworm pupae were heavier when larvae fed on fertilized seedlings (272.61 mg ± 6.92 SE), than when larvae fed on non-fertilized seedlings (171.13.61 mg ± 4.97 SE) ($F_{1,96} = 175.55$, $p < 0.001$), regardless of the crop species or sex of the individuals (Figure 3-14). Furthermore, the influence of crop species on pupal weight was dependent on the sex of the individuals ($F_{1,96} = 7.38$, $p = 0.007$). Females reared on fertilized canola had the heaviest pupal weight, followed by those reared on fertilized spring wheat, non-fertilized canola and lastly the non-fertilized spring wheat. The pupal weight of males reared on fertilized canola or spring wheat was heavier than that of males reared on non-fertilized hosts.

The effect of fertilizer treatment on pale western cutworm pupal weight was dependent on crop plant species (fertilizer × crop $F_{1,96} = 14.49$, $p < 0.001$) (Figure 3-15). Individuals reared on fertilized canola or spring wheat had a similar high pupal weight (292.43 ± 8.54 and 291.43 ± 8.91 mg SE), that was significantly heavier than the pupal weight of individuals reared on non-fertilized spring wheat (223.86 mg ± 7.81 SE) and non-fertilized canola (161.62 mg ± 7.85 SE). There was no difference in pupal weight between males and females ($F_{1,96} = 1.29$, $p = 0.257$).

Discussion

This study assessed the larval performance of two generalist insect herbivores, the redbacked cutworm and the pale western cutworm, on different crop plant species compared to an artificial diet. As expected, both cutworm species had the fastest developmental time and the highest pupal weight when reared on artificial diet as compared to any of the crop species tested. Artificial diets can provide a richer source of nutrients than host plants when formulated for optimal nutritional requirements (Han et al., 2012, Anato et al., 2017, Favaro et al., 2017). For example, the generalist black cutworm, *Agrotis ipsilon* (Hugnagel) (Lepidoptera: Noctuidae), has a longer developmental time and greater number of larval instars when reared on susceptible corn seedlings (*Zea mays* L.) (Poaceae) than on a pinto bean-based artificial diet (Santos and Shields, 1998). Similarly, larvae from the generalist butterfly, the Painted Lady (*Vanessa cynthia* L.) (Lepidoptera: Nymphalidae), have a higher growth rate and pupal weight when reared on artificial diet than on leaves from the host *Plantago* spp. (Plantaginaceae) (Ellis and Bowers, 1998). Although insect herbivores are adapted to obtain nutrients from plants species within their host range, they also encounter indigestible structural compounds, such as lignin and cellulose, and an array of plant secondary metabolites that can impact performance (Schoonhoven et al., 2005). For instance, powdered silica and cellulose incorporated into artificial diet reduce nutrient digestibility and consumption rate in larvae of the generalist southern armyworm *Spodoptera* *eridiana* (Cramer) (Lepidoptera: Noctuidae) (Peterson et al., 1988). Larvae of the generalist armyworms *Helicoverpa armiguera* (Hübner) and *S. litura* (Frabicius) (Lepidoptera: Noctuidae) also have reduced larval weight and high mortality rates when the phenolic compounds, cinnamic acid and *p*-couramic acid, from cotton (*Gossypium hirsutum* L.) (Malvacea) leaves are incorporated into an artificial diet (Dixit et al., 2017). In contrast, larvae of the specialist butterfly, Buckeye (*Junconia coenia* L.) (Lepidoptera: Nymphalidae), have higher performance on *Plantago* spp. leaves than on artificial diet due to its adaptation to the plant secondary metabolite, iridoid glycoside (Ellis and Bowers, 1998). Plant secondary metabolites that are toxic or act as feeding deterrents to generalist herbivores can be used by specialist herbivores for host finding cues or for protection against predators (Ali and Agrawal, 2012). The redbacked and pale western cutworm are generalist herbivores and may not require plant secondary metabolites from larval host plants to enhance their performance. Larvae from both cutworm species had the highest performance on artificial diet, and therefore, the artificial diet employed in the current study provides adequate nutrition to support a cutworm colony in the laboratory.

Although both cutworm species are considered generalist herbivores, larval performance of both species varied with the crop species tested. Overall, canola and field peas are more suitable hosts than spring wheat for the redbacked cutworm, whereas, spring wheat is a more suitable host than canola for the pale western cutworm. Field peas are not a suitable host for pale western cutworm as there was low survival on this host. I observed differences in nutrient content among crop plants, but larval performance cannot be directly linked to the nutrient availability in the different crop species tested. Field pea is a nutritionally superior crop species with the highest content of nitrogen and sulphur, canola has a similar concentration of sulphur to field peas but has the lowest nitrogen concentration, and spring wheat has an intermediate level of nitrogen and the lowest concentration of sulphur. Higher performance on host plants with comparatively low nutritional quality occurs in other generalist herbivores, like the cabbage looper *Trichoplusia ni* (Hübner) (Lepidoptera: Noctuidae) (Coapio et al., 2018). Neonate and second instar *T. ni* larvae have a higher larval weight when reared on cabbage (*B. oleracea* L. var. *capitata*) (Brasicaceae) that is nutritionally inferior to other tested hosts. Although both cutworm species are generalists, it appears that the redbacked cutworm is better adapted to cope with plant defense compounds in canola and field peas, while the pale western cutworm is better adapted to spring wheat.

Generalist herbivores are able to feed and complete larval development on multiple plant species from different plant families, however, their performance and fitness varies between host plants species. For example, soybean and cotton are more suitable hosts for the generalist armyworms *S. eridania* (Stoll) and *S. cosmioides* Walker (Lepidoptera: Noctuidae) than oat, maize and wheat. This performance hierarchy may be due to adaptation of larvae to the chemical profile of soybean and cotton as they develop faster and have higher survival rates on these hosts (Silva et al., 2017). Suitability of host plants to the polyphagous bertha armyworm *Mamestra configurata* Walker (Lepidoptera: Noctuidae) varies among plant species within its host range (Dosdall and Ulmer, 2004). *Brassica rapa* L, *Sinapis alba* L. (Brassicaceae) and *Chenopodium album* L. (Chenopodiaceae) are the most suitable hosts compared to *Cirsium averse* L. (Compositae) and *Linum usitatissimum* L. (Linaceae). The generalist *H. armigera* has higher fitness, as measured by the total number of eggs laid by females, when reared on chickpeas (*Cicer arietinum* L.) (Fabaceae) than tomato (*Lycopersicon esculentum* Mill) (Solanaceae) (Razmjou et al., 2014). For several insect herbivores, pupal weight is strongly correlated with potential fecundity (Awmack and Leather, 2002). Redbacked cutworm larvae that feed on canola or field peas and pale western cutworm that feed on spring wheat may have higher adult fitness, and therefore, the effect of host plant species may lead to a potential increase in cutworm population density.

Orientation to food resources by insect herbivores can involve random movement, which leads to chance host encounters, or oriented movement guided by host plant cues (Schoonhoven et al., 2005). Larvae of the redbacked and the pale western cutworms appear to have a random searching behaviour, as I found no difference by host plant in the first feeding choice across several host choice experiments. Insect herbivores assess the quality of host plants through multiple sensory receptors, and acceptance of food sources is evidenced by sustained feeding on a given host plant (Schoonhoven et al., 2005). Although both cutworm species demonstrated random searching behaviour, I observed larval feeding preference as measured by the total amount of consumed plant biomass per crop species tested after 36 hours. The redbacked cutworm consumed more canola and spring wheat than field peas, while the pale western cutworm preferred spring wheat than canola and field pea seedlings. Furthermore, the larval feeding preferences match the larval performance in both cutworm species. A positive link between larval feeding preference and performance, although rarer than in insect specialists, occurs in some polyphagous larvae. Neonate and second instar *T. ni* larvae orient and select cabbage leaf discs over other hosts in multiple-choice feeding experiments; these choices match the host plant species that support the highest larval performance (Coapio et al., 2018). Similarly, *H. armigera* and *H. assulta* (Guenée) larvae have faster development and higher pupal weight on host species that match the larval feeding preference in multiple-choice experiments (Liu et al., 2012). Although there is no evidence of oviposition preference between crops in these species, our results suggest hierarchical host selection by larvae of both cutworm species, and that cutworm larvae could have a more active role in host selection than females.

The current study also evaluated the effect of fertilization on cutworm larval performance. As expected, fertilizer input increased host nutrition quality in canola and spring wheat seedlings, and therefore, enhanced the performance of both cutworm species. Similar results have been reported in other insect lepidopteran systems. For instance, the cabbage white butterfly (*Pieris* spp.) (Lepidoptera: Pieridae) (Chen et al., 2004), the beet armyworm *S. exigua* (Hübner) (Lepidoptera: Noctuidae) (Chen et al., 2008) and the bertha armyworm (Weeraddana and Evenden, 2018) have faster development and higher pupal weight when reared on fertilized than non-fertilized host plants.

For the redbacked cutworm, larvae reared on fertilized seedlings develop faster and have a higher pupal weight than those reared on non-fertilized seedlings. Furthermore, female redbacked cutworm larvae have a higher pupal weight on canola than on spring wheat, while male larvae perform the same on both crop seedlings. Difference in performance between sexes on different host plant species is dependent on the herbivore species. For instance, pupal weight of females of the pine beauty moth, *Panolis flammea* (Denis & Schiffermüller) (Lepidoptera: Noctuidae), reared on *Pinus sylvestris* L. (Pinaceae) are heavier than those reared on *P. contorta* L., however, this difference does not occur in males (Leather et al., 1998). It appears that redbacked cutworm differs in host utilization between sexes, in which females are more influenced by host plant food quality than males. Future work should examine resource allocation to reproduction in female redbacked cutworms.

Fertilizer input does not influence developmental time of pale western cutworm larvae. Larvae reared on fertilized seedlings attained higher larval weight and head capsule width within instars than those reared on non-fertilized seedlings. This cutworm species has a prolonged prepupal phase as an adaptation to hot dry summers to delay moth emergence until conditions are favourable for oviposition (Byers, 1992). Although nutrient content does not influence larval development time in the pale western cutworm, crop species has a strong influence in this and previous studies. Larvae reared on the wheat cultivar Thatcher develop faster than those reared on the barley cultivar Compana and the oats cultivar Exter (Jacobson, 1971). Therefore, crop species may have a stronger influence on larval developmental time than fertilizer input or nutritional content of the plant.

The pupal weight of the pale western cutworm is influenced by fertilizer input. Larvae reared on non-fertilized wheat have a higher pupal weight than those reared on non-fertilized canola, however, larvae attain similar high pupal weights when reared on fertilized plants of either species. Similar patterns have been found for *P. rapae crucivora* and *P. canidia canidia* (Hwang et al., 2008). Larvae reared on non-fertilized *Rorippa indica* L. (Brassicaceae) have lower pupal weight compared to those reared on non-fertilized *B. campestris*, however, there are no differences in pupal weight when reared on fertilized plants. Fertilizer input alters host suitability for pale western cutworm, and consequently, larvae that feed on fertilized canola or spring wheat seedling will have a similarly high performance.

In conclusion, the redbacked cutworm and the pale western cutworm are generalist pests, however, our results indicate that both cutworm species have a larval feeding preference which matches the host plant that promotes high performance. The redbacked cutworm has higher performance on canola and field peas, while the pale western cutworm has the highest performance on spring wheat seedlings. Field peas are not a suitable host for pale western cutworm. Although both cutworm species have a random movement pattern to orient to host plants, mature cutworm larvae assess the suitability of a host plant and may have a more active role in host selection than the adult females that lay eggs in the soil. Fertilizer input at seeding will alter host plant suitability for both cutworm species and increase the performance of individuals reared on either canola or spring wheat. Nutrient content of host plants enhances the larval performance of both cutworm species, which may lead to an increase in cutworm fitness and an increase in population density. Canola-cereal crops is a common crop rotation schedule in the Canadian Prairie Provinces to disrupt pest life cycles, however, this IPM tactic does not negatively impact cutworm performance.

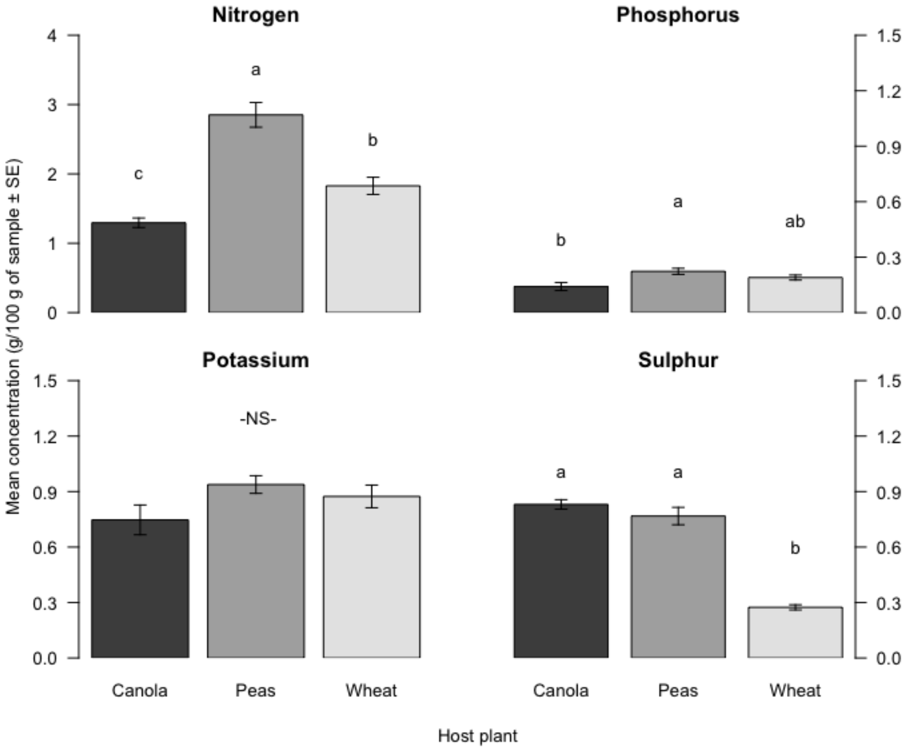

Figure 3-1. Mean nutrient concentration (g/100 g of sample ± SE) of above ground biomass of three crop species: Canola variety "Q2", field peas variety "Cutlass" and spring wheat variety "CDC GO". Seedlings were watered every other day and harvested 21 days after sowing and watered every other day. Bars marked with different letters within each nutrient are statically different (Tukey method, α = 0.05). -NS- represents no significant difference.

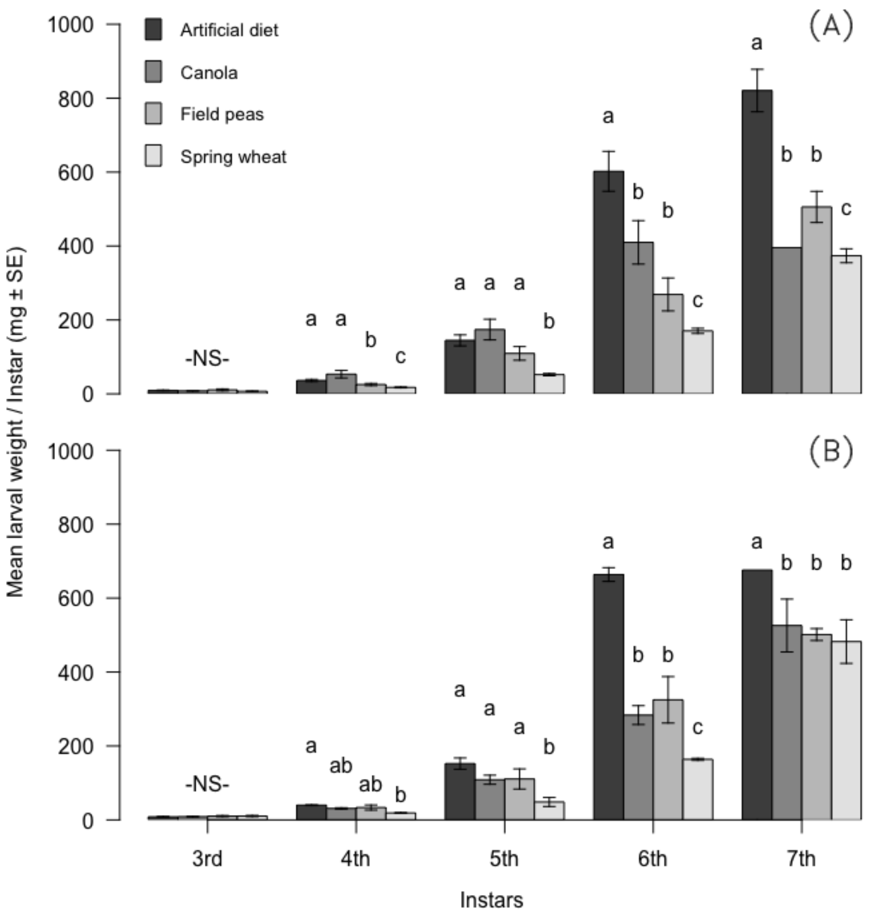

Figure 3-2. Redbacked cutworm (*Euxoa ochrogaster*) mean larval weight (mg ± SE) by instar. **(A)** Females. **(B)** Males. Means comparison was performed for differences among food source treatment within instar. Bars marked with different letters within each instar are statistically different (Tukey method, α = 0.05). -NS- represents no significant difference.

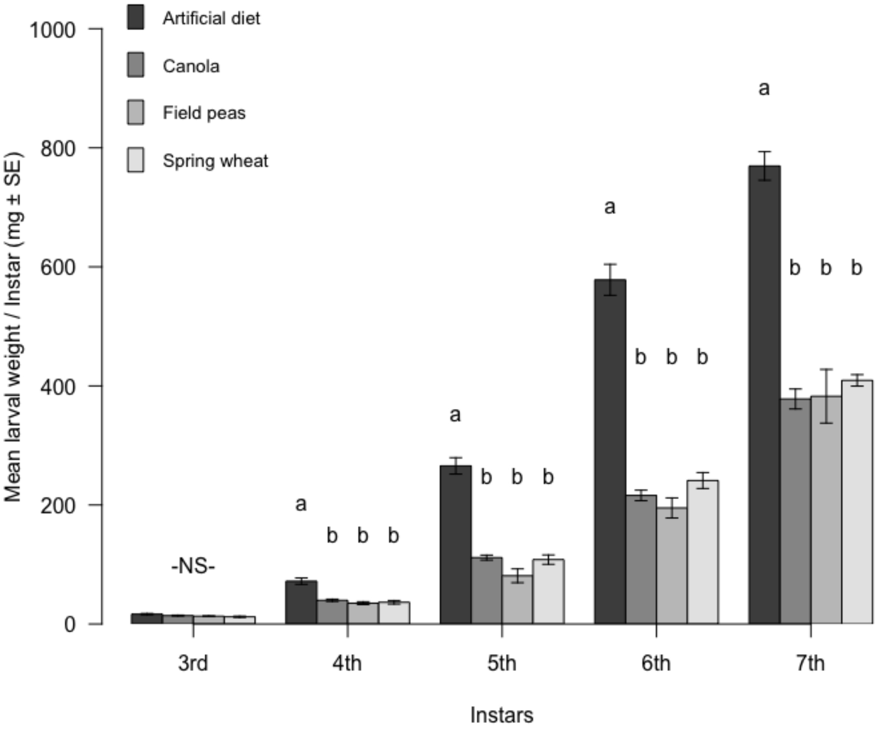

Figure 3-3. Pale western cutworm (*Agrotis orthogonia*) mean larval weight (mg ± SE) within each instar. There is no difference in weight between male and female individuals. Means comparison was performed for differences among food source treatment within each instar. Bars marked with different letters within each instar are statistically different (Tukey method, α = 0.05). -NS- represents no significant difference.

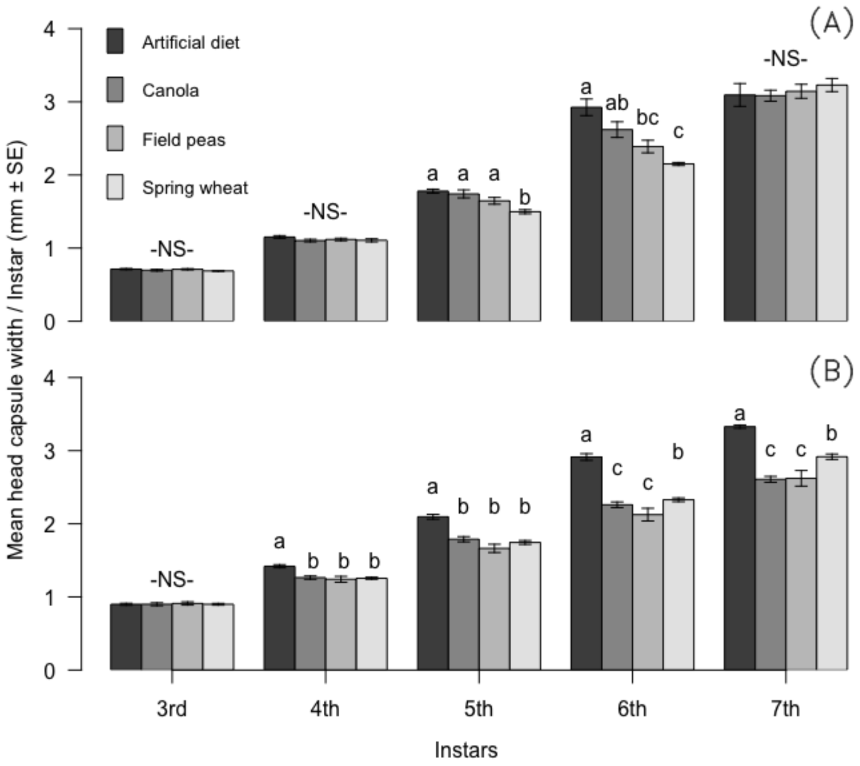

Figure 3-4. Mean head capsule width (mm ± SE) within each instar. There is no difference in weight between male and female individuals. **(A)** Redbacked cutworm (*Euxoa ochrogaster*) **(B)** Pale western cutworm (*Agrotis orthogonia*). Means comparison was performed for differences among food source treatment within each instar. Bars marked with different letters within each instar are statistically different (Tukey method, α = 0.05). -NS- represents no significant difference.

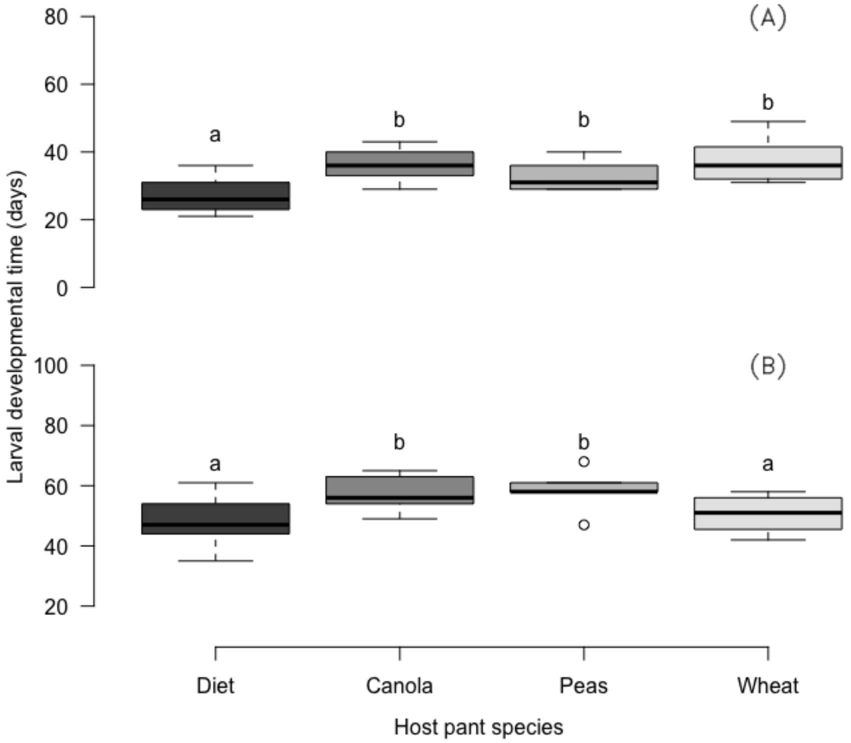

Figure 3-5. Boxplot of larval developmental time (days) from third instar to pupation. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the maximum value or 1.5 interquartile range of the data, and open circles represent points more than 1.5 times the interquartile range. There is no difference in weight between male and female individuals. **(A)** Redbacked cutworm (*Euxoa ochrogaster*) **(B)** Pale western cutworm (*Agrotis orthogonia*). Means comparison was performed for differences between food source treatment within cutworm species. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

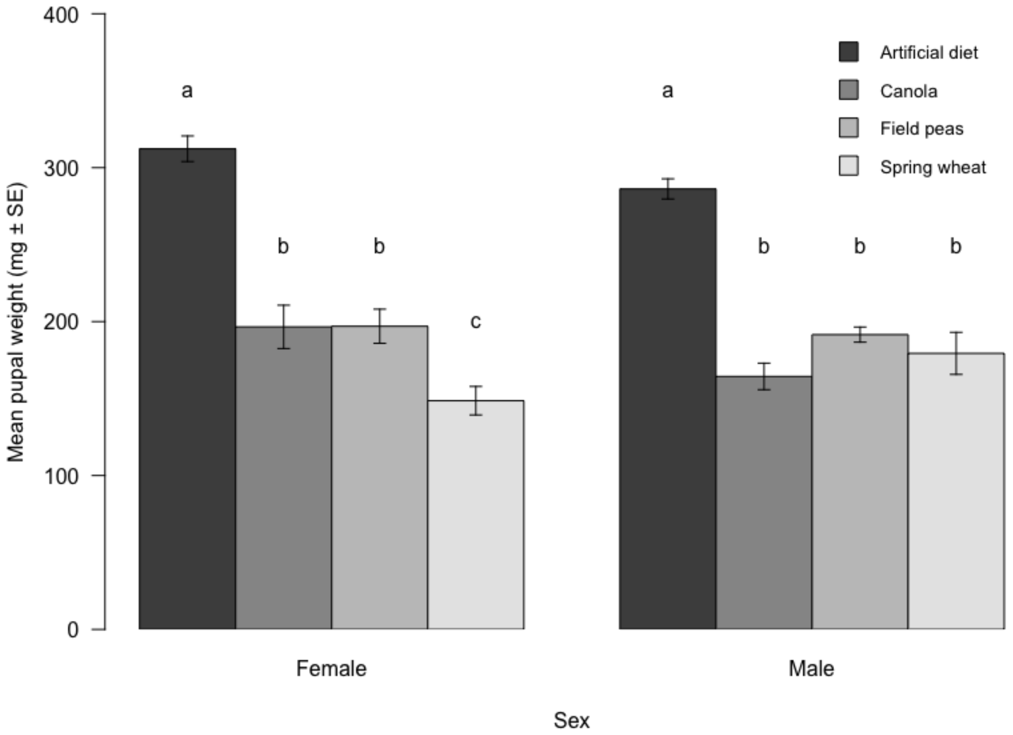

Figure 3-6. Redbacked cutworm (*Euxoa ochrogaster*) mean pupal weight (mg ± SE) by sex. Means comparison was performed for differences between food source treatment within sex. Bars marked with different letters within sex are statistically different (Tukey method, α = 0.05).

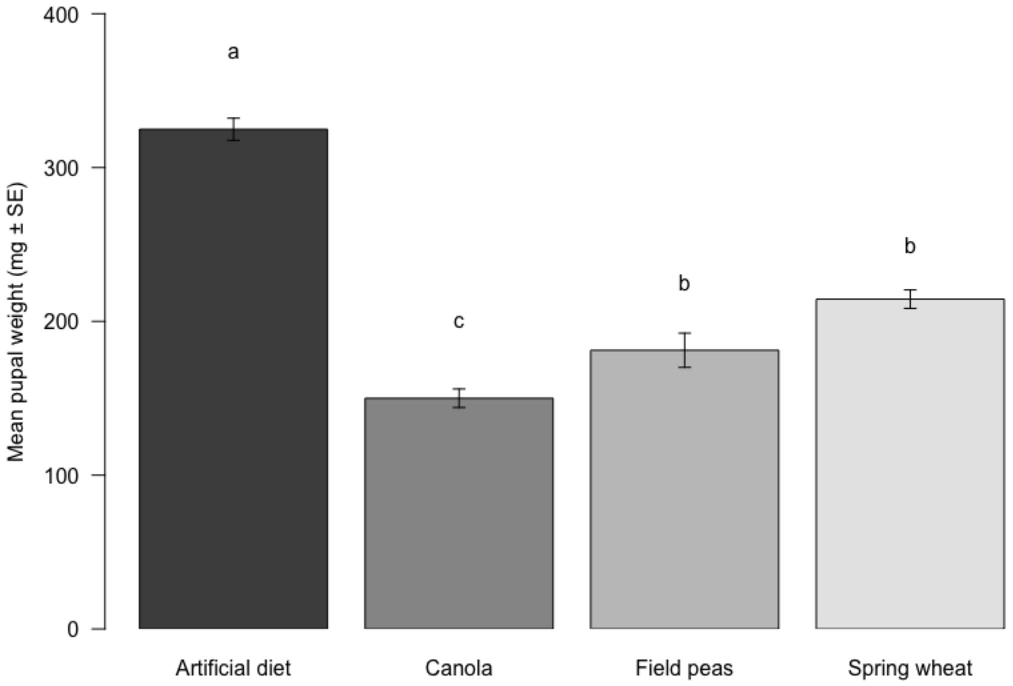

Figure 3-7. Pale western cutworm (*Agrotis orthogonia*) mean pupal weight (mg ± SE). There is no difference in weight between male and female individuals. Means comparison was performed for differences between food source treatment. Bars marked with different letters are statistically different (Tukey method, α = 0.05).

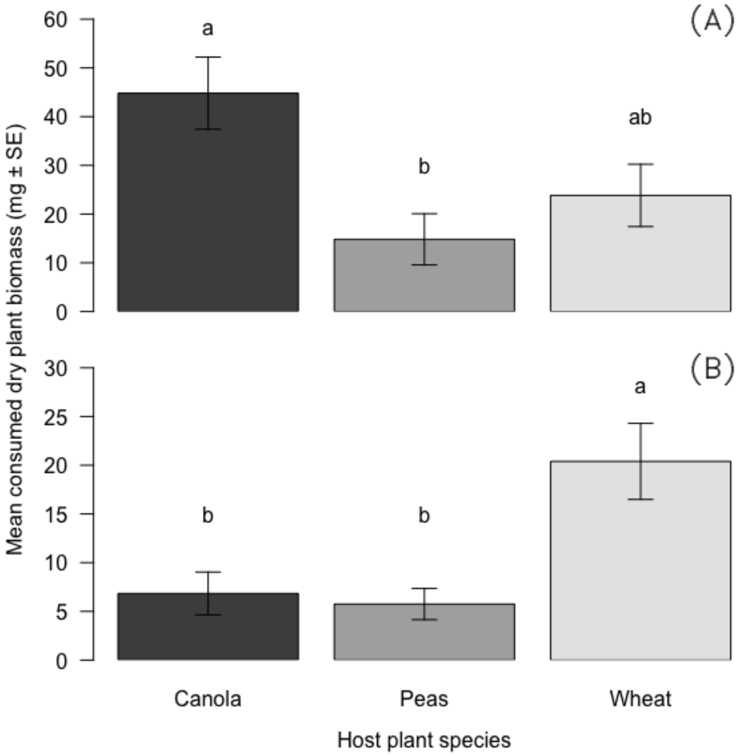

Figure 3-8. Cutworm larval feeding preference in three-way choice assays. Mean consumed dry plant biomass (mg ± SE) per crop species. **(A)** Redbacked cutworm (*Euxoa ochrogaster*) **(B)** Pale western cutworm (*Agrotis orthogonia*). Means comparison was performed for differences between crop species within cutworm species. Bars marked with different letters within species are statistically different (Tukey method, α = 0.05).

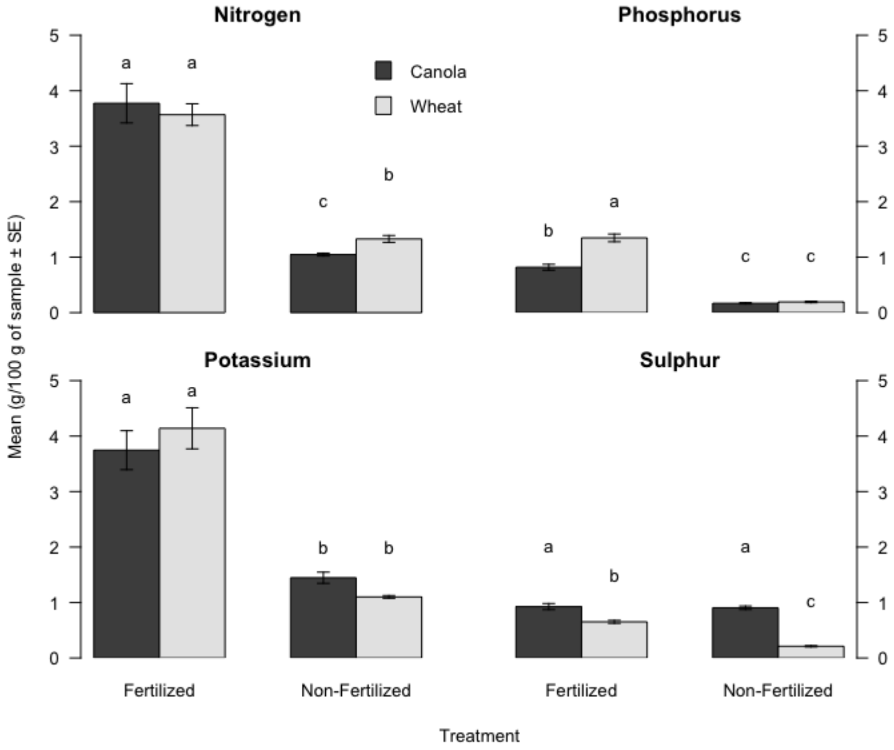

Figure 3-9. Mean nutrient concentration (g/100 g of sample ± SE) of above ground biomass of two crop species, Canola variety "Q2" and spring wheat variety "CDC GO", at two fertilizer levels, fertilized and non-fertilized. Seedlings were collected 21 days after sowing. Bars marked with different letters within each nutrient are statically different (Tukey method, α = 0.05).

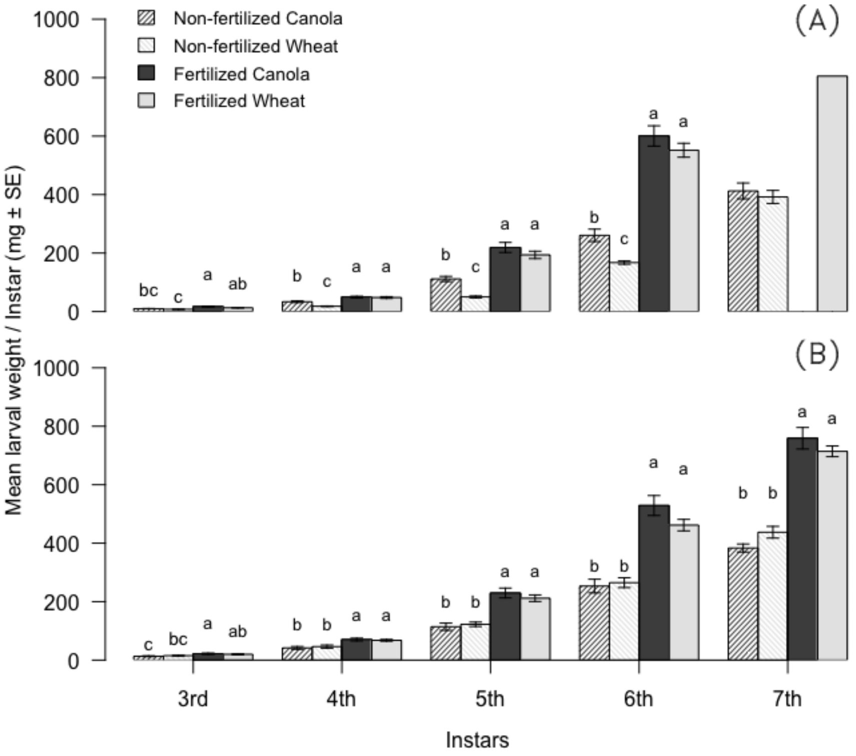

Figure 3-10. Mean larval weight (mg ± SE) per instar. **(A)** Redbacked cutworm (*Euxoa ochrogaster*) **(B)** Pale western cutworm (*Agrotis orthogonia*). Means comparison was performed between crop species × fertilizer treatment within each instar. Bars marked with different letters within each instar of each species are statistically different (Tukey method, α = 0.05).

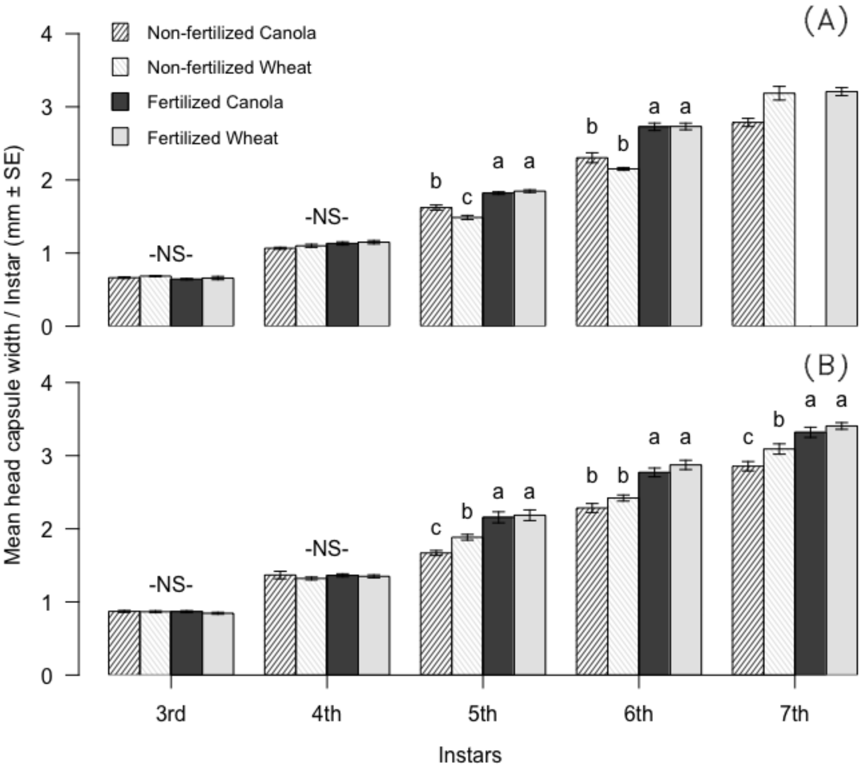

Figure 3-11. Mean head capsule width (mm ± SE) within each instar. **(A)** Redbacked cutworm (*Euxoa ochrogaster*) **(B)** Pale western cutworm (*Agrotis orthogonia*). Means comparison was performed between crop species × fertilizer treatment within each instar. Bars marked with different letters within each instar of each species are statistically different (Tukey method, α = 0.05). -NS- represents no significant difference.

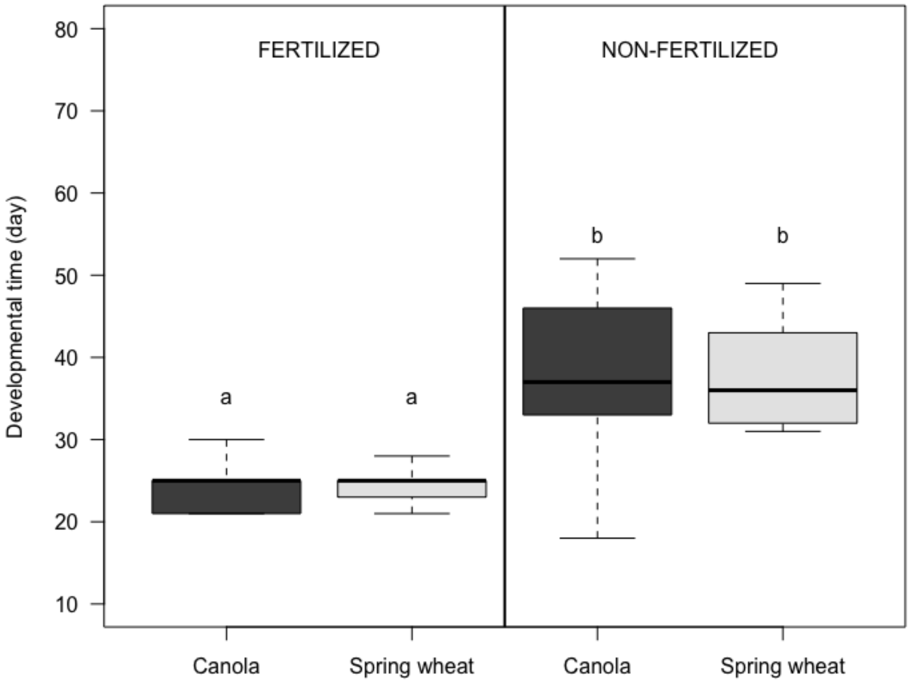

Figure 3-12. Boxplot of redbacked cutworm (*Euxoa ochrogaster*) larval developmental time (days), from third instar to pupation. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the maximum value or 1.5 interquartile range of the data. There is no difference in weight between male and female individuals. Means comparison was performed for differences between crop species × fertilizer treatment. Boxplots marked with different letters are statistically different (Tukey method, $\alpha = 0.05$).

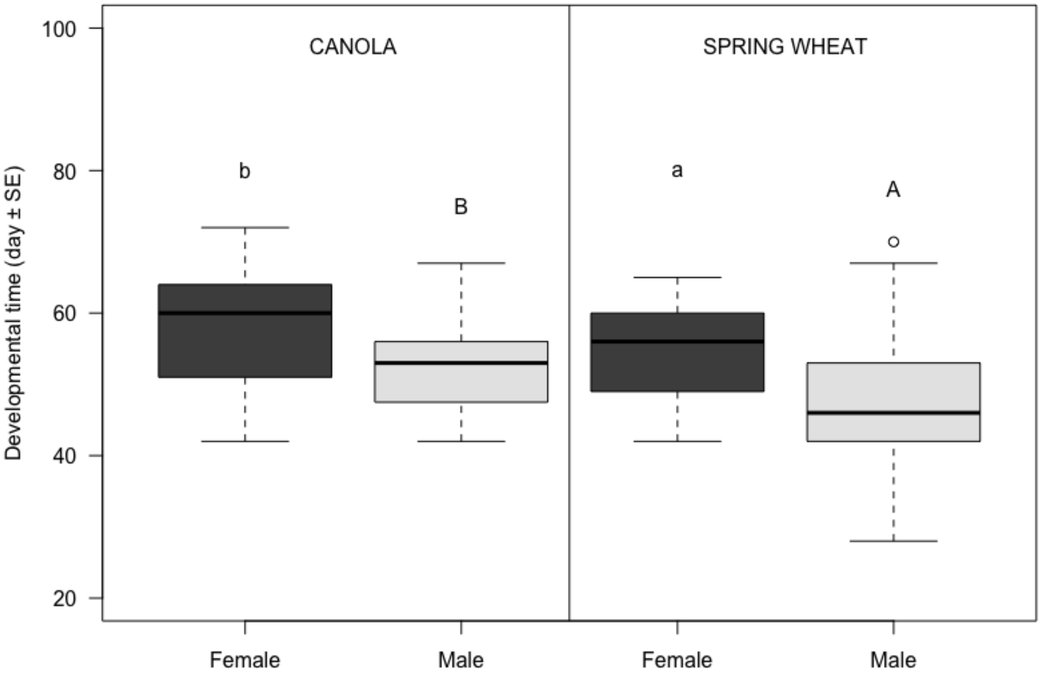

Figure 3-13. Boxplot of pale western cutworm (*Agrotis orthogonia*) larval developmental time from third instar to pupation. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the maximum value or 1.5 interquartile range of the data, and open circles represent points more than 1.5 times the interquartile range. Means comparison was performed for differences between sexes and crop species. Boxplots marked with different letters between crop species are statistically different (Tukey method, α = 0.05). Upper and lower case represent significant differences between sex within crop species (Tukey method, α = 0.05).

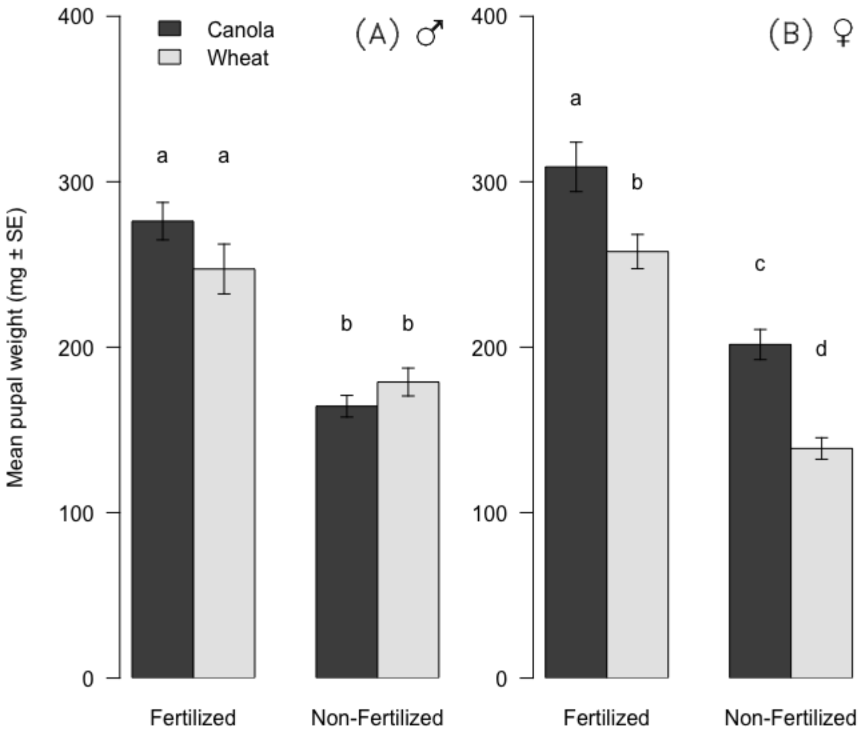

Figure 3-14. Redbacked cutworm (*Euxoa ochrogaster*) mean pupal weight (mg ± SE) by crop species and fertilizer treatment. **(A)** Males. **(B)** Females. Means comparison was performed for differences between crop species and fertilizer treatment. Bars marked with different letters within sex are statistically different (Tukey method, $\alpha = 0.05$).

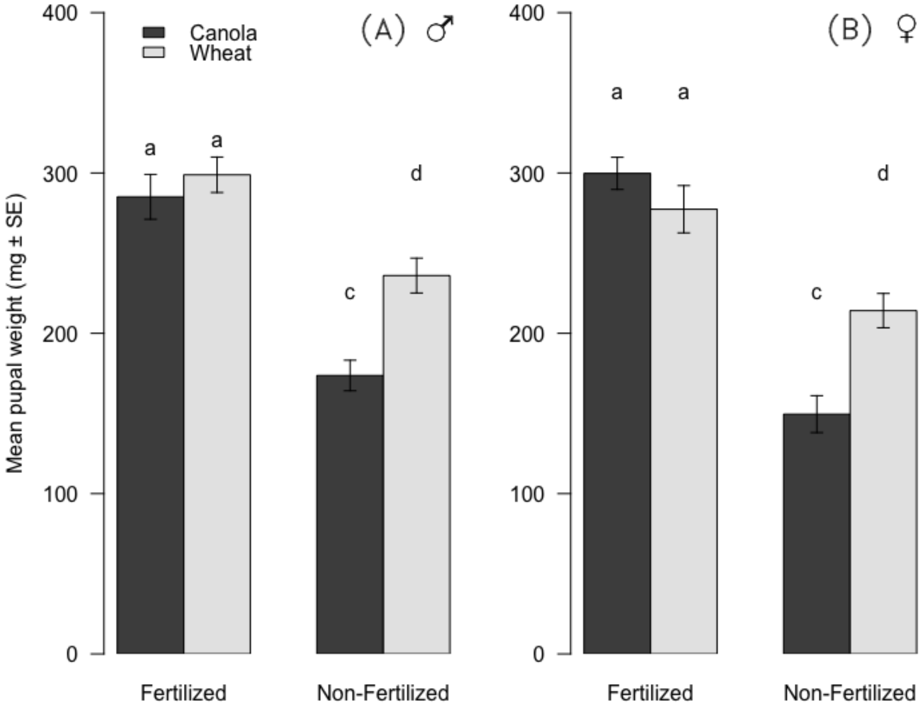

Figure 3-15. Pale western cutworm (*Agrotis orthogonia*) mean pupal weight (mg ± SE) by crop species and fertilizer treatment. **(A)** Males. **(B)** Females. Means comparison performed for differences between crop species and fertilizer treatment. Bars marked with different letters within sex are statistically different (Tukey method, $\alpha = 0.05$).

Table 3-1. Results of the optimal statistical models used in the several experiments to determine the influence of host plant species and fertilization regime on larval performance and feeding preference of the redbacked cutworm, *Euxoa ochrogaster*, and the pale western cutworm, *Agrotis orthogonia*, (Lepidoptera: Noctuidae).

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
1 Host Plant Species											
Plant nutrient analysis	Nitrogen	lm	N ~ Host	Host	F-value	36.2	2,15	< 0.001		10.5	35.7
	Phosphorus	lm	Ln (P) ~ Host	Host	F-value	6.97	2,15	0.007		3.5	11.3
	Potassium	lm	K ~ Host	Host	F-value	2.27	2,15	0.138		-10.6	-9.8
	Sulphur	lm	S ~ Host	Host	F-value	91.10	2,15	< 0.001		-35.9	6.4
RBC Larval performance	Larval weight	lmer	Ln (Weight) ~ Host + Sex + Instar + Host:Sex + Instar:Sex + (Instar|Larva ID)	Host	Wald χ^2	59.13	3	< 0.001	126.85	129.9	458.3
				Sex		3.78	1	0.052			
				Instar		10267.59	4	< 0.001			
				Host:Sex		13.29	3	0.004			
				Host:Instart		126.39	12	< 0.001			
	Head capsule	lmer	Ln (HC) ~ Host + Sex + Instar + Instar + Host:Insar + (Instar|Larva ID)	Host	Wald χ^2	6.18	3	0.003	-587.4	-566.0	-300
				Sex		0.00	1	0.945			
				Instar		10093.36	4	< 0.001			
				Host:Instart		71.89	12	< 0.001			
	Larval time	glm	Time ~ Host + Sex	Host	LR $\chi 2$	23.44	3	< 0.001	354.1	357.5	370.5
				Sex		1.54	1	0.215			
	Pupal weight	lm	Ln (Pupa) ~ Host + Sex + Host:Sex	Host	F-value	57.43	3,49	< 0.001		-43.2	31.2
				Sex		0.51	1,49	0.479			
				Host:Sex		2.97	3,49	0.040			

Table 3-1. (Continued).

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
1 Host Plant Species											
PWC Larval performance	Larval weight	lmer	Ln (Weight) ~ Host + Sex + Instar + Host:Sex + Instar:Sex + (Instar|Larva ID)	Host	Wald χ^2	287.77	3	< 0.001	-17.8	-1.1	473.7
				Sex		0.35	1	0.555			
				Instar		10878.92	4	< 0.001			
				Host:Sex		1.66	3	0.646			
				Host:Instart		150.90	12	< 0.001			
	Head capsule	lmer	Ln (HC) ~ Host + Sex + Instar + Instar + Host:Insar + (Instar|Larva ID)	Host	Wald χ^2	15.8	3	0.001	-1481.7	-1481.7	-1043
				Sex		0.33	1	0.565			
				Instar		14122.15	4	< 0.001			
				Host:Instart		347.33	12	< 0.001			
	Larval time	glm	Time ~ Host + Sex	Host	LR χ2	26.22	3	< 0.001	561	564.1	582.9
				Sex		1.16	1	0.282			
	Pupal weight	lm	(Pupa)$^{1/4}$ ~ Host + Sex	Host	F-value	122.89	3,80	< 0.001	-84.1	-85.3	54.4
				Sex		0.08	3,80	0.772			
2 Larval Preference											
RBC	Feeding choice	Chisq.test	.	.	Chisq	3.8	2	0.149	.	.	.
	Consumed mass	lmer	Consumed ~ Host + (1|Pot ID)	Host	Wald χ^2	11.51	2	0.003	.	886.4	905.7
PWC	Feeding choice	Chisq.test	.	.	Chisq	1.75	2	0.417	.	.	.
	Consumed mass	lmer	Consumed ~ Host + (1|Pot ID)	Host	Wald χ^2	17.65	2	< 0.001	.	574.0	595.0

Table 3-1. (Continued).

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
3 Fertilization Regimes											
Plant nutrient analysis	Nitrogen	lm	N ~ Host + Fertlizer + Host:Fertilizer	Host	F-value	10.52	1,20	0.004		-51.9	14.9
				Fertilizer		374.19	1,20	< 0.001			
				Host:Fertilizer		11.34	1,20	0.003			
	Phosphorus		Ln(P) ~ Host + Fertlizer + Host:Fertilizer	Host	F-value	23.65	1,20	< 0.001 .		-13.9	67.8
				Fertilizer		718.97	1,20	< 0.001			
				Host:Fertilizer		7.71	1,20	0.011			
	Potassium		K ~ Host + Fertlizer + Host:Fertilizer	Host	F-value	0.01	1,20	0.927	52.4	52.2	90.5
				Fertilizer		105.03	1,20	< 0.001			
	Sulphure		S ~ Host + Fertlizer + Host:Fertilizer	Host	F-value	192.79	1,20	< 0.001		-44.3	14.1
				Fertilizer		43.79	1,20	< 0.001			
				Host:Fertilizer		36	1,20	< 0.001			
RBC Larval Performance	Larval weight	lmer	Ln (Weight) ~ Host + Fertilizer + Sex + Instar + Host:Fertilizer + Host:Sex + Fertilizer:Sex + Host:Instar + Fertilizer:Instar + Sex:Instar + Host:Fertilizer:Instar + (Instar|Larva ID)	Host	Wald χ^2	28.85	1	< 0.001	271.9	281.9	815.2
				Fertilizer		282.68	1	< 0.001			
				Sex		0.00	1	0.951			
				Instar		8855.88	3	< 0.001			
				Host:Fertilizer		11.09	1	< 0.001			
				Host:Sex		0.27	1	0.601			
				Fertilizer:Sex		0.80	1	0.372			
				Host:Instar		4.38	3	0.223			
				Fertilizer:Instar		50.60	3	< 0.001			
				Sex:Instar		13.12	3	0.004			
				Host:Fertilizer:Instar		8.98	3	0.029			

Table 3-1. (Continued).

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
3 Fertilization Regimes											
RBC Larval Performance	Head capsule	lmer	Ln (HC) ~ Host + Fertilizer + Sex + Instar + Host:Fertizer + Host:Sex + Fertilizer:Sex + Host:Instar + Fertilizer:Instar + Sex:Instar + Host:Fertilizer:Instar + (Instar|Larva ID)	Host	Wald χ^2	0.45	1	0.500	-811	-808.5	-314.4
				Fertilizer		20.52	1	< 0.001			
				Sex		0.08	1	0.775			
				Instar		13432.45	3	< 0.001			
				Host:Fertilizer		2.31	1	0.129			
				Host:Sex		0.01	1	0.932			
				Fertilizer:Sex		1.28	1	0.258			
				Host:Instar		16.16	3	0.001			
				Fertilizer:Instar		124.06	3	< 0.001			
				Sex:Instar		1.74	3	0.627			
				Host:Fertilizer:Instar		15.18	3	0.002			
	Larval time	glm	Time ~ Host + Sex + Fertilizer	Host	LR χ2	0.13	1	0.712	628	632.8	774.6
				Sex		2.62	1	0.105			
				Fertilizer		147.24	1	< 0.001			
	Pupal weight	lm	Pupa ~ Host + Sex + Fertilizer + Host:Sex	Host	F-value	4.66	1,96	0.033	1036.2	1037	1139.2
				Sex		4.53	1,96	0.036			
				Fertilizer		175.55	1,96	< 0.001			
				Host:Sex		7.38	1,96	0.007			

Table 3-1. (Concluded).

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
3 Fertilization Regimes											
PWC Larval Performance	Larval weight	lmer	Ln (Weight) ~ Host + Fertilizer + Sex + Instar + Host: Fertilizer + Fertilizer:Instar + (Instar|Larva ID)	Host	Wald χ^2	0.03	1	0.862	-3.4	33.2	501.7
				Fertilizer		158.74	1	< 0.001			
				Sex		0.43	1	0.501			
				Instar		10402.46	4	< 0.001			
				Host:Fertilizer		5.17	1	0.023			
				Fertilizer:Instar		21.78	4	< 0.001			
	Head capsule	lmer	Ln (HC) ~ Host + Fertilizer + Sex + Instar + Host:Fertizer + Host:Sex + Fertilizer:Sex + Host:Instar + Fertilizer:Instar + Sex:Instar + Host:Fertilizer:Instar + (Instar|Larva ID)	Host	Wald χ^2	0.22	1	0.636	-895	-890.9	-365.2
				Fertilizer		2.64	1	0.104			
				Sex		0.00	1	0.971			
				Instar		20287.46	4	< 0.001			
				Host:Fertilizer		0.11	1	0.741			
				Host:Sex		0.11	1	0.743			
				Fertilizer:Sex		9.66	1	0.002			
				Host:Instar		21.00	4	< 0.001			
				Fertilizer:Instar		155.79	4	< 0.001			
				Sex:Instar		9.12	4	0.058			
				Host:Fertilizer:Instar		13.09	4	0.011			
	Larval time	glm	Time ~ Host + Fertilizer + Sex	Host	LR χ2	6.64	1	0.009	649.1	655.9	669.1
				Fertilizer		3.12	1	0.07			
				Sex		14.29	1	< 0.001			
	Pupal weight	lmer	Pupa ~ Host + Fertilizer + Sex + Host:Fertilizer	Host	F-value	5.27	1,86	0.024	937.6	939.9	1018.7
				Fertilizer		121.71	1,86	< 0.001			
				Sex		1.29	1,86	0.259			
				Host:Fertilizer		14.49	1,86	< 0.001			

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Chapter 4: Development of a general food bait lure for monitoring cutworm and armyworm moths (Lepidoptera: Noctuidae) in the Canadian Prairies

Abstract

Cutworms and armyworms (Lepidoptera: Noctuidae) are a pest complex native to North America that affect multiple annual crops grown across the Canadian Prairies. Outbreak infestations result in destruction of entire fields and yield loss, however, no methods reliably monitor population densities. Food-based semiochemicals to monitor multiple cutworm species possess an advantage over sex-pheromone lures, as they attract both male and female moths. The microbial volatile organic compounds acetic acid and 3-methyl-1-butanol (AAMB) attract adult moths of several noctuid pests, however, AAMB caught few cutworm moths in previous field experiments conducted in Alberta. The objective of this study is to enhance the attractiveness of food bait lures to attract and monitor redbacked cutworm, the most common cutworm pest in the Canadian Prairie Provinces. In an effort to enhance the attractiveness of AAMB lures, I test: 1) different release rates of AAMB released from different devices; and 2) the addition of other food-based semiochemicals to the AAMB lures. I also evaluate the attractiveness of volatile compounds released from Canada thistle as a potential lure to monitor noctuid pests; and 4) the influence of moth physiological state on the response to food-based semiochemicals. Results focus on food bait lure development to efficiently monitor multiple cutworm moth species with a single lure and, with less native pollinator by-catch that occurs in sex pheromone-baited traps.

Introduction

The Canadian Prairies is a grassland ecosystem that has been highly modified by humans to support livestock production and crop cultivation (Shorthouse, 2010). Spring-sown annual crops and perennial forage under intensive farming practices dominate the agroecosystems in the Canadian Prairies, and therefore, these ecosystems are in a constant state of disturbance on an annual basis (Vankosky et al., 2017). Agronomic practices have a strong impact on insect community structure, and variation in population density of certain herbivores may increase crop vulnerability to pest outbreaks (Shennan, 2008). Integrated Pest Management (IPM) programs bring an applied ecological approach to study and monitor crop pest complexes in order to prevent them from reaching economic injury levels. The foundation for any IPM program is to implement efficient sampling tools to detect changes in population densities of multiple pests (Kogan, 1998).

Cutworms and armyworms (Lepidoptera: Noctuidae) are part of a pest complex native to North America that can cause economic damage to multiple annual crops grown across the Canadian Prairies (Beirne, 1971, Floate, 2017). Both larvae and adults are generalist herbivores on a wide range of hosts in several different plant families (Beirne, 1971). Adult cutworms and armyworms are large, robust-bodied moths that are able to disperse over long distances (McNeil, 1987, Showers et al., 1989, Hendrix III and Showers, 1992). Larval feeding at low population densities results in crop thinning, however, outbreaks can cause complete destruction of fields and yield loss (Beirne, 1971). Sporadic outbreaks have been reported for several species, including the army cutworm (*Euxoa auxiliaris* Grote) (Byers et al., 1993), bertha armyworm (*Mamestra configurata* Walker) (Mason et al., 1998), the true armyworm (*Mythimna unipuncta* [Haworth]) (Guppy, 1961) and the glassy cutworm (*Apamea devastator* [Brace]) (Dosdall et al., 2000). Within these agroecosystems, the redbacked cutworm, *Euxoa ochrogaster* (Guenée), and the pale western cutworm, *Agrotis orthogonia* Morrison, are the most common species with localized outbreaks across the Canadian Prairie Provinces in canola and cereal crops (W.C.C.P., 2015, W.C.C.P., 2016). Infestation by two or more species may co-occur in the same field (Ayre and Lamb, 1990). Systematic monitoring of cutworm and armyworm populations in high and low population phases is needed to detect and predict population surges.

Female-produced sex pheromones have been identified for most cutworm and armyworm pest species found in the Canadian Prairies (Steck et al., 1982b). Monitoring programs using synthetic sex pheromone-baited traps were implemented across the Prairie Provinces in the 1980s; however, these programs were not widely adopted because moth trap catch did not reflect crop damage (Byers and Struble, 1987, Ayre and Lamb, 1990). Furthermore, pheromone-based monitoring programs require individual traps for each species, which makes monitoring several pests costly by increasing the time spent to check traps and identify moth trap catch. Lastly, there is evidence for pollinator by-catch in lepidopteran sex-pheromone baited traps (Gross and Carpenter, 1991, Mori and Evenden, 2013, Spears et al., 2016). There are no reliable tools to monitor variation in density of most cutworm pest species in the Prairie Provinces.

Although multiple cues mediate plant-insect interactions, olfaction is perhaps the primary mechanism moths employ for host selection (Visser, 1988, Davis and Landolt, 2013). Cutworm and armyworm moths, like many Lepidoptera, use host plant volatiles for orientation towards food sources, and females may also use these volatiles to select oviposition sites (Schoonhoven et al., 2005). Furthermore, insects are sensitive to cues produced by microbes associated with their food sources and oviposition sites, referred to as microbial volatile organic compounds

(MVOC) (Davis et al., 2013). Microbes present in floral nectars and fruits produce MVOCs, which in combination with floral volatiles, can act synergistically to attract lepidopteran herbivores to their hosts (Herrera et al., 2008). For example, the chemical mixture of acetic acid, a by-product from fermented sugar, and phenylacetaldehyde, a floral volatile, attracts two noctuid moths (Lepidoptera: Noctuidae), the alfalfa looper, *Autorgrapha californica* (Speyer), and the armyworm *Spodoptera albula* (Walker) to baited traps (Landolt et al., 2013). The MVOC hypothesis states that microbial emissions serve as semiochemicals that provide cues regarding suitability and nutritional quality of hosts (Davis et al., 2013).

Food-based semiochemicals could monitor multiple cutworm and armyworm species using a single lure, as these cues attract both sexes of moths (Joyce and Lingren, 1998). Overall, food-based semiochemicals are classified into three groups: host plant volatiles, floral volatiles and MVOCs from fermented sugar. Few host plant volatile lures are commercially available to monitor moth pest flight activity or for pest control in attract-and-kill formulations (Light et al., 2001, Gregg et al., 2010). Host plant volatiles may not be important cues for generalist pests like the redbacked cutworm or the pale western cutworm, as females of both species oviposit in loose-dry soil under crop stubble or in fallow fields rather than on live plant material (Beirne, 1971). Lures baited with floral volatiles from several plants visited by noctuid moths as adult food sources have been used to monitor populations in field experiments (Cantelo and Jacobson, 1979, Landolt and Smithhisler, 2003). For instance, traps baited with phenylacetaldehyde captured soybean looper moths, *Chrysodeixis includens* (Walker) (Lepidoptera: Noctuidae), in cotton fields (Meagher Jr, 2001a). Likewise, traps baited with the floral blend of the butterfly bush (*Buddleja davidii* Franch) (Loganiaceae) captured high numbers of the cabbage looper, *Trichoplusia ni* (Hübner) (Lepidoptera: Noctuidae), and alfalfa looper moths (Guédot et al., 2008). Floral volatile baited traps, however, result in high pollinator by-catch and have not been adopted commercially to monitor noctuid moths (Meagher Jr and Mitchell, 1999, Landolt et al., 2007).

Fermented sugar baits were some of the first food-based semiochemicals used to monitor diversity of Lepidoptera (Utrio and Eriksson, 1977). Noctuidae, Geometridae, Tortricidae and Pyralidae are the major lepidopteran families attracted to these types of baits (El-Sayed et al., 2005). The most common MVOCs produced from fermented sugar baits are acetic acid, isoamyl alcohol (3-methyl-1-butanol) and isobutanol (2-methyl-1-propanol) (El-Sayed et al., 2005, Davis et al., 2013). Food-based semiochemical lures based on these volatile compounds attract both sexes of many species of noctuid moths (Tóth et al., 2010).

The chemical mixture of acetic acid and 3-methyl-1-butanol (AAMB) is attractive to several noctuid pests in multiple cropping systems, including the bertha armyworm (Landolt, 2000), the true armyworm (Landolt and Higbee, 2002) and the redbacked cutworm (Landolt et al., 2007). Preliminary field experiments with AAMB lures in Alberta, however, had low trap catch of target pest noctuids (unpublished data).

The objective of this study is to develop a food-based semiochemical lure to monitor the cutworm and armyworm pest complex in the Canadian Prairie agroecosystems. Our approach is to enhance the attractiveness of AAMB lures to the most common cutworm species across the prairies, the redbacked cutworm, in canola (*Brassica napus* L.) (Brassicaceae) and wheat (*Triticum aestivum* L.) (Poaceae) fields in Alberta. First, I determined the attractiveness of AAMB baited traps compared to unbaited traps and sex pheromone-baited traps. Second, I tested the attractiveness of AAMB lures at different release rates when it was released from different devices. Third, I measured the attraction of the AAMB lure in combination with additional food-based semiochemicals. Fourth, I evaluated the potential of the floral blend released by Canada thistle (*Cirsium arvense* L.) (Asteraceae) at different doses to attract the redbacked cutworm. Lastly, electrophysiological studies on the redbacked cutworm moth were conducted to understand the influence of moth physiological state on response to food-based semiochemicals.

To develop a successful IPM program for cutworm and armyworm pests in the Canadian Prairies, a monitoring system is required. This tool should monitor populations of multiple pest species with a single trap and lure and have minimal impact on native pollinators. Cutworms and armyworms are a good system to understand behavioural responses of generalist herbivores to food-based semiochemicals from an ecological perspective.

Materials and Methods

Study Area

A series of experiments to develop food-based monitoring tools for cutworms and armyworms were conducted between 2014 and 2016 in wheat and canola fields located in the Aspen Parkland Ecoregion of Alberta, Canada. The landscape in this region is characterised by extensive agricultural plains with discontinuous clusters of trembling aspen (*Populus tremuloides* Michx) (Salicaceae) and balsam poplar (*P. balsamifera* L.) trees (Shorthouse, 2010). Seven sites were selected for moth monitoring across central Alberta, dispersed over an area of approximately 7 350 km^2 throughout five counties (Table 4-2). Sites were separated by at least 20 km from other experimental sites. Each site consisted of a canola field paired with a wheat field, separated by at least 500 m. All experiments were conducted at the same seven sites each year. Due to crop rotation practices, a canola field in the first year was rotated to wheat in the second year and back to canola in the third year.

Lures

Two types of lures targeting cutworm and armyworm moths were used in all experiments: synthetic sex pheromone lures and custom-made food-based semiochemicals. Sex pheromone lures targeting different species of cutworm and armyworm moths were used in different experiments (Table 4-3). Sex pheromone blends for each of the target species were prepared and loaded onto pre-extracted red rubber septa; prepared by Contech Enterprise Inc. (Delta, BC). Food bait lures were prepared in the laboratory, following the methods of Landolt et al. (2007). The AAMB lure consisted of acetic acid and 3-methyl-1-butanol in a 50:50 by weight mixture [glacial acetic acid (99.7% purity) Fisher Scientific, Fair Lawn, NJ; 3-methyl-1-butanol (98.5% purity) Sigma Aldrich, St. Louis, MO]. The AAMB chemical mixture was dispensed into a 15 mL narrow-mouth Nalgene HDPE bottle (Thermo Scientific, Rochester, NY) with two cotton balls inserted at the bottom. Each bottle received 10 mL of AAMB chemical mixture. A 3.0 mm diameter hole drilled in the centre of the bottle cap allowed for release of volatiles.

Monitoring and moth identification

Non-saturating green universal moth traps (Unitrap, Contech Enterprise Inc. Delta, BC) were employed in all experiments. Traps were positioned 1.5 m above ground, spaced 25 m apart in a linear transect positioned approximately 5 m from the field edge. Unitraps were baited with either a sex pheromone or a food bait lure. Sex pheromone lures were placed inside baskets positioned under the roof of the unitrap, and were replaced every four weeks. Food bait lures were secured to the inside wall of the unitrap buckets with a twist-tie and were replaced every two weeks, based on the methods of Landolt et al. (2007). An insecticidal strip of Hercon Vaportape II (10% dichlorvos) (Hercon Environmental. Emigsville, PA) was placed inside the bucket of each trap to kill captured insects. Insecticidal strips were replaced every four weeks.

Insect trap catch was collected every week in plastic bags, labelled and frozen at – 20 ^{o}C until it was sorted and identified. In the laboratory, moth trap catch and Hymenoptera by-catch were separated from other arthropods. Moths were separated by sex and pinned. If noctuid moths were in poor condition (i.e. no scales on wings or missing body parts), genitalic dissections were performed following the methods by Hardwick (1950). To dissect the genitalia, abdomens were removed from moths and immersed in 1 mL potassium hydroxide solution (10 % KOH w/v) (Biosev, Frenchtown, NJ) in 1.8 mL glass vials (Fisher Scientific, Fair Lawn, NJ) for 48 hours to dissolve organs and fatty tissue. Moth genitalia were spread and mounted on cardstock (2.0 × 0.5 cm) with Euparal mounting medium (Bioquip Products Inc. Rancho Dominguez, CA). Moths were identified to species through wing maculation and/or morphological characters of genitalia following taxonomic keys from “The Moths of America North of Mexico” book series (Lafontaine, 1987, 1998, 2004, Lafontaine and Robert, 1991, Mikkola et al., 2009). Identifications were verified using comparisons with reference collections at the E. H. Strickland Entomological Museum (University of Alberta, Edmonton, AB).

Hymenoptera by-catch was categorized into two guilds: 1) pollinators, which grouped honeybees (*Apis mellifera* L.) (Apidae), bumblebees (*Bombus* spp.) (Apidae) and leaf-cutter bees (Megachilidae); and 2) vespids (Vespidae), which grouped the bald-faced hornet (*Dolichovespula maculata* L.), the blackjacket (*Vespula consobrina* Saussure) and the common aerial yellowjacket (*D. arenaria* Fabricius).

Pinned moths in the best conditions and mounted genitalia dissections from each identified species were selected as voucher specimens and deposited at the E. H. Strickland Entomological Museum, Department of Biological Sciences, University of Alberta, Edmonton.

Experiment 1 – Food bait (AAMB) lures

Experiment 1 evaluated the efficiency of the AAMB lure to monitor the flight activity and abundance of several cutworm and armyworm species. The number of redbacked cutworm (RBC), bertha armyworm (BAW), true armyworm (TAW) and army cutworm (ACW) captured in AAMB-baited traps was compared to capture in the respective sex pheromone-baited trap and in the unbaited control trap.

Unitraps were baited with either: RBC pheromone, BAW pheromone, TAW pheromone, ACW pheromone, AAMB lure or left unbaited (Table 4-3). The six baited traps were positioned in a linear transect, as described above, in random order in both canola and wheat fields at each of the seven sites. The experiment was conducted from 10 June to 10 October 2014. Sex pheromone-baited traps were deployed in the field according to the flight period of the target moth species (Table 4-3), while the AAMB- and unbaited traps remained in the field throughout the 17-week sampling period. The target moths: redbacked cutworm, bertha armyworm, true armyworm and army cutworm were identified to species and other cutworm and armyworm species were grouped as "other noctuid pest species". The remaining captured moths were considered as non-target Lepidoptera.

Statistical analyses were conducted on the total number of moths captured per baited trap over the sampling season. First, individual analyses on the total number of target moths captured in the AAMB-baited traps was compared to that in the unbaited traps and the respective sex pheromone-baited traps. To determine the response of the other noctuid pest species to AAMB lures, a separate analysis compared capture of all sex pheromone-, AAMB- and unbaited traps. Lastly, the response of hymenopterans to lures targeting cutworm-moths was analysed with individual tests conducted on pollinators and vespids that compared the total number captured in the differently baited traps.

For all analyses in Experiment 1, crop and lure type were specified as explanatory fixed variables and site as a random block factor (Table 4-1).

Experiment 2 – Effect of release rate of food bait (AAMB) lures

A second experiment tested the attractiveness of AAMB lure at different release-rates to the most abundant cutworm species determined in Experiment 1, the redbacked cutworm moth (RBC). Ten milliliters of the AAMB chemical mixture were loaded in Nalgene HDPE bottle, as previously described. Release rate was manipulated by the diameter of holes drilled in the center of the bottle cap. Three release-rates were tested: low (1.0 mm), standard (3.0 mm), and high (5.0 mm). Capture of RBC moths in traps baited with AAMB at different release rates was compared to that in unbaited control traps. The four traps were positioned in a linear transect in random order in both canola and wheat fields at each of the seven sites. The experiment was conducted from 10 June to 02 October, 2014. AAMB lures were weighed to the nearest 0.001 g (Balance model: XS105 DualRange, Mettler Toledo) before and after deployment in the field to estimate differences in release rates among treatments. The difference in weight (mg) was divided by the period lures were out in the field (14 days) to calculate an average release rate per day (mg/day). The difference in release rates among the lures was compared with a linear mixed model (Gaussian distribution) with the ‘lme’ command in the R package ‘nlme' v.3.1-117 (Pinheiro et al., 2014). The average release rate per day (mg/day) was square root transformed for normality and crop and release-rate treatments were specified as explanatory fixed variables, and site as random block factor in the model. Individual analyses were performed after each lure retrieval.

Moth trap catch in traps baited with the different release-rate treatments over the 16-week trapping period was analysed in two separate analyses, on the total noctuid moth trap catch and the total RBC captured. Crop, moth sex and release-rate treatment were specified as explanatory fixed variables and site was considered a random factor (Table 4-1).

Experiment 3 – Effect of release device of food bait (AAMB) lures

Experiment 3 tested the attractiveness of the AAMB emitted from different release devices on RBC capture. Release-device treatments included 10 mL of AAMB loaded into: 1) a Nalgene HDPE bottle, as previously described, with a 3.0 mm diameter hole in the bottle cap secured within the unitrap bucket. 2) a polyethylene bag (12.5 × 3.0 cm) (Contech Enterprise Inc, Delta, BC) with cellulose sponge (10.0 × 2.5 cm) (Contech Enterprise Inc, Delta, BC). Bags were hot-sealed with an impulse sealer (Midwest Pacific, Taiwan) and hung from the center of the unitrap lid. A third treatment consisted of a 10 g droplet of an inert matrix- Splat™, prepared by ISCA Technologies Inc. (Riverside, CA) loaded with AAMB (1:1 w:w), secured to the inside of the unitrap baskets. An unbaited trap served as a control. The four traps were positioned in a linear transect in random order only on canola fields at each of the seven sites. The experiment was conducted during the peak flight period of RBC, from 18 August to 15 September, 2015. All release devices were replaced every two weeks.

Following moth identification, trap catch from release-device treatments was summed over the 4-week trapping period. The total number of noctuid moths and total number of RBC moths captured in the variously baited traps were compared to test the attraction of AAMB released from different devices. Moth sex and release-device treatment were specified as explanatory fixed variables and site as random factor (Table 4-1).

Experiment 4 – Augmentation of AAMB lures with additional food-based semiochemicals

Experiment 4 evaluated the addition of other food-based semiochemicals to enhance the attraction of the AAMB (acetic acid + 3-methyl-1-butanol) lure to RBC. The tested chemicals were an alcohol from fermented sugar bait by-products, 2-methyl-1-propanol (MP) (> 99% purity) (Acros Organics, Fair Lawn, NJ), and a floral volatile, phenylacetaldehyde (PAA) (> 98% purity) (Acros Organics, Fair Lawn, NJ). Traps were baited with: AAMB alone, AAMB+MP, AAMB+PAA, AAMB+MP+PAA and an unbaited trap served as control. All lures were prepared in the laboratory in equal proportions by weight mixture. Ten millilitres of the chemical mixtures were loaded in Nalgene HDPE bottle, as previously described, with a 3.0 mm diameter hole in the bottle cap for release of the volatile chemical mixture. Bottles were secured to the inside wall of the unitrap bucket with a twist-tie and were replaced every two weeks. In addition to the different food bait lures, sex pheromone-baited traps targeting RBC, bertha armyworm (BAW), pale western cutworm (PWC) and true armyworm (TAW) were deployed to ensure target moths were present in the field at the time of the experiment (Table 4-3). The nine baited traps were positioned in a linear transect in random order in both canola and wheat fields at the seven sites. The experiment was conducted from 22 June to 15 September 2015.

Following moth identification, trap catch of the target moth species in the sex pheromone-baited traps was summed over the 12-week trapping period and analysed independently for each species. A separate analysis was conducted on the total number of RBC that compared trap catch in the traps baited with the different food bait lures (Table 4-1). Two analyses compared the total number of pollinators and vespids captured in traps baited with the various food-bait lures targeting cutworm-moths (Table 4-1).

Experiment 5 – Canada thistle floral volatiles

Experiment 5 tested the attractiveness of synthetic copies of Canada thistle floral volatiles at different doses to attract RBC. The floral scent of the Canada thistle is a blend of aromatic aldehydes and alcohol (Table 4-4). Treatments included traps baited with Canada thistle lures at different doses (0.1×, 1.0×, 2.0× and 4.0×) compared to phenylacetaldehyde alone (PAA) and the unbaited control trap (Table 4-4). The floral lures were dispensed in clear polyethylene bags (5.0 × 4.0 cm) with a piece of white felt (3.0 × 2.5 cm), which was hot sealed with an impulse sealer. Lures were prepared by collaborators at New Zealand Institute of Plant and Food Research (Chistchurch, New Zealand). Floral lures were placed inside the unitrap baskets while the control trap remain unbaited. To minimize *Bombus* spp. by-catch, the experiment was conducted from 02 August to 05 September 2016, when most bumblebee species have completed their life cycle in Alberta, Canada.

Following moth identification, trap catch was summed in each trap type over the 5-week trapping period. The total number of noctuid moths captured were compared to determine the attraction to Canada thistle lure. A second analysis compared the total number of RBC moths captured in the differently floral baited traps. In both analyses, moth sex and the floral lure treatments were specified as explanatory fixed variables and site was considered as a random block factor (Table 4-1). Lastly, a separate analysis compared pollinator by-catch in the variously baited traps to determine the attraction to Canada thistle lure at different doses. Floral lure treatments were specified as explanatory fixed variables and site was considered as a random block factor (Table 4-1).

Experiment 6 – Electrophysiological response of RBC to food bait volatiles

The antennal response plasticity of RBC to feeding attractants volatiles was evaluated for moths in different physiological conditions through electroantennogram recordings (EAG). The sex and feeding status (starved or fed) of RBC served as physiological treatments. Redbacked cutworm moths were obtained from a laboratory colony maintained on a pinto-based meridic diet (Chapter 2) under controlled conditions (Intellus Environmental Controller, Percival Scientific, Iowa, US) at 21 °C and a photo regime of 16:8 (light: dark). Recently eclosed moths were housed individually in 1000 mL plastic containers with either water or 10% sugar solution. Moths were separated by sex and housed in different growth chambers (Intellus Environmental Controller, Percival Scientific, Iowa, US) to avoid exposure of the males to female sex pheromone. Electroantennogram recordings were performed for 10 male and 10 female moths in each feeding group (n = 10 per treatment combination). Electroantennogram recordings were performed on RBC moths past the pre-oviposition period. Moths were 9-10 days old when EAG recordings were performed.

The feeding attractant volatiles presented to RBC antennae were acetic acid (AA) (99.7% purity) (Fisher, Fair Lawn, NJ), 3-methyl-1-butanol (MB) (98.5% purity) (Sigma Aldrich, St. Louis, MO) and phenylacetaldehyde (PAA) (98% purity) (Acros Organics, Fair Lawn, NJ). The chemicals were serially diluted in HPLC grade hexane (Fisher, Fair Lawn, NJ) to obtain six concentrations (µg/µL): 0.001, 0.01, 0.1, 1.0, 10.0 and 100.0. For each dilution, 50 µL was dispensed on a filter paper strip (0.2 × 7 cm) (Whatman® qualitative filter paper, Grade 1), placed within a disposable Pasteur pipette (14.6 cm, Borosilicate glass, Fisher, Fair Lawn, NJ), and allowed to evaporate in the fume hood for 30 minutes. In addition, 50 µL of hexane and a common plant volatile, (*E*)-2-hexenal (1 µg/µl) (> 95% purity) (Aldrich Chemical Co., WI, USA) were also dispensed on filter paper strips to serve as control and standard, respectively.

The EAG system consists of an IDAC-02 data acquisition controller system, a Syntech EAG probe (Type PRG-2, internal gain 10X), and EAG 2000 software (Syntech, Hilversum, The Netherlands). Moths were chilled at 4°C for five minutes before the right antenna was excised and attached to a stainless-steel antenna holder using Spectra 360 conductive gel (Parker Laboratories, Orange, NJ, USA). Carbon-filtered and humidified air, from a Syntech CS-55 stimulus controller, flowed at 50 ml/min over each mounted antenna. Stimulus puffs were triggered by hand via the stimulus controller with pulse duration of 0.2 s and a flow of 10 ml/sec. The three compounds were tested on each antenna in the same sequential order: First AA, followed MB and PAA last. The stimuli were applied to each antenna once per minute in ascending order of concentration, separated by the standard (i.e., hexane, plant volatile, 0.001 µg/µL tested compound, plant volatile, 0.01 µg/µL tested compound, plant volatile, 0.1 µg/µL tested compound, plant volatile, 1.0 µg/µL tested compound, plant volatile, 10.0 µg/µL tested compound, plant volatile, 100.0 µg/µL tested compound, plant volatile). Stimuli were replaced every three hours.

Independent analyses were conducted for each of the feeding attractant compounds tested. EAG responses were natural logarithm transformed [ln(x+1)] to meet assumptions of normality. EAG responses were analysed in a linear mixed model with random intercept and slope to account for the repeated measures on the same moth antenna with the 'lme' command in the R package 'nlme' v.3.1-117. Moth sex, feeding status and dose of the stimulus were specified as explanatory fixed variables (Table 4-1). Dose of the stimulus was also specified as the random intercept and the antenna identification number was considered as the random slope (~ Dose | Antenna ID) (Table 4-1).

Statistical Analyses

For all field experiments, data were tested for normality and heteroscedasticity using visual techniques and the Shapiro-Wilks test. Generalized linear mixed models with Poisson family distribution were used to analyze trap catch data due to properties of count data, which are bounded to zero, and non-normality of errors (Crawley, 2012). A negative binomial family distribution was specified in models, instead of Poisson, when trap catch data was over-dispersed (Zuur et al., 2009). Models were fitted as "full models" at first, in which the fixed component of the models included the main effect of all relevant explanatory variables and all possible interactions. Generalized linear mixed models were analysed with the 'glmer' command, for Poisson distribution, or 'glmer.nb' command, for negative binomial distribution, in the R package 'lme4' v.1.1-17 (Bates et al., 2015). For all statistical analyses, model simplification was performed in step-wise *a posteriori* procedure by removing non-significant interaction terms and comparing nested models through Likelihood-ratio chi-square test with the 'anova' command in R package 'car' v.3.0-0 (Fox and Weisberg, 2011). The optimal model was selected using Akaike's information criterion (AIC). Test statistic values, degree of freedom numbers and p-values were obtained from the 'Anova' function in R package 'car' v.3.0-0 (Fox and Weisberg, 2011). The 'Anova' function produces analysis of variance tables from models created by 'lme', 'glmer' or 'glmer.nb' commands. Wald chi-square (Wald χ^2) tests are calculated for linear mixed models and Likelihood-ratio chi-square (LR χ^2) are calculated for generalized linear mixed models. Means comparison for all experiments was performed using Tukey method ($\alpha = 0.05$) with 'lsmeans' package v.2.17 (Lenth and Hervé, 2015). All statistical analyses were conducted using the freely available statistical package ‘R v.3.5.0’ in ‘RStudio v0.98.’ (http://www.rstudio.com).

Results

Experiment 1 – Food bait (AAMB) lures

The RBC was the most abundant pest noctuid species captured across all trapping sites. Peak RBC flight activity occurred from 12 August to 10 September 2014 (Figure 4-1A). Baited traps captured similar numbers of RBC moths in canola and wheat fields (Wald $\chi^2 = 2.02$; df = 1; p = 0.154). Redbacked cutworm moth trap catch differed by lure type (Wald $\chi^2 = 822.92$; df = 2; $p < 0.001$). More RBC moths were captured in traps baited with the RBC pheromone lure than in traps baited with AAMB or in unbaited traps. More RBC moths were captured in AAMB-baited than unbaited traps (Figure 4-1B). Although RBC pheromone-baited traps had high trap catch in 2014, infestations were not reported by the farmers in 2015.

Peak flight of BAW ranged from 30 June to 22 July, 2014 (Figure 4-2A). Similar numbers of BAW moths were captured in traps positioned in canola and wheat fields (Wald $\chi^2 = 0.10$; df = 1; p = 0.748). Bertha armyworm moths were only caught the BAW pheromone-baited trap, and no BAW were found in AAMB or the unbaited control traps (Wald $\chi^2 =131.13$; df=2; $p < 0.001$) (Figure 4-2B).

Only low numbers of TAW were captured at all sites, but more TAW were recovered from traps in wheat than in canola fields (Wald $\chi^2 = 11.57$; df = 1; $p < 0.001$). Lure type affected the catch of TAW (Wald $\chi^2 =11.28$; df = 2; p = 0.003), as traps baited with either pheromone or AAMB similarly caught more TAW than unbaited traps (Figure 4-3A). The TAW does not overwinter in Canada and infestations result from immigrating moths in the early summer (Fields and McNeil, 1984). The immigrating-moths mate and produces a summer-generation in early fall. There were two peaks of TAW captured in baited traps throughout the season (Figure 4-3B), which suggests two flight periods in the Canadian Prairies. Interestingly, TAW moths responded differently to the tested lures depending on the generation of moth. Immigrating moths were attracted to pheromone-baited traps in early summer, while summer-generation moths were attracted to AAMB lure-baited traps in early fall.

No ACW were found in AAMB or unbaited traps, and the ACW pheromone-baited traps caught extremely low numbers (1 – 4 at three sites throughout the trapping period). There was no difference in ACW trap catch in the variously baited traps.

Only eleven percent of moth trap catch in the AAMB-baited traps consisted of the target moth species, while approximately 30 % consisted of other cutworm and armyworm species (Table 4-5). This group of other noctuid pest species occurred in higher numbers in the AAMB-baited traps than in the unbaited control traps or traps baited with sex pheromone of the target species, with the exception of the TAW sex pheromone trap (Figure 4-4) (Wald $\chi^2 = 175.10$; df = 5; $p < 0.001$). Trap catch in the ACW sex pheromone-baited traps was dominated by one non-target species, the clover cutworm (*Anarta trifolii* [Hugnagel]). Abundant pest species in the AAMB lure-baited traps were strawberry cutworm (*Amphipoea interoceanica* Smith), dingy cutworm (*Feltia jaculifera* [Guenée]) and the glassy cutworm (*Apamea devastator* [Brace]).

Baited traps captured the highest number of pollinators in early summer, from 10 June to 15 July, 2014 (Figure 4-5A). A similar number of pollinators was captured in baited traps in canola and wheat fields (Wald $\chi^2 = 3.04$; df = 1; $p = 0.081$), however, lure type significantly influenced pollinator by-catch (Wald $\chi^2 = 40.76$; df = 4; $p < 0.001$). More pollinators were captured in the various sex pheromone-baited traps compared to AAMB lure- and unbaited traps (Figure 4-5B).

Traps captured the highest number of vespids in mid-summer, from 15 July to 10 September (Figure 4-6A). Vespids were found in equal numbers in baited-traps in canola and wheat fields (Wald $\chi^2 = 1.63$; df = 1; $p = 0.200$). Vespid by-catch was influenced by lure type (Wald $\chi^2 = 40.76$; df = 4; $p < 0.001$). In contrast to the pollinator response to lures, vespid wasps were attracted to AAMB lure-baited traps compared to the unbaited and sex pheromone-baited traps (Figure 4-6B).

Experiment 2 – Effect of release rate of food bait (AAMB) lures

The average release rate (mg/day) fluctuated with treatment across dates. This fluctuation across dates can be attributed to the influence of weather throughout the sampling period. The average release rate differed by treatment on each date (24-Jun: $F_{2,30} = 69.84$; 08-Jul: $F_{2,30} = 50.84$; 22-Jul: $F_{2,30} = 63.69$; 05-Aug: $F_{2,30} = 109.32$; 18-Aug: $F_{2,30} = 113.25$; 02-Sep: $F_{2,30} = 45.39$; 16-Sep: $F_{2,30} = 20.11$; 02-Oct: $F_{2,30} = 18.90$) (for all dates: p-value < 0.001). The high release rate AAMB lures had a higher average release rate than the standard or low release rate AAMB lures (Figure 4-7). The standard AAMB lure had a higher average release rate than the low release rate AMMB lure from 24 June to 18 August, however both treatments had equal average release rates at the end of the season from 02 September to 02 October (Figure 4-7). The release rates did not differ by trap placement in either canola or wheat fields.

Overall, traps baited with AAMB lures at different release-rates captured more noctuid moths than unbaited traps. Furthermore, AAMB lures captured overall more noctuid moths in wheat fields than in canola (Wald $\chi^2 = 51.150$; df = 1; $p < 0.001$); and a larger number of male noctuid moths were attracted to AAMB lures than females (Wald $\chi^2 = 111.709$; df = 1; p <

0.001). The effect of the release-rate treatment on noctuid moth trap catch depended on interactions with moth sex (release-rate × moth sex; Wald $\chi^2 = 10.09$; df = 3; p-value = 0.01) and crop (release rate × crop; Wald $\chi^2 = 23.46$; df = 3; $p < 0.001$). Male noctuid moths were captured in similar numbers in traps baited with different release-rate treatments in canola fields, whereas low release-rate lures attracted more male noctuid moths than high-release rate lures in wheat fields (Figure 4-8). In contrast, female noctuid moth capture did not differ with release rate treatment in wheat fields, but more females were captured in traps baited with the high release rate lures in canola fields (Figure 4-8).

Traps baited with AAMB lures captured more RBC in wheat fields than canola (Wald $\chi^2 = 19.96$; df = 1; $p < 0.001$); and more RBC females were attracted to AAMB lures than males (Wald $\chi^2 = 18.67$; df = 1; $p < 0.001$). Traps baited with AAMB lures captured more RBC moths than unbaited traps (Wald $\chi^2 = 30.827$; df = 1; $p < 0.001$), however, RBC moths captured was similar among traps baited with different release rates of AAMB (Figure 4-9).

Experiment 3 – Effect of release device of food bait (AAMB) lures

Overall, traps baited with AAMB lures in different release devices captured more noctuid moths than unbaited traps. The effect of the release device on total noctuid moth trap catch was dependent on moth sex (release device × moth sex; Wald $\chi^2 = 9.95$; df = 3; p = 0.01). Traps baited with Splat™ captured the highest number of male noctuid moths, while the polyethylene bag and Nalgene bottle lures attracted a similar number of male noctuid moths (Figure 4-10). Splat™ baited traps captured the highest number of female noctuid moths, followed by the polyethylene bag-baited traps and lastly traps baited Nalgene bottles lures (Figure 4-10).

Male and female RBC were captured in similar numbers in traps baited with the different release devices (Wald $\chi^2 = 2.94$; df = 1; p = 0.08). Release device had a significant effect on

RBC trap catch (Wald $\chi^2 = 30.827$; df = 1; $p < 0.001$). The traps baited with Splat™ captured significantly more RBC compared to traps baited with the Nalgene bottles lures, while polyethylene bag captured RBC in similar numbers to both release devices (Figure 4-11).

Experiment 4 – Augmentation of AAMB lures with additional food-based semiochemicals

True armyworm moths were not captured in the traps baited with sex pheromone, food bait lures or in unbaited traps in Exp. 4, and thus, were considered absent from monitoring sites in 2015. Redbacked cutworm, BAW and PWC were captured in high numbers in traps baited with their respective sex pheromones in 2015 (Figure 4-12). More RBC and BAW were captured in canola than wheat fields (RBC: Wald $\chi^2 = 1038.5$; df = 1; $p < 0.001$; BAW: Wald $\chi^2 = 170.8$; df = 1; $p < 0.001$), while similar numbers of PWC were captured in both crops (Wald $\chi^2 = 0.38$; df = 1; $p = 0.536$).

The additional chemical compounds added to augment the AAMB lure had a significant effect on RBC trap catch (Wald $\chi^2 = 56.94$; df = 4; $p < 0.001$), and this response differed between crops (food bait lure × crop, Wald $\chi^2 = 10.74$; df = 4; $p = 0.029$). Overall, baited traps captured more RBC than unbaited traps. All traps baited with the various food bait lures captured a similar number of RBC in canola fields (Figure 4-13). Conversely, traps baited with food bait lures containing the additional alcohol captured more RBC than food bait lures with floral volatiles in wheat fields. Traps baited with AAMB plus 2-mehtyl-1-propanol (AAMB+MP) and AAMB alone captured the highest numbers of RBC, followed by AAMB plus phenylacetaldehyde (AAMB+PAA), and lastly the four-component food bait lure (AAMB+MP+PAA) (Figure 4-13).

Response of RBC moths to the different food bait lures also varied with moth sex (food bait lure × moth sex, Wald $\chi^2 = 27.61$; df = 4; $p < 0.001$). Traps baited with the AAMB+MP lures captured significantly more female RBC than traps baited with the four-component lure (AAMB+MP+PAA). Female RBC trap catch was intermediate in traps baited with the AAMB lure alone and AAMB+PAA (Figure 4-14). In contrast, male RBC capture was similar in traps baited with AAMB alone, AAMB+MP and AAMB+MP+PAA lures. Traps baited with food bait lures and floral volatiles, AAMB+PAA and the four-component lure, AAMB+MP+PAA, had lower male RBC trap catch that did not differ from trap catch in the unbaited control traps (Figure 4-14).

The additional chemical compounds also influenced hymenopteran by-catch. More pollinators were captured in baited traps positioned in canola than wheat fields (Wald $\chi^2 = 9.45$; df = 1; p = 0.002). Pollinator responses differed with lure type (Wald $\chi^2 = 85.68$; df = 8; $p < 0.001$). More pollinators were captured in sex pheromone-baited traps compared to unbaited traps and traps baited with food bait lures (AAMB alone and AAMB+MP). The addition of phenylacetaldehyde to AAMB lures, however, attracted pollinators. Traps baited with food bait lures with the floral volatiles, AAMB+PAA and the four-component lure AAMB+MP+PAA, had similar levels of hymenopteran by-catch to that of sex pheromone-baited traps (Figure 4-15). Vespid wasps were found in equal numbers in baited-traps in canola and wheat fields (Wald $\chi^2 = 0.06$; df = 1; p = 0.794). Vespid by-catch was influenced by lure type (Wald $\chi^2 = 542.0$; df = 8; $p < 0.001$). In contrast to the pollinator response, a higher number of vespids were captured in traps baited with food bait lures alone and containing the additional alcohol from fermented by-products, AAMB and AAMB+MP, than in traps with food bait lures and floral volatiles, AAMB+PAA and the four-component lure AAMB+MP+PAA (Figure 4-16). Sex pheromone traps and unbaited traps had the lowest vespid wasp by-catch.

Experiment 5 – Canada thistle floral volatiles

More male noctuid moths were attracted to Canada thistle lures than female moths (Wald $\chi^2 = 24.44$; df = 1; $p < 0.001$). Furthermore, the total number of noctuid moths captured varied by dose of the Canada thistle volatiles (Wald $\chi^2 = 196.36$; df = 5; $p < 0.001$). More noctuid moths were captured in traps baited with the high dose Canada thistle lures (2.0× and 4.0×) than the low dose lures (0.1× and 1.0×), phenylacetaldehyde (PAA) and the unbaited control (Figure 4-17).

Both male and female RBC moths were equally attracted to the Canada thistle lures regardless of the dose (Wald $\chi^2 = 1.40$; df = 1; $p = 0.236$). Canada thistle lure dose had an effect on RBC trap catch (Wald $\chi^2 = 57.90$; df = 5; $p < 0.001$). A similar number of RBC moths were captured in traps baited with Canada thistle lures at 1.0×, 2.0×, 4.0× and phenylacetaldehyde alone, while trap catch in traps baited with Canada thistle lures at the lowest dose (0.1×) was not different from that in the unbaited traps (Figure 4-18).

The Canada thistle lure experiment was conducted in the late summer to minimize bumblebee by-catch. A low number of *Bombus* spp. was captured in all traps. The most abundant pollinator by-catch in the Canada thistle lure-baited traps were honey bees and their response was dependent on lure dose (Wald $\chi^2 = 101.37$; df = 5; $p < 0.001$). Most honeybees were captured in traps baited with the highest doses of the Canada thistle lure (2.0× and 4.0×), followed by the standard concentration (1.0×). Although traps baited with phenylacetaldehyde lures alone had the same concentration of phenylacetaldehyde as the 2.0× Canada thistle lure, they captured a low number of honey bees equal to that of traps baited with the 0.1× Canada thistle lure and the unbaited trap (Figure 4-19)

Experiment 6 – Electrophysiological response of RBC to food bait volatiles

Feeding status did not influence EAG response of RBC moths to acetic acid ($F_{1,35}$ = 0.284, p = 0.597). Males had a higher EAG response to acetic acid than females ($F_{1,35}$ = 4.71, p = 0.036). Dose had a strong effect on EAG response ($F_{6,210}$ = 562.62, $p < 0.001$). Responses to the lower doses of acetic acid (0.001, 0.01 and 0.1 µg/µL) did not differ from hexane, while significant responses were elicited to the higher doses of acetic acid. The 100.0 µg/µL dose had the highest EAG response, followed by 10.0 and 1.0 µg/µL (Figure 4-20A & B).

The influence of feeding status on EAG response to 3-methyl-1-butanol was dependent on RBC sex (feeding × sex, $F_{2,35}$ = 6.52, p-value = 0.015). There were no differences in EAG response between fed or unfed male RBC, regardless of the dose (Figure 4-20D). Fed female RBC had higher EAG responses than unfed females, regardless of the dose (Figure 4-20C). Dose had a strong effect on EAG response ($F_{6,210}$ = 346.94, $p < 0.001$), and this effect was dependent on moth sex (dose × sex, $F_{6,210}$ = 7.697, $p < 0.001$). Response to the lower doses (0.001, 0.01 and 0.1 µg/µL) were not different from hexane, while higher doses elicited a significant response. Female antennae had the highest response to the 100.0 µg/µL dose, followed by 10.0 and 1.0 µg/µL (Figure 4-20C). For male antennae, the 100.0 µg/µL dose elicited the highest EAG response, followed by 10.0 µg/µL, but response to the 1.0 µg/µL dose did not differ from hexane (Figure 4-20D).

Dose had a strong effect on RBC EAG response to phenylacetaldehyde ($F_{6,210}$ = 549.16; $p < 0.001$), and this effect was dependent on moth sex and feeding status (concentration × sex × feeding, $F_{6,210}$ = 2.25, p = 0.039). There were no differences in EAG response to the floral volatile between fed or unfed RBC, regardless of the dose (Figure 4-20F). In contrast, fed females had a higher EAG response than unfed females only at the 10.0 µg/µL dose (Figure 4-

20E). Moth antennae detected phenylacetaldehyde at lower doses, compared to acetic acid and 3-methyl-1-butanol. Only response to the 0.001 µg/µL dose was not different from hexane for females (Figure 24 E), while response to doses of 0.001 and 0.01 µg/µL were not different from hexane for males (Figure 24 F). There was a significant dose response with the highest EAG response to 100.0 µg/µL, followed by 10.0 µg/µL, 1.0 µg/µL and 0.1 µg/µL (Figure 4-20 E and F).

Discussion

This research explores the development of a general food bait lure to monitor the cutworm and armyworm pest complex with a single trap baited with a single lure in canola and wheat fields in the Canadian Prairies. Field experiments were conducted in canola and wheat fields to evaluate the AAMB lure, a food bait based on microbial volatile compounds from by-products of fermented sugar baits, developed by Landolt (2000). As expected, traps baited with sex pheromone lures captured a larger number of target moths than any of the food bait lures tested. The most abundant pest species were the redbacked cutworm (RBC) followed by the bertha armyworm (BAW) in 2014 and 2015, and the pale western cutworm (PWC) in 2015. True armyworm moths (TAW) were captured in low numbers in 2014 but were absent in 2015. Although sex pheromones had a high moth trap catch of RBC, BAW and PWC throughout the field season, farmers did not report cutworm damage in 2015 and 2016. Noctuid moths are strong flyers and may be attracted to sex pheromone-baited traps over long distances, and thus, moth trap catch may not reflect the local population density. *Agrotis orthogonia* male moths showed a maximum flight distance of 24 km in flight mill experiments, whereas female moths flew 5 km (Jacobson, 1965). Males noctuid moths can disperse over longer distances than females to find a mate. For instance, mark-recapture experiments with sex pheromone baited traps of the tobacco budworm, *Heliothis virescens* (Fabricious) (Lepidoptera: Noctuidae), showed that moths can disperse up to 30 km from the release point (Schneider, 1999). Furthermore, sex pheromones attract male moths only, and thus, monitoring results may not be representative of female density. Redbacked cutworm moth trap catch in sex pheromone-baited traps showed no relationship with larval densities in alfalfa fields in Manitoba, Canada (Ayre and Lamb, 1990).

Although food baits had a lower moth trap catch than sex pheromone, AAMB lure attracted several cutworm and armyworm species, including the target species RBC and TAW. Pale western cutworm (PWC) and BAW moths were not captured in AAMB lure baited traps. Army cutworm (ACW) attraction to AAMB lures could not be determined since this species was not present at monitoring sites in 2014. It remains to be tested if numbers of target moth species captured in AAMB-baited traps represent local population densities.

Traps baited with the AAMB lure captured RBC throughout its flight period. The peak flight activity of the RBC recorded from traps baited with AAMB lures followed the same pattern as trap catch in the sex pheromone-baited traps, and thus, the AAMB lure is a potential tool for monitoring the flight activity of RBC moths. For TAW, however, only the summer-generation moths can be monitored with traps baited with the AAMB lure. Moths from the immigrating-generation were captured in sex pheromone but not AAMB lure-baited traps, while summer-generation TAW were attracted to the AAMB lure but not sex pheromone lures. Differences in response to sex pheromone lures between TAW generations has been observed in field experiments (McNeil, 1987), in which immigrating moths were captured in sex pheromone-baited and light traps in early summer, while summer-generation moths were captured only in light traps in early fall but not in pheromone traps. Sexual maturation in the summer-generation moths is delayed under short-day and low-temperature conditions of early fall (Delisle and McNeil, 1987). These cues induce physiological and behavioural changes in summer-generation moths to undertake a southern migration from deteriorating habitats in northern latitudes (McNeil, 1987), and therefore, male moths do not respond to sex pheromone lures.

True armyworm may have a plasticity in response to food-based semiochemicals between generations. Variation in attraction to semiochemicals by insects in different insect physiological states has been reported in several moth species. For instance, the response of female *Caloptilia fraxinella* (Ely) (Lepidoptera: Gracillaridae) moths, to host plant volatiles is higher when they are reproductively active than when females are in reproductive diapause (Lemmen-Lechelt et al., 2018). Similarly, females of the cotton leafworm moth, *Spodoptera littoralis* (Boisduval) (Lepdipotera: Noctuidae), are attracted to host plant volatiles more than to floral volatiles after mating (Saveer et al., 2012). The immigrating-generation of TAW may respond to cues for mate finding or oviposition host selection in early summer, while the summer-generation moths may have a higher response to food-based semiochemicals to locate food resources prior to southern migration.

In an attempt to enhance the attractiveness of the AAMB lure to target noctuid species, especially RBC, different AAMB release rates and release devices were tested. Differences in response between male and female noctuid moths to varying release rates depended on the crops where traps were deployed. It is possible that variation in response is influenced by host plant volatiles from crops in the background where baited traps were positioned. The response of diamondback moths, *Plutella xylostella* L. (Lepidoptera: Plutellidae), to sex pheromone-baited traps is enhanced when combined with green leaf volatiles if traps are deployed in cabbage fields

(Reddy and Guerrero, 2000) but not in canola fields (Miluch et al., 2014). Similarly, pea leaf weevil (*Sitona lineatus* L.) (Coleoptera: Curculionidae) has a higher response to semiochemical lures with host plant volatiles in the fall when pea plants are beginning to senescence and crops are harvested, than in spring when crops are at the vegetative growth stage and produce more host plant volatiles that may mask the host volatiles released from baited traps (Evenden et al., 2016). Overall, baited traps deployed in wheat fields captured more noctuid moths than baited traps in canola fields. Acetic acid is one of the most prominent volatile organic compounds emitted by canola plants at the flowering stage (Veromann et al., 2013), whereas acetic acid is not part of the volatile profile in wheat plants (Piesik et al., 2010, Piesik et al., 2011). AAMB lures at varying release rates may be more apparent to target moths in wheat than canola fields.

Among the different release devices tested, the AAMB chemical mixture incorporated into the Splat™ matrix attracted the most noctuid moths and RBC to baited traps. Although release rates of AAMB from the different devices were not recorded in this experiment, it is likely that the AAMB Splat mixture has a higher release rate than Nalgene bottles and polyethylene bags. Phenylacetaldehyde incorporated into the wax developed for dispensing semiochemicals has a higher release compared to that from rubber stopper lures, and thus, attracts more moths to baited traps (Meagher Jr, 2002).

The AAMB lure combined with 2-methyl-1-propanol (MP) or phenylacetaldehyde (PAA) attracts several noctuid pest species in Europe (Tóth et al., 2010), and therefore, may enhance attraction of RBC moths to AAMB lures in Canadian Prairie agroecosystems. Redbacked cutworm moths were equally attracted to the different food bait lure types in canola fields, however, moths had a higher response to the AAMB lure with 2-methyl-1-propanol than phenylacetaldehyde in wheat fields. Furthermore, more female RBC are attracted to AAMB lures with the additional alcohol from fermented by-products than AAMB lures with the floral volatile. Several insects rely specifically on microbial volatile organic compounds as cues to locate food sources (Davis et al., 2013). For instance, over 90 % of moth species captured in traps baited with different sources of fermented sugar baits are noctuids (Noctuidae) (El-Sayed et al., 2005). Interestingly, some microbial volatile organic compounds are also constituents of male pheromone signals in noctuid moths. For example, phenylethanol is a component of the male sex pheromone of the flounced chestnut moth, *Agrochola helvola* L. (Lepidoptera: Noctuidae) (Bestmann et al., 1977). Similarly, hair pencils of male TAW release acetic acid as part of its courtship pheromone blend (Fitzpatrick et al., 1989). Like many noctuid moths, RBC is active at night, and therefore, moths may rely on microbial volatile organic compounds over floral volatiles to locate food sources. Food bait lures that attract both male and female moths are more suitable tools for monitoring pest species since capture of females might be a better indicator of population density (Joyce and Lingren, 1998). Capture of females can provide information on the reproductive status of females and egg loading.

High *Bombus* spp. bycatch in cutworm and armyworm sex-pheromone baited traps occurs in other noctuid pest systems (Gross and Carpenter, 1991, Meagher Jr and Mitchell, 1999, Spears et al., 2016). The underlying mechanism of response by *Bombus* spp. to syntethic noctuid sex pheromones, however, has not been assessed. Traps baited with food bait lures based on fermented by-products from sugar baits have a low pollinator by-catch. The addition of floral compounds to food bait traps, however, attracts more *Bombus* spp. by-catch. Food bait lures based on microbial volatile organic compounds may be especially suitable for monitoring cutworm and armyworm moths because pollinators do not appear to be attracted to these compounds. In contrast, traps baited with AAMB lures attract more vespid by-catch, and this attraction is elicited by the short chain alcohol in the food bait chemical mixture (Landolt et al., 2000). Further studies should evaluate food bait lures with longer chain alcohols to reduced vespid by-catch.

The floral blend of the Canada thistle is a potential general lure to monitor noctuid moths, and attracts pest species like the cabbage looper moth, *Trichoplusia ni* (Hübner), and the corn earworm moth, *Helicoverpa zea* (Boddie) (El-Sayed et al., 2008). In contrast to results from the AAMB lure at different release rates experiment, noctuid moths in central Alberta respond in a dose-dependent manner to lures baited with Canada thistle floral volatiles, and traps baited with higher dose lures capture more noctuid moths. Volatile organic compounds from canola plants at the flowering stage are characterized by green leaf volatiles, terpenes and carboxylic acids in addition to few aromatic compounds (Veromann et al., 2013). The volatile profile from canola plants differs from the aromatic blend of the Canada thistle, and therefore, Canada thistle lures at different doses are more apparent to noctuid moths in canola fields than fermented by-products from sugar baits like the AAMB lure. Although noctuid moths respond in a dose-dependent manner to Canada thistle volatiles, similar numbers of both male and female RBC were captured in traps baited with lures at different doses, and in traps baited with phenylacetaldehyde alone. This indicates RBC attraction may be driven by the main component of the floral blend, phenylacetaldehyde.

In accordance to the finding of El-Sayed et al. (2008), honeybees were the most abundant pollinator captured in Canada thistle lure-baited traps. Moreover, honeybees responded to the volatile blend in a dose-dependent manner. No honeybees were captured in traps baited with phenylacetaldehyde alone. Similarly, phenylacetaldehyde-baited traps captured a high number of *Bombus* spp. and wasps from the family Sphecidae, but no honeybees in traps positioned in cotton and corn fields (Meagher Jr, 2001b). These results indicate that honeybees respond to the complete floral blend of Canada thistle and not its main component alone. This experiment was conducted in late summer, and therefore, bumblebee response to Canada thistle floral volatiles could not be determined.

Redbacked cutworm antennae responded to the different food-based semiochemicals in a dose dependent manner. Higher doses of acetic acid and 3-methyl-1-butanol elicited significant EAG responses, whereas phenylacetaldehyde elicited significant EAG responses at all doses tested. Other moths exhibit dose dependent antennal responses to host plant volatiles. For example, the host plant volatile, hexan-1-ol, elicits high antennal response at a dose of 0.1 µg in the cotton bollworm moth, *H. armigera* (Hübner) (Lepidoptera: Noctuidae), while response to lower doses (0.0001 to 0.01 µg) does not differ from the solvent control (Burguiere et al., 2001). Similarly, phenylacetaldehyde elicits the strongest antennal responses in the lichnis moth, *Hadena bicurris* Hufnagel (Lepidoptera: Noctuidae), at low and high concentrations, while the green leaf volatile, cis-3-hexen-1-yl acetate, elicits antennal recordings only at high concentrations (Dötterl et al., 2006). The cabbage butterfly, *Pieris rapae* L. (Lepidoptera: Pieridae), antennal response to microbial volatile emissions at high doses many be important for close-range location of food sources (Ômura et al., 1999) rather than the long-range attraction assessed for RBC in the current study. Phenylacetaldehyde elicits higher EAG responses than acetic acid and 3-methyl-1-butanol in RBC antennae, however, these patterns may be confounded to differences in volatility of the compounds tested. Aromatic aldehydes elicit higher EAG response than alcohols in the cotton bollworm moth (Burguiere et al., 2001).

The physiological state of insects influences the antennal response to food-based semiochemicals (Bruce and Pickett, 2011). In the RBC moth, males have a higher EAG response to phenylacetaldehyde at higher doses than female moths, while both sexes respond similarly to acetic acid and 3-methyl-butanol. Antennal response to acetic acid by TAW does not differ between males and females, however, male antennal response to benzaldehyde, a common floral volatile and component of the male TAW pheromone blend, is significantly greater than females (Fitzpatrick et al. 1989). Several lepidopteran male courtship pheromones are derived from ingested plant compounds, and some of these components are also components of floral scents like benzaldehyde or phenylacetaldehyde (Knudsen and Tollsten, 1993).

In RBC, feeding status did not influence the antennal response to acetic acid and phenylacetaldehyde in either sex, whereas feeding status did affect the response to 3-methyl-1-butanol in female moths but not in males. Fed virgin female moths had a higher EAG response than unfed females. The influence of feeding status on antennal response may be specific to the insect species and the semiochemical cue. For example, fed female *C. fraxinella* have a marginally higher antennal response to the host plant volatiles *(E, E)-α-*farnesene and methyl salicylate compared to unfed females, however, unfed females have a higher EAG response to linalool than fed females (Lemmen-Lechelt et al., 2018). Feeding status, however, highly influences female *C. fraxinella* behavioural response to host plant volatiles, as fed females orient to host plant volatiles more readily than unfed females in wind tunnel experiments (Lemmen-Lechelt et al., 2018). In general, the insect central nervous system seems to be more sensitive to changes in insect physiological state compared to the peripheral system that is less plastic (Anton et al., 2007). For example, isothiocyanates stimulate upwind flight in female cabbage moths, *Mamestra brassicae* L. (Lepidoptera: Noctuidae), despite the low antennal response to this compounds (Rojas, 1999). Further studies should evaluate the influence of the tested compounds and the food bait lure blend on RBC behaviour in wind tunnel studies under controlled conditions.

In conclusion, food bait lures based on microbial volatile organic compounds can be further developed to monitor RBC moths and potentially other cutworm and armyworm pests in Prairie agroecosystems, and have a minimum negative effect on native pollinator by-catch. Although food bait lures capture lower numbers of targeted moths compared to sex pheromone-baited traps, both male and females of multiple cutworm species are attracted to AAMB lure. The low number of moths captured in food bait traps may indicate that only moths in the immediate area detect and are attracted to the food bait lures. Future studies should evaluate the attractive radius of these lures and determine if trap capture represents local population density (Byers et al., 1989). Traps baited with the AAMB lure caught more moths in wheat fields than canola, and thus, the background volatile profile of the crop may influence the response to lure. It is possible that microbial volatile organic compounds are more reliable cues for locating food sources than floral volatiles for RBC and potentially other noctuid pest species. These types of lures may be more reliable than specific host plant volatiles as several cutworm and armyworm pests are generalists and do not oviposit on host plant tissue, including RBC and PWC. The AAMB lures have little impact on pollinator bycatch, but other alcohols should be tested to reduce attraction of vespid wasps to food bait traps. Food bait traps catch a variety of non-pest noctuid moths and entomological expertise is required to separate the species captured.

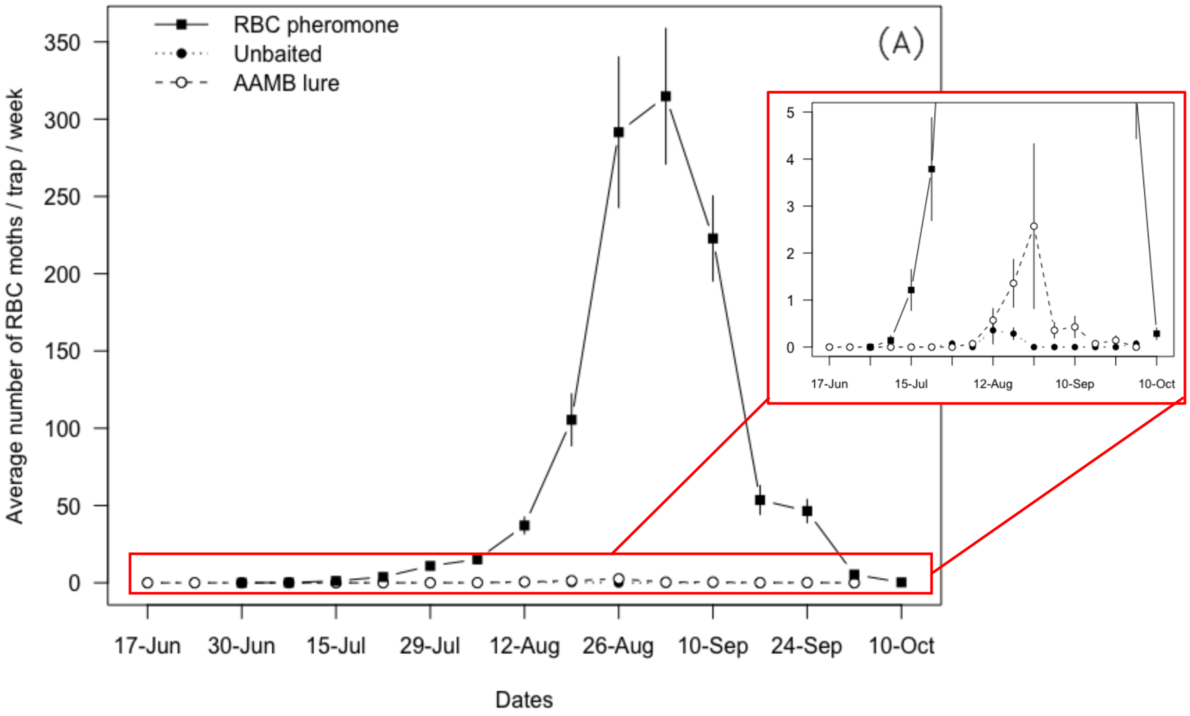

Figure 4-1A. Experiment 1 (2014) - Average number of redbacked cutworm (RBC) (*Euxoa ochrogaster*) moths captured per trap per week at seven sites in central Alberta, Canada. RBC moths were monitored with three traps: RBC sex pheromone, AAMB lure and an unbaited trap.

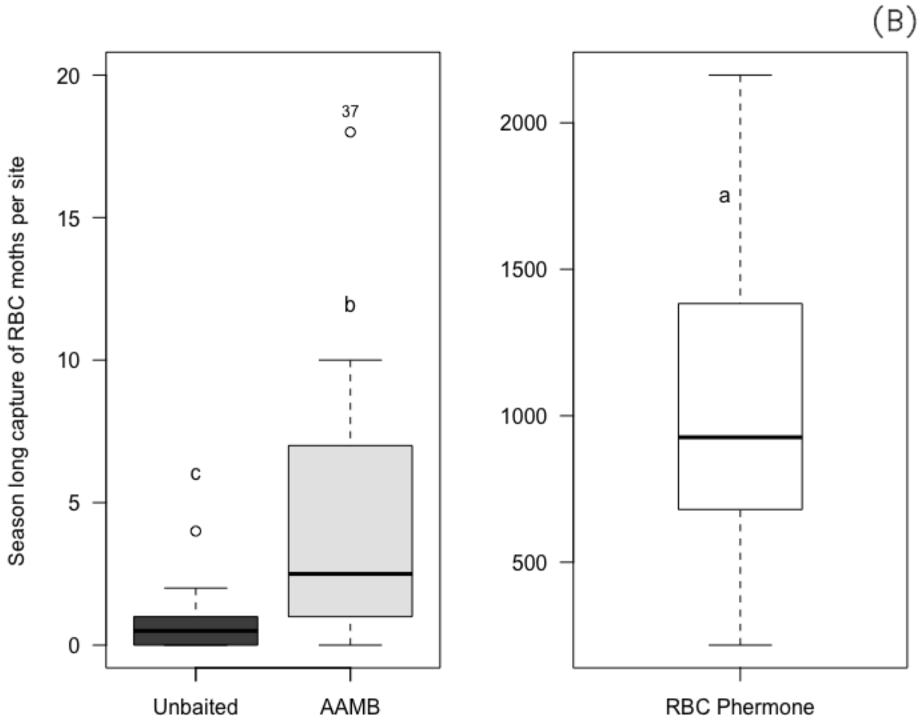

Figure 4-1B. Experiment 1 (2014) - Boxplots of the season long capture of redbacked cutworm (RBC) (*Euxoa ochrogaster*) moths per baited trap. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. There is no difference in moth trap catch between canola or wheat fields. Means comparisons were performed for differences in trap capture in traps baited with RBC pheromone lure, AAMB lure and in unbaited traps. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

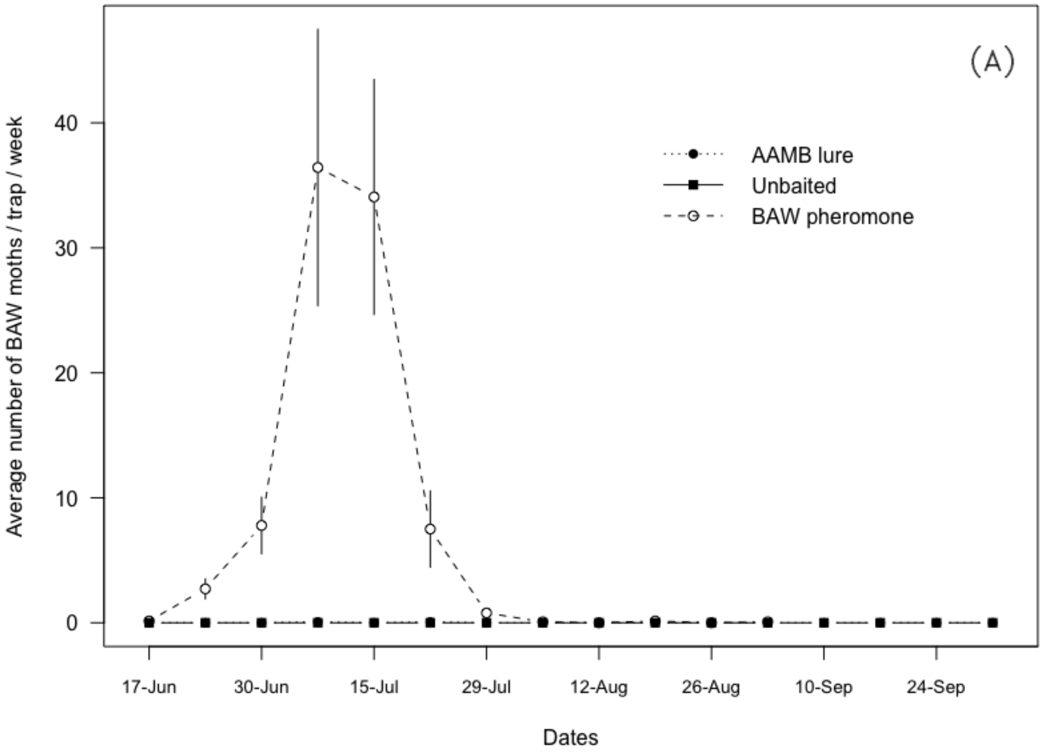

Figure 4-2A. Experiment 1 (2014) - Average number of bertha armyworm (BAW) (*Mamestra configurata*) moths captured per trap per week at seven sites in central Alberta, Canada. BAW moths were monitored with three traps: BAW sex pheromone, AAMB lure and an unbaited trap.

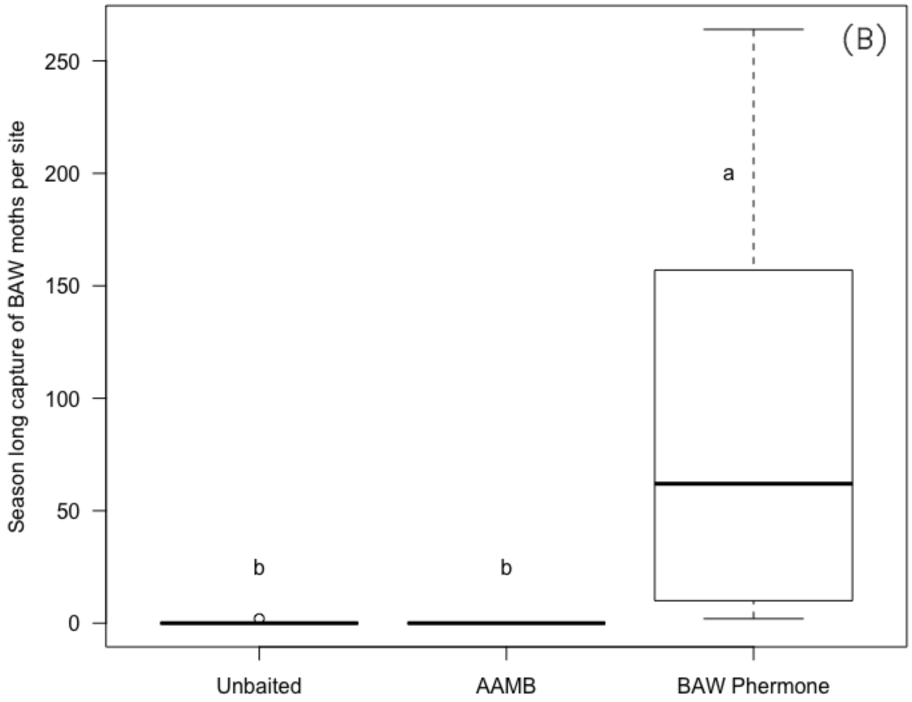

Figure 4-2B. Experiment 1 (2014) - Boxplots of the season long capture of bertha armyworm (BAW) (*Mamestra configurata*) moths per baited trap. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. There is no difference in moth trap catch between canola or wheat fields. Means comparisons were performed for differences in trap capture in traps baited with BAW pheromone lure, AAMB lure and in unbaited traps. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

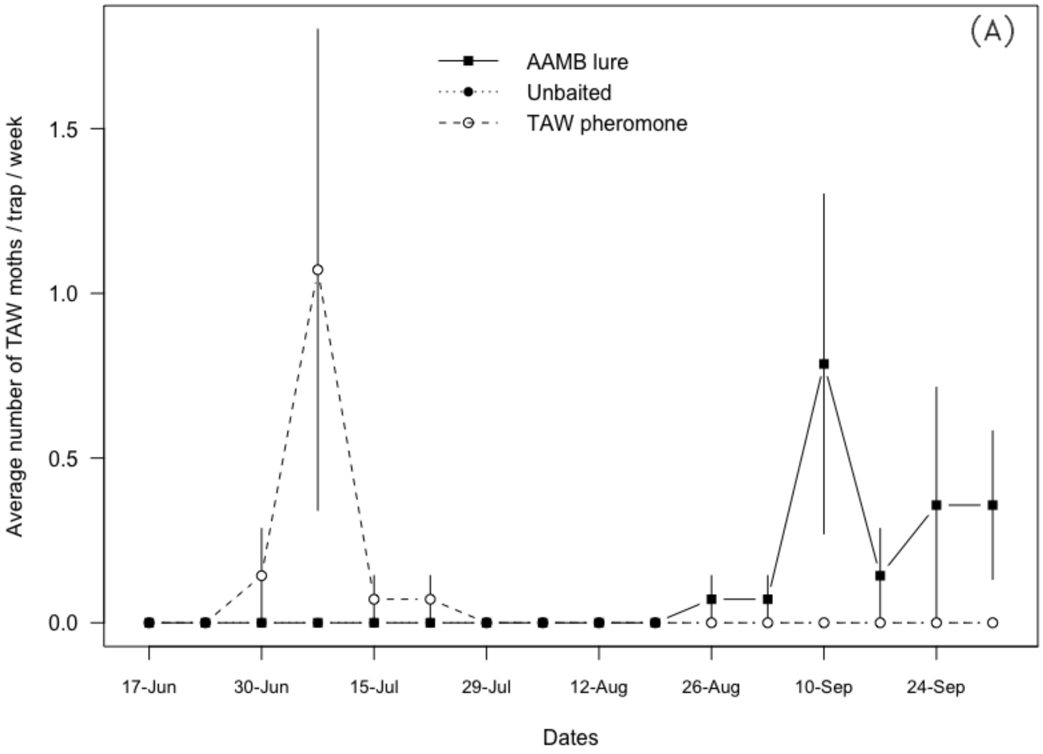

Figure 4-3A. Experiment 1 (2014) - Average number of true armyworm (TAW) (*Mythimna unipuncta*) moths captured per trap per week at seven sites in central Alberta, Canada. TAW moths monitored with three traps: TAW sex pheromone, AAMB lure and in an unbaited trap.

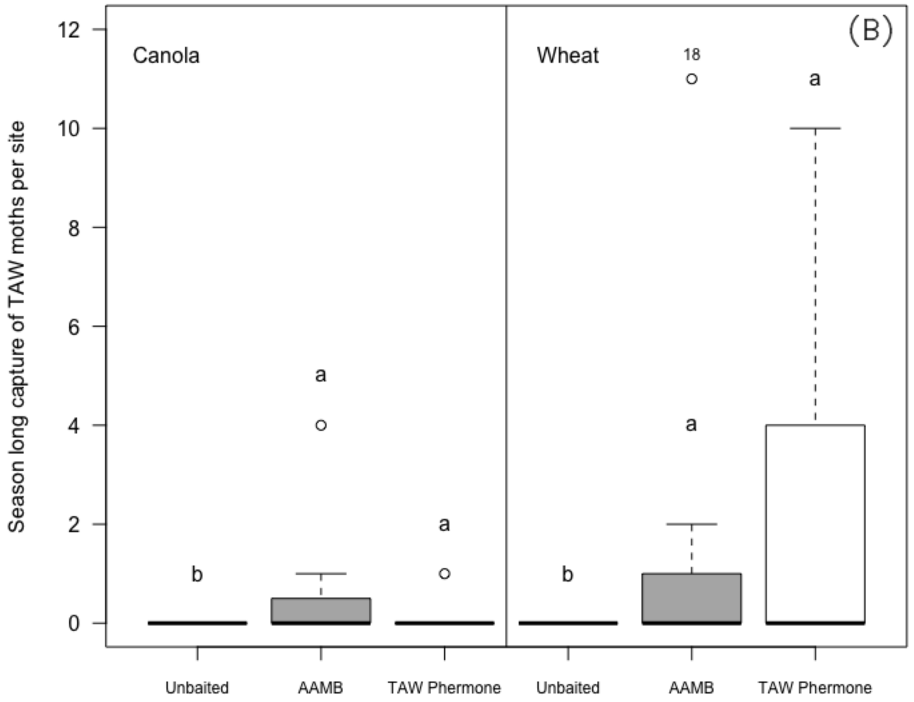

Figure 4-3B. Experiment 1 (2014) - Boxplots of the season long capture of true armyworm (TAW) (*Mythimna unipuncta*) moths per baited trap. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. Means comparisons were performed for differences in trap capture in traps baited with TAW pheromone lure, AAMB lure and in unbaited traps by crop. Boxplots marked with different letters within crop are statistically different (Tukey method, α = 0.05).

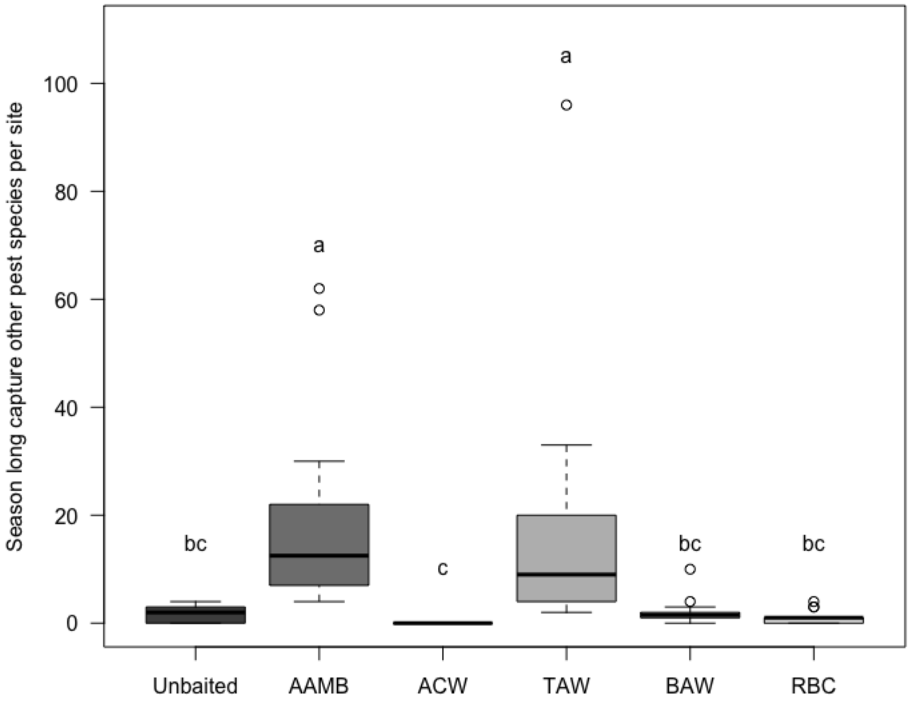

Figure 4-4. Experiment 1 (2014) - Boxplots of the season long capture of non-target cutworm and armyworm moth species captured per baited trap. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. There is no difference in moth trap catch between canola or wheat fields. Means comparisons were performed for differences in trap capture in traps baited with: RBC = redbacked cutworm sex pheromone; BAW = bertha armyworm sex pheromone; TAW = true armyworm sex pheromone; ACW = army cutworm sex pheromone; AAMB lure and in unbaited traps. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

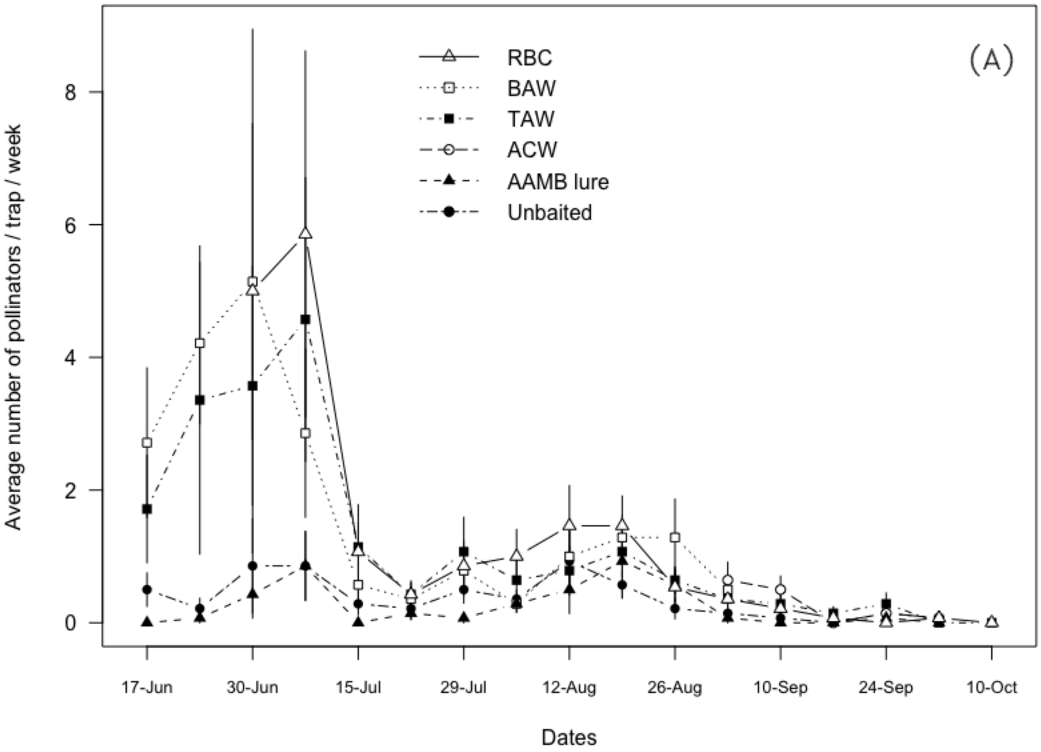

Figure 4-5A. Experiment 1 (2014) - Average number of pollinators captured per week in traps baited with lures targeting cutworm-moths at seven sites in central Alberta, Canada. Lure types: RBC = redbacked cutworm sex pheromone; BAW = bertha armyworm sex pheromone; TAW = true armyworm sex pheromone; ACW = army cutworm sex pheromone; AAMB lure and unbaited trap.

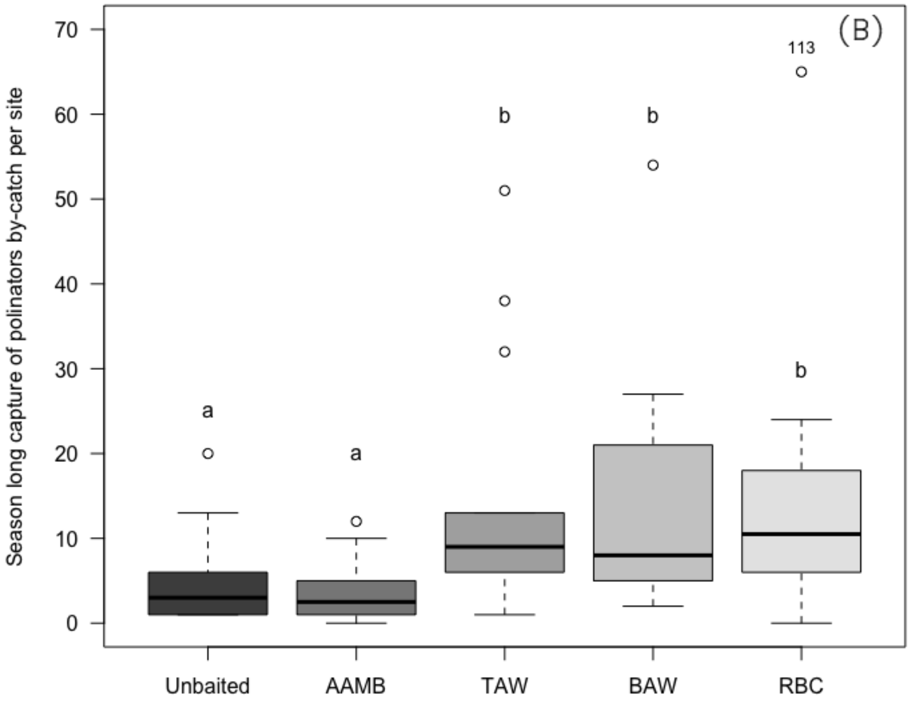

Figure 4-5B. Experiment 1 (2014) - Boxplots of the season long capture of pollinator by-catch captured in traps baited with lures targeting cutworm-moths. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. There is no difference in pollinator by-catch between canola or wheat fields. Means comparisons were performed for differences in trap capture in traps baited with: RBC = redbacked cutworm sex pheromone; BAW = bertha armyworm sex pheromone; TAW = true armyworm sex pheromone; ACW = army cutworm sex pheromone; AAMB lure and unbaited trap. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

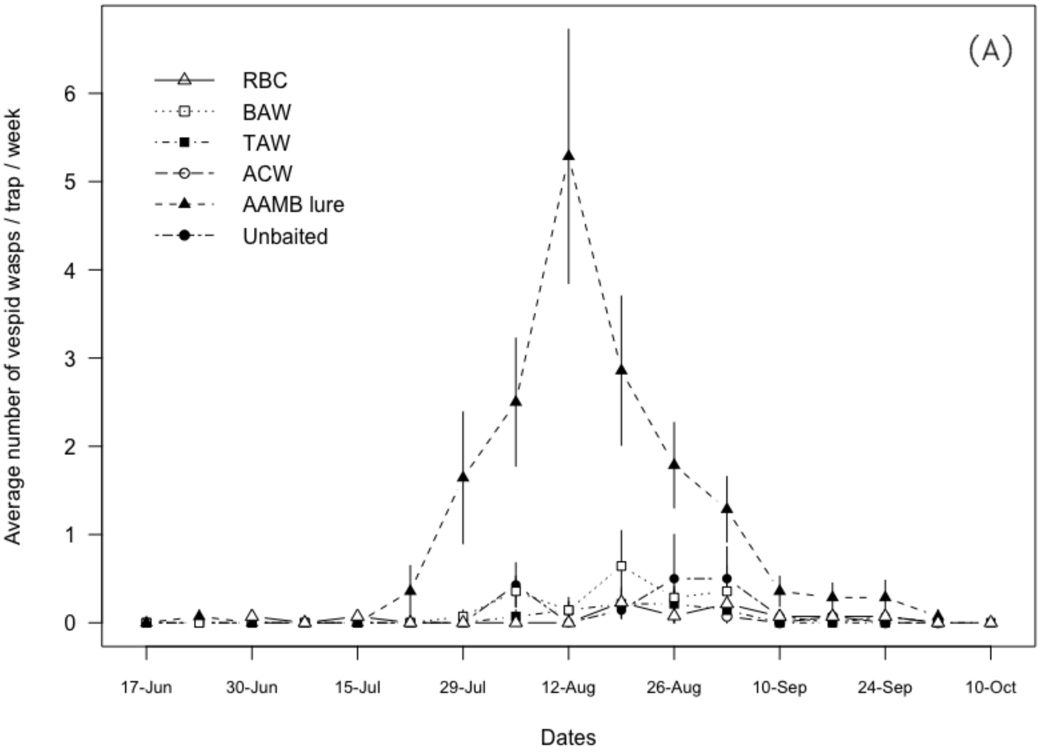

Figure 4-6A. Experiment 1 (2014) - Average number of vepids captured per week in traps baited with lures targeting cutworm-moths at seven sites in central Alberta, Canada. Lure types: RBC = redbacked cutworm sex pheromone; BAW = bertha armyworm sex pheromone; TAW = true armyworm sex pheromone; ACW = army cutworm sex pheromone; AAMB and unbaited trap. There is no difference in vespid trap capture between canola or wheat fields.

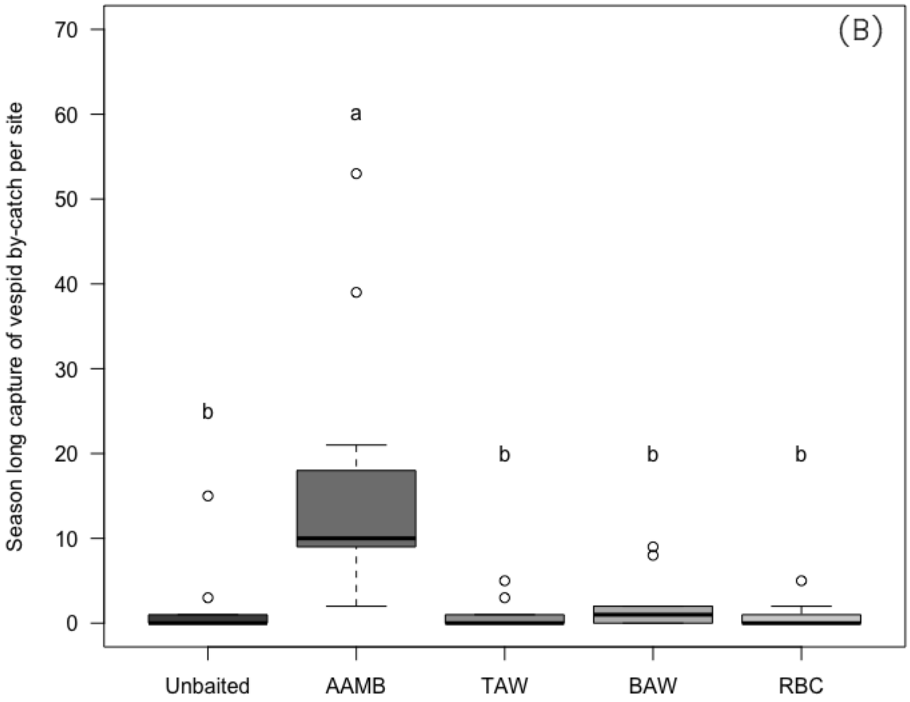

Figure 4-6B. Experiment 1 (2014) - Boxplots of the season long capture of vespid by-catch captured in traps baited with lures targeting cutworm-moths. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. There is no difference in vespid-bycatch between canola or wheat fields. Means comparisons were performed for differences in trap capture in traps baited with: RBC = redbacked cutworm sex pheromone; BAW = bertha armyworm sex pheromone; TAW = true armyworm sex pheromone; ACW = army cutworm sex pheromone; AAMB lure and unbaited trap. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

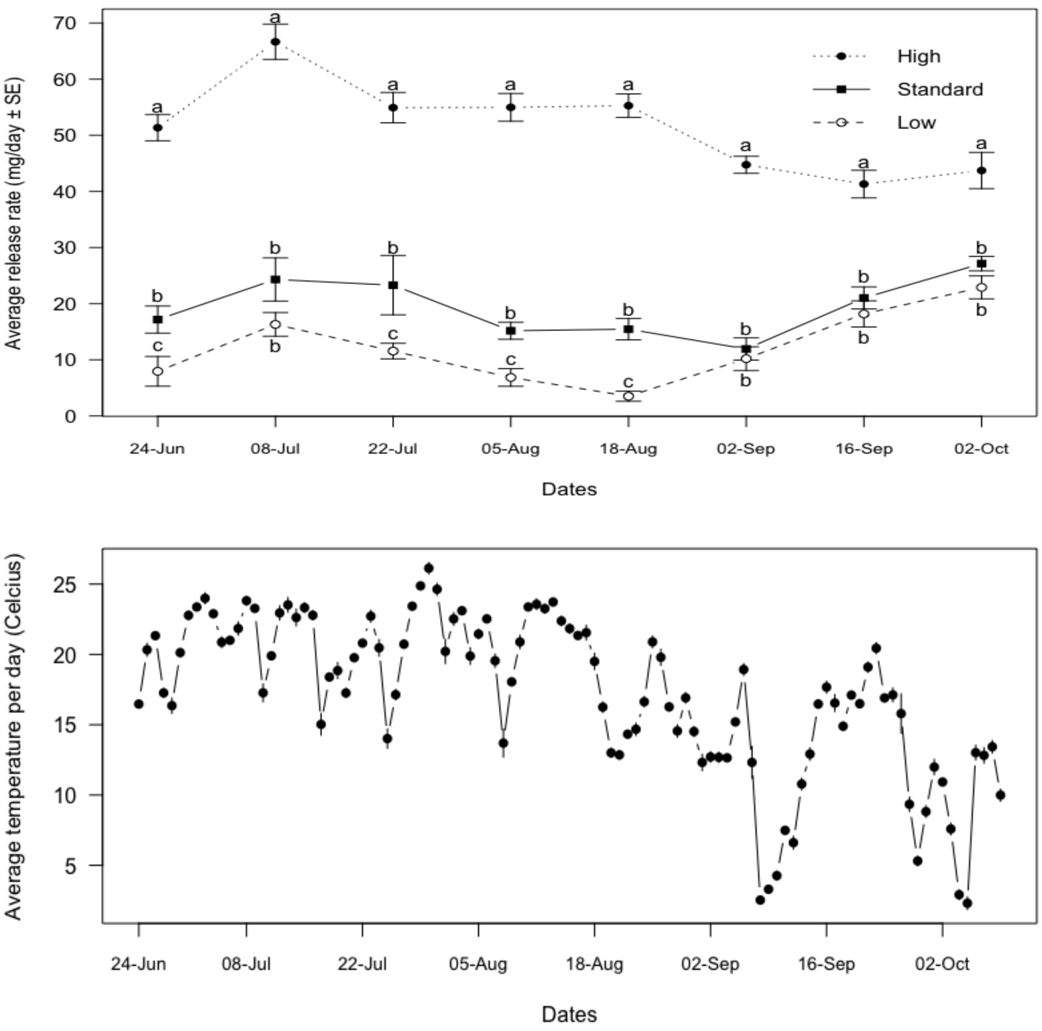

Figure 4-7. Experiment 2 (2014) – Top panel: Average release rate per day (mg/day ± SE) of AAMB lure from Nalgene 10 mL bottle lures with different sized holes in the centre of the bottle cap. Three release-rates were tested: low (1.0 mm diam. hole in lid), standard (3.0 mm diam. hole in lid), high (5.0 mm diam. hole in lid). Lures were replaced every 2 weeks, at which time individual analyses were performed for AAMB lures retrieved from the field. There is no difference in average release rate of lures positioned in traps in canola or wheat fields. Means comparisons were performed for differences among release rate treatments. Points marked with different letters within date are statistically different (Tukey method, α = 0.05).

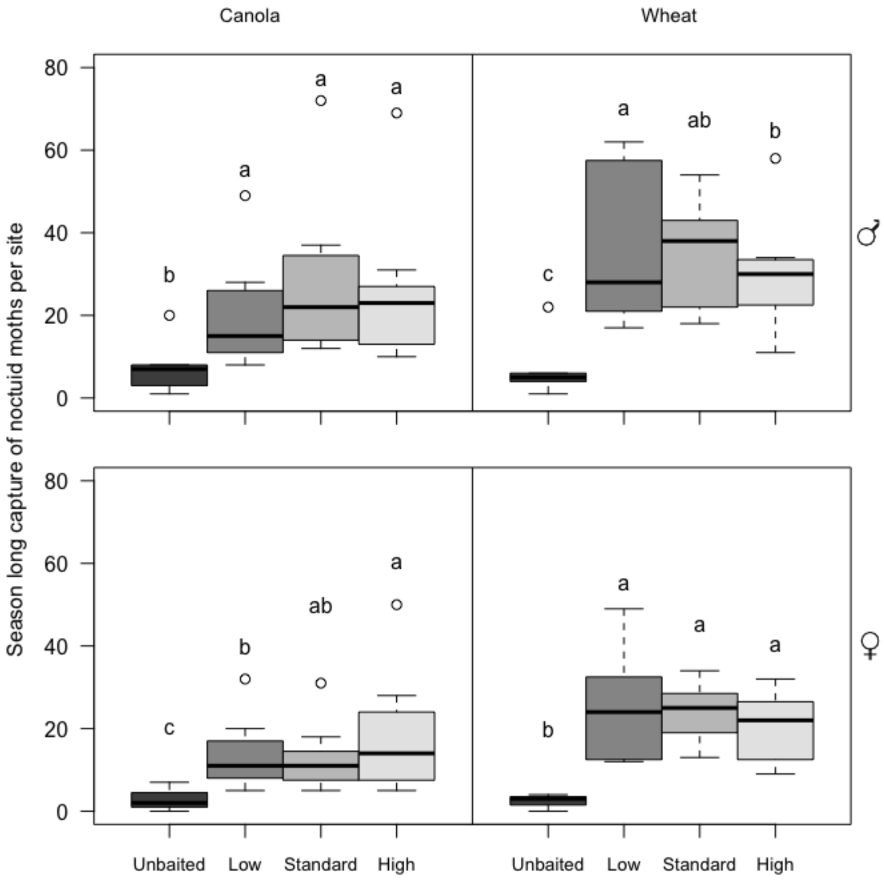

Figure 4-8. Experiment 2 (2104) - Boxplots of the season long capture of male (top panels) and female (bottom panels) noctuid moths in AAMB baited traps at different release rates manipulated by the diameter of holes drilled in the centre of the bottle cap. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. Three release rates were tested: low (1.0 mm), standard (3.0 mm), high (5.0 mm); and an unbaited trap. Means comparisons were performed for difference in moth trap catch among the treatments by the interaction of crop and sex. Boxplots marked with different letters within moth sex and crop panel are statistically different (Tukey method, α = 0.05).

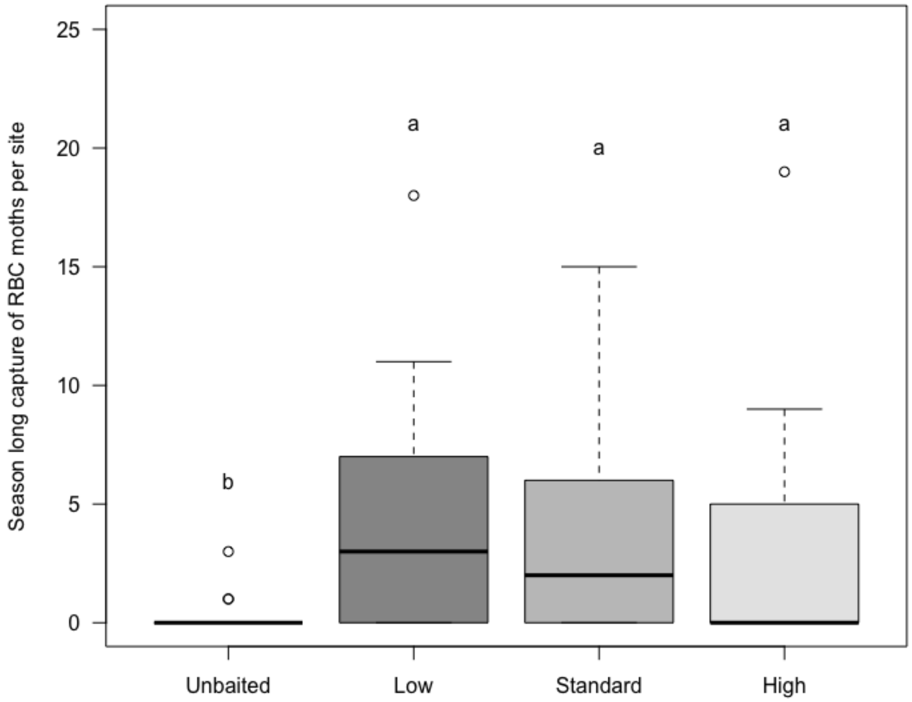

Figure 4-9. Experiment 2 (2014) - Boxplots of the season long capture of redbacked cutworm (RBC) (*Euxoa ochrogaster*) moths in AAMB baited traps at different release rates of AAMB lures. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. Three release-rates were tested: low (1.0 mm diam. hole in lid), standard (3.0 mm diam. hole in lid), high (5.0 mm diam. hole in lid); and an unbaited trap. Means comparisons were performed for difference in moth trap catch among traps baited with the different release rate treatments. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

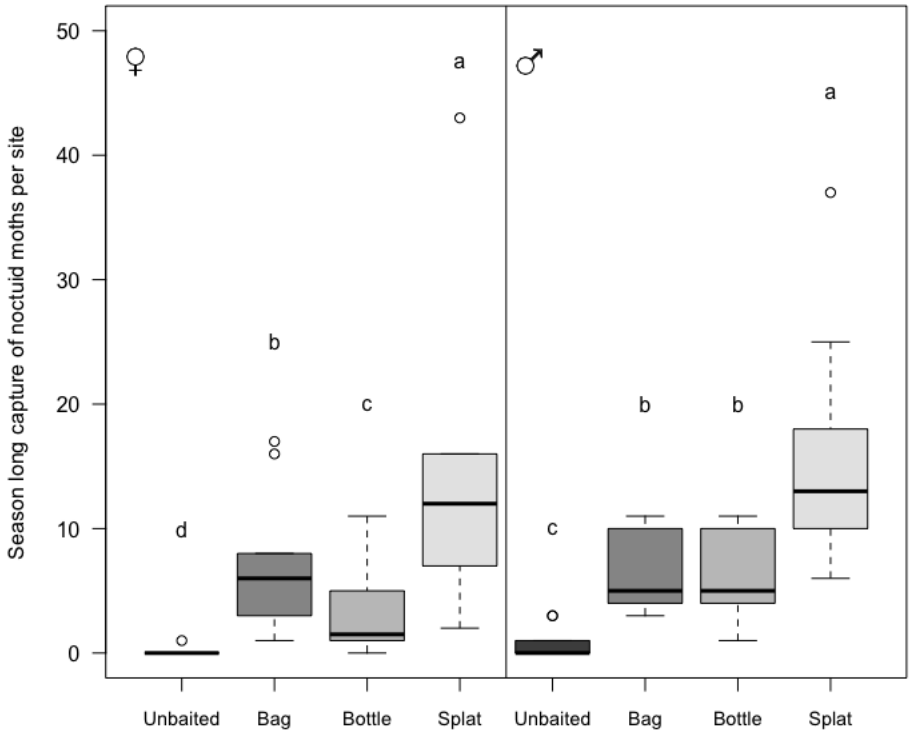

Figure 4-10. Experiment 3 (2015) - Boxplots of the season long capture of female (left panel) and male (right panel) noctuid moths in traps baited with AAMB lures from different release devices. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. Three release-devices were tested: 10 mL nalgene bottle, 10 mL polyethylene bag and 10 g splat matrix; and an unbaited trap. Means comparisons were performed for difference in moth trap catch in traps baited with the different release devices. Boxplots marked with different letters within moth sex are statistically different (Tukey method, α = 0.05).

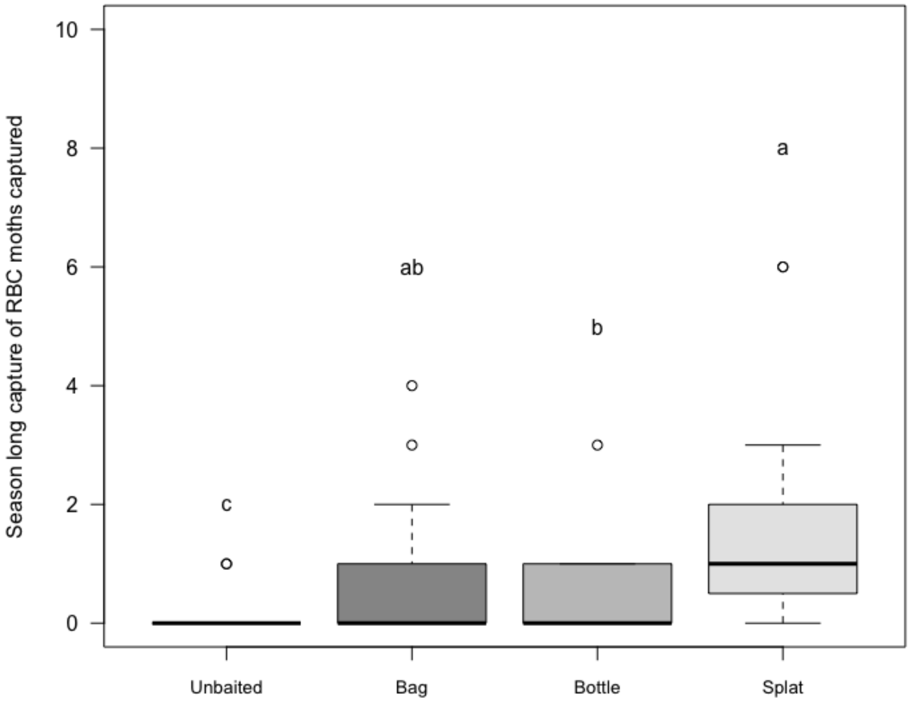

Figure 4-11. Experiment 3 (2015) - Boxplots of the total number redbacked cutworm (RBC) (*Euxoa ochrogaster*) moths capture in traps baited with AAMB released from different devices. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. Three release devices were tested: 10 mL nalgene bottle, 10 mL polyethylene bag and 10 g splat matrix; and in an unbaited trap. Means comparison was performed for differences in moth trap catch in traps baited with the different release devices. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

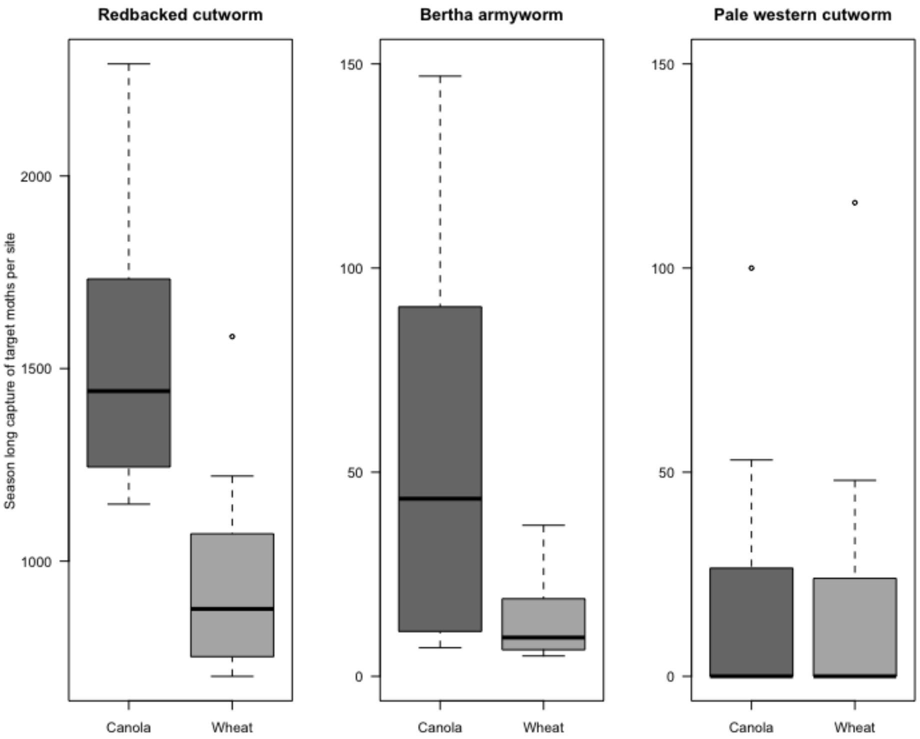

Figure 4-12. Experiment 4 (2015) - Boxplots of the season long capture of target pest species in respective sex pheromone baited traps positioned in canola or wheat fields. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range.

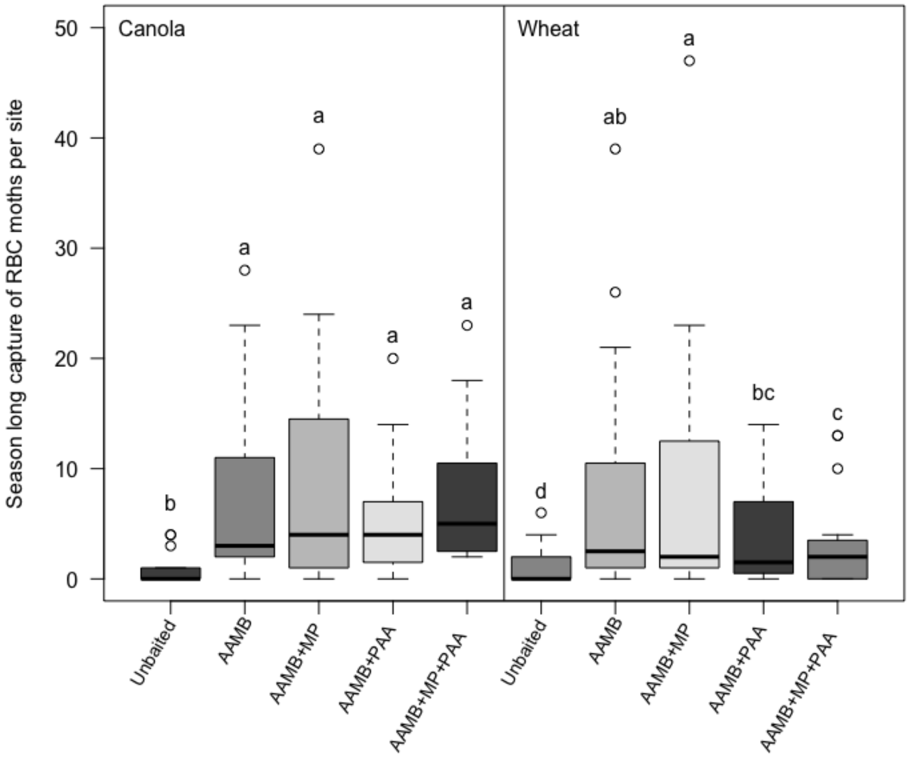

Figure 4-13. Experiment 4 (2015) - Boxplots of the season long capture of redbacked cutworm (RBC) (*Euxoa ochrogaster*) moths in traps baited with AAMB lures with and without additional chemical compounds. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. The tested chemicals were an alcohol from fermented by-products, 2-methyl-1-propanol (MP), and a floral volatile, phenylacetaldehyde (PAA). Treatments included: AAMB alone, AAMB+MP, AAMB+PAA, AAMB+MP+PAA and an unbaited trap that served as control. Means comparisons were performed for difference in moth trap catch in traps baited with the different food bait lures. Boxplots marked with different letters with crop panel are statistically different (Tukey method, α = 0.05).

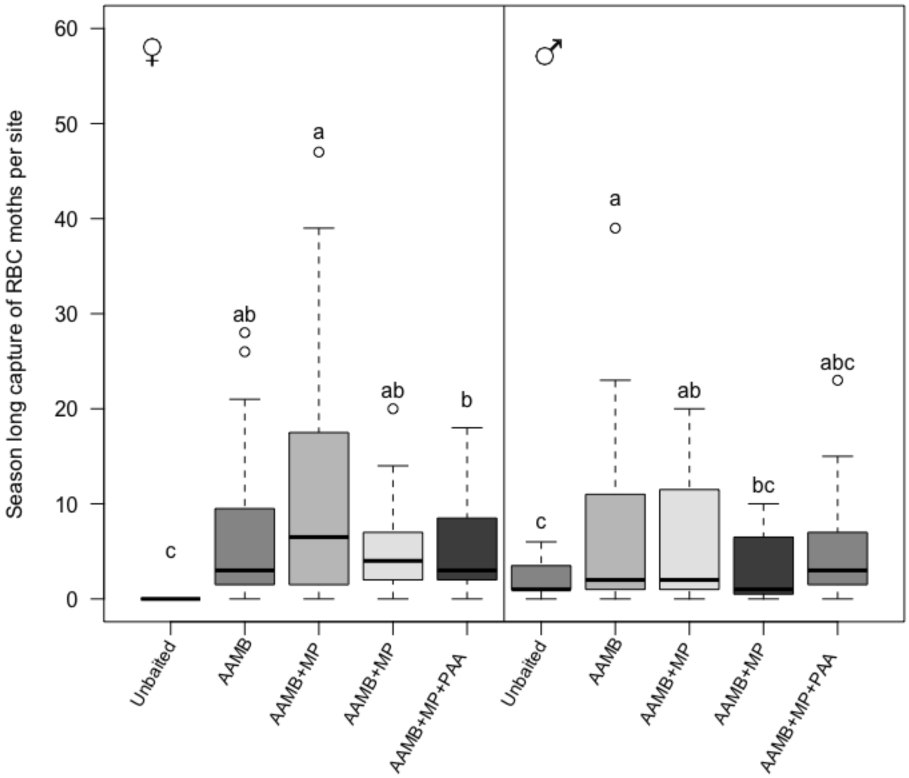

Figure 4-14. Experiment 4 (2015) - Boxplots of the season long capture of redbacked cutworm (RBC) (*Euxoa ochrogaster*) moths in traps baited with AAMB lures with and without additional chemical compounds. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. The tested chemicals were an alcohol from fermented by-products, 2-methyl-1-propanol (MP), and a floral volatile, phenylacetaldehyde (PAA). Treatments included: AAMB alone, AAMB+MP, AAMB+PAA, AAMB+MP+PAA and an unbaited trap that served as control. Means comparison were performed for differences in moth trap catch in traps baited with the different food bait lures. Boxplots marked with different letters with sex panel are statistically different (Tukey method, α = 0.05).

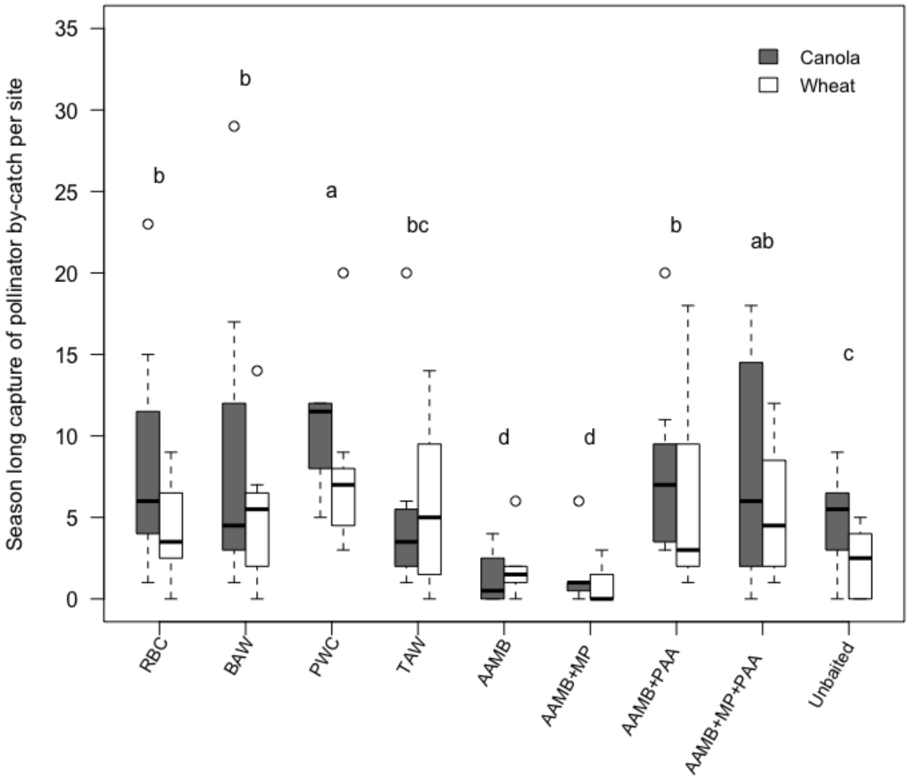

Figure 4-15. Experiment 4 (2015) - Boxplots of the season long capture of pollinator by-catch captured in traps baited with lures targeting cutworm-moths. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. More pollinators were captured in canola fields than wheat. Means comparison were performed for differences in season long pollinator by-catch in traps baited with the different lure types: RBC = redbacked cutworm sex pheromone; BAW = bertha armyworm sex pheromone; PWC = army cutworm sex pheromone; TAW = true armyworm sex pheromone; AAMB alone; AAMB+MP = AAMB plus 2-methyl-1-propanol; AAMB+PAA = AAMB plus phenylacetaldehyde; AAMB+MP+PAA and an unbaited trap that served as control. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

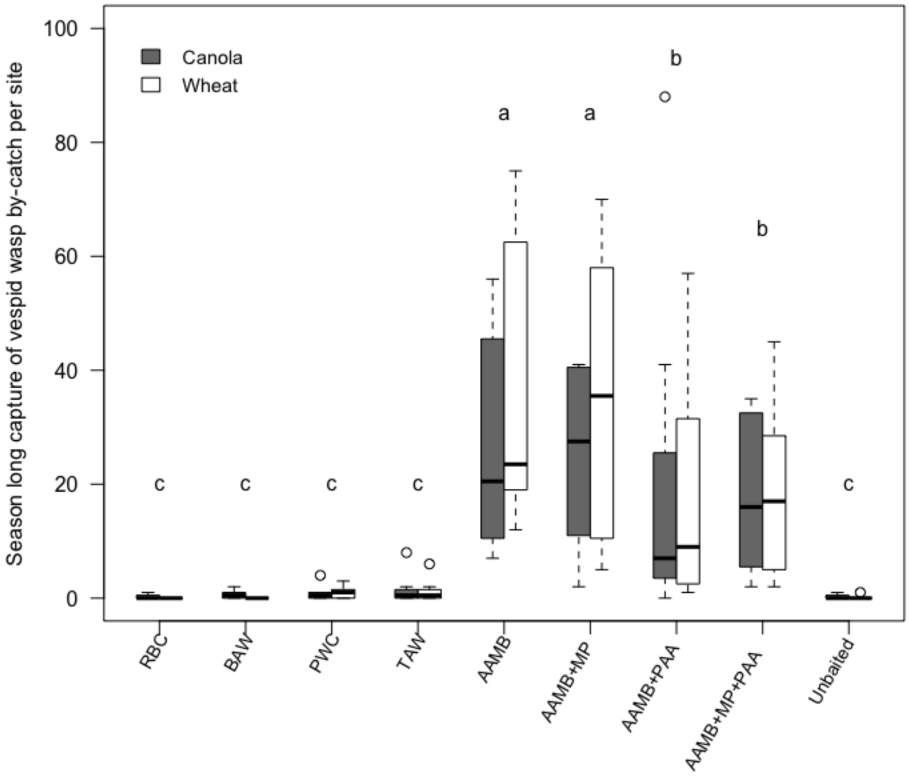

Figure 4-16. Experiment 4 (2015) - Boxplots of the season long capture of vespid by-catch captured in traps baited with lures targeting cutworm-moths. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. There was no difference in vespid by-catch in traps positioned in canola and wheat fields. Means comparisons were performed for differences in total trap catch in traps baited with different lure types: RBC = redbacked cutworm sex pheromone; BAW = bertha armyworm sex pheromone; PWC = army cutworm sex pheromone; TAW = true armyworm sex pheromone; AAMB alone; AAMB+MP = AAMB plus 2-methyl-1-propanol; AAMB+PAA = AAMB plus phenylacetaldehyde; AAMB+MP+PAA and in an unbaited trap that served as control. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05)

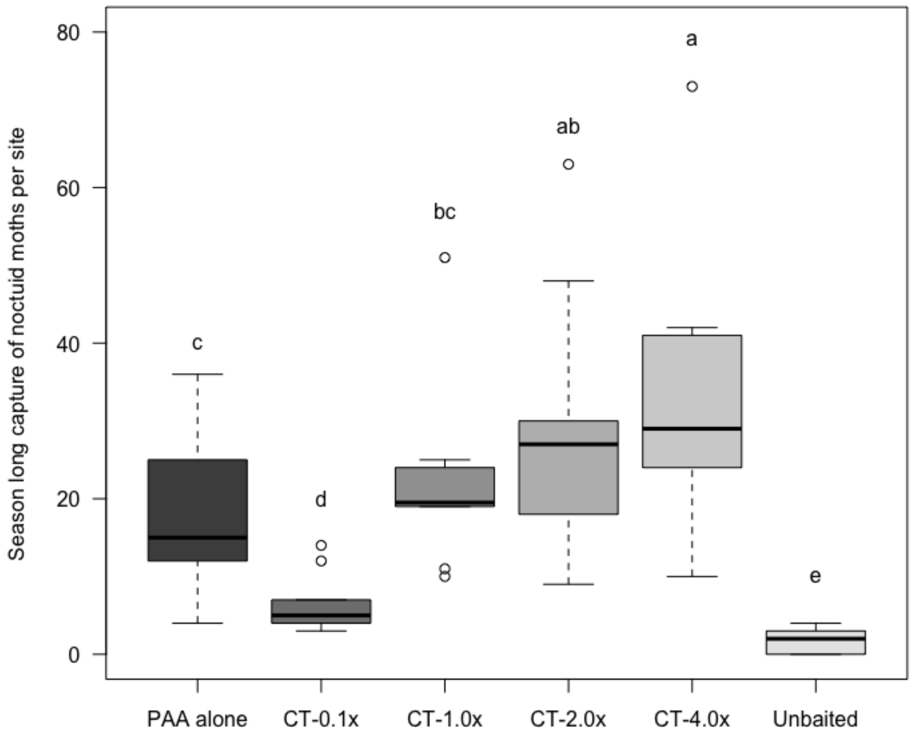

Figure 4-17. Experiment 5 (2016) - Boxplots of the season long capture of noctuid moths captured in traps baited with lures releasing a Canada thistle (CT) floral blend at different doses. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. Treatments included: CT 0.1×; CT 1.0×; CT 2.0×; CT 4.0×; phenylacetaldehyde (PAA) alone and an unbaited trap. Means comparisons were performed for differences in moth trap catch in traps baited with the different lures. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

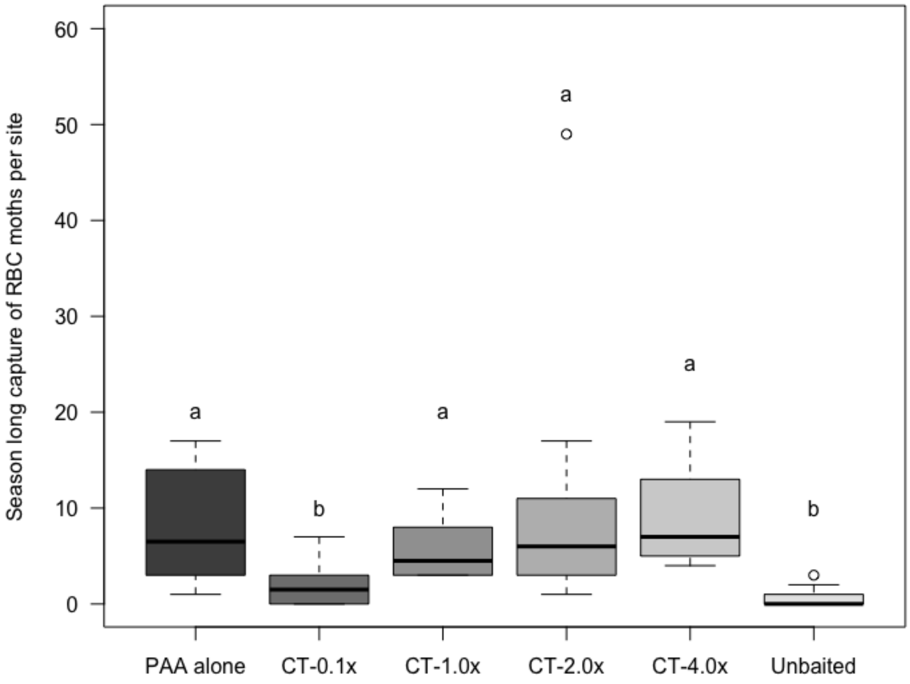

Figure 4-18. Experiment 5 (2016) - Boxplot of the season long capture of redbacked cutworm (RBC) (*Euxoa ochrogaster*) moths captured in traps baited with lures releasing a Canada thistle (CT) floral blend at different doses. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. Treatments included: CT 0.1×; CT 1.0×; CT 2.0×; CT 4.0×; phenylacetaldehyde (PAA) alone and an unbaited trap. Means comparisons were performed for differences in moth trap catch in traps baited with the different lures. Boxplots marked with different letters are statistically different (Tukey method, $\alpha = 0.05$).

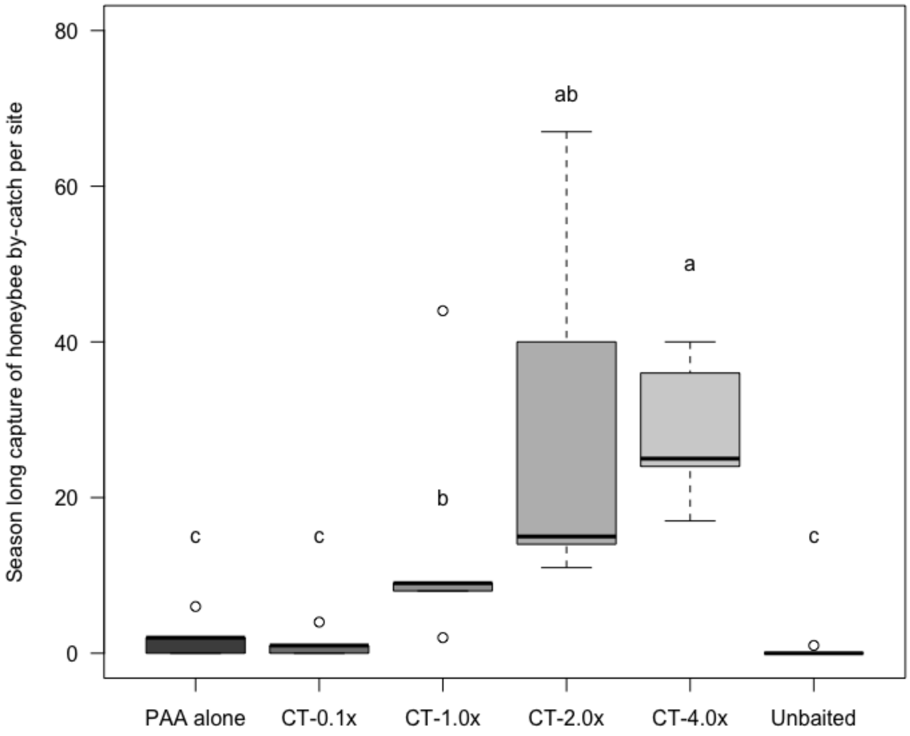

Figure 4-19. Experiment 5 (2016) - Boxplots of the total number of honeybees (*Apis mellifera*) captured in traps baited with lures releasing the Canada thistle (CT) floral blend at different doses. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. Treatments included: CT 0.1×; CT 1.0×; CT 2.0×; CT 4.0×; phenylacetaldehyde (PAA) alone and an unbaited trap. Means comparisons were performed for difference in trap catch in traps baited with the different lures. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

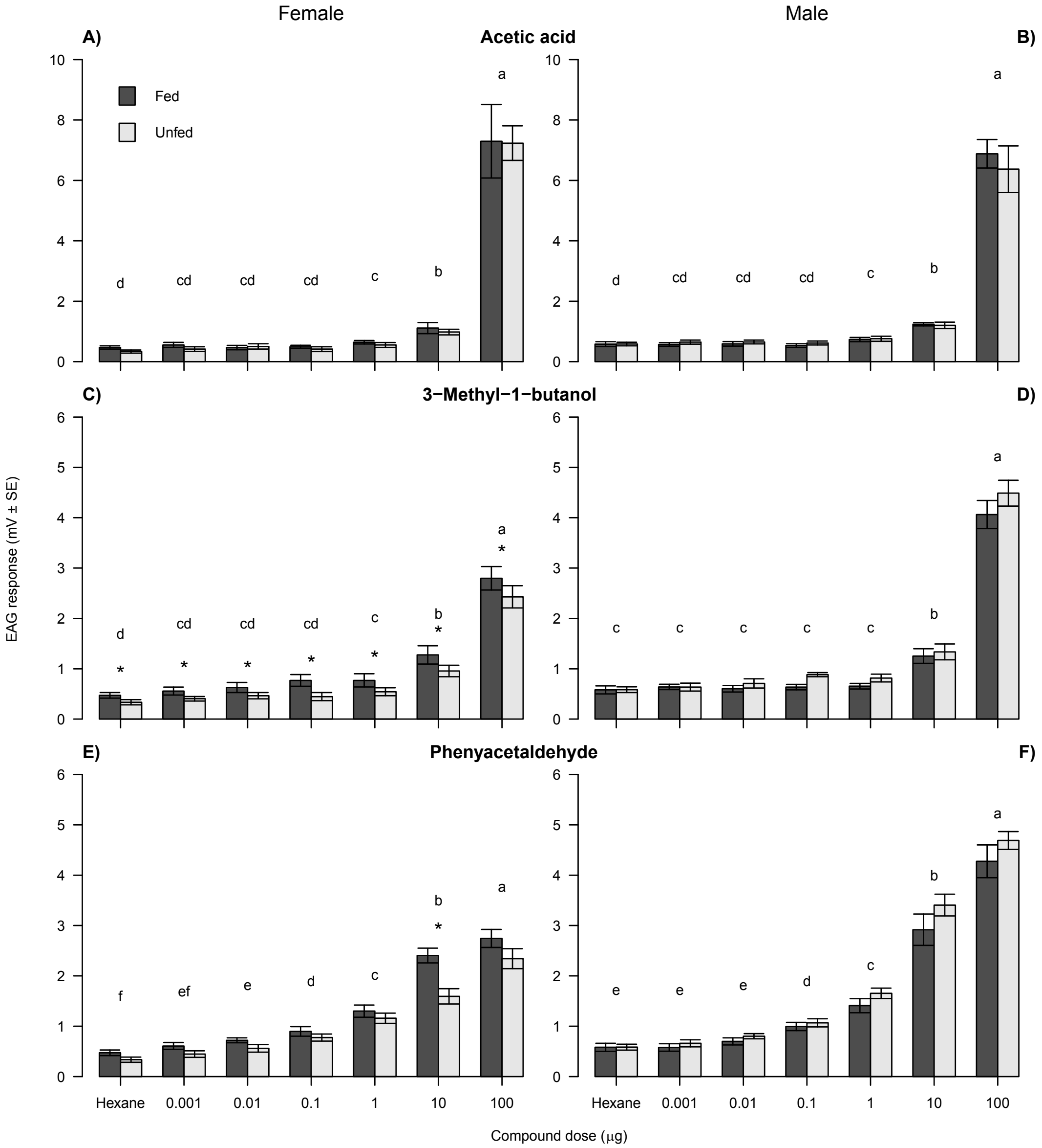

Figure 4-20. Experiment 6 (2017) – Average EAG response (mV ± SE) of female (A,C,E) and male (B,D,F) redbacked cutworm (RBC) (*Euxoa ochrogaster*) antennae (n=10) to feeding attractant volatiles: acetic acid (A, B), 3-methyl-1-butanol (C, D) and phenylacetaldehyde (E, F). Means comparisons were conducted among dose within sex and chemical compound. Bars marked with different letters within each panel represent are significantly different (Tukey method, α = 0.05). Significant difference between antennal response of fed or unfed moths within dose and chemical compound is represented by (*) (Tukey α = 0.05).

Table 4-1. Results of the optimal statistical models used in the several experiments to development of a general food bait lure for monitoring cutworm and armyworm moths (Lepidoptera: Noctuidae) in the Canadian Prairies.

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
Experiment 1 (2014)											
AAMB, pheromones and unbaited	Total RBC	glmer.nb	(RBC + 1) ~ Crop + Lure type + (1|Site)	Crop	Wald χ^2	2.03	1	0.1546	352.8	355.6	470.9
		Negative binomial		Lure type		801.54	2	< 0.001			
	Total BAW	glmer.nb	(BAW + 1) ~ Crop + Lure type + (1|Site)	Crop	Wald χ^2	0.10	1	0.7478	244.2	248.1	319.8
		Negative binomial		Lure type		801.54	2	< 0.001			
	Total TAW	glmer	(TAW + 1) ~ Crop + Lure type + (1|Site)	Crop	Wald χ^2	11.58	1	< 0.001	168.3	176.2	186.6
		Poisson		Lure type		11.28	2	0.003			
	Total ACW	glmer	(ACW + 1) ~ Crop + Lure type + Crop:Lure type (1|Site)	Crop	Wald χ^2	0.32	1	0.571	107.3	107.3	99.5
		Poisson		Lure type		1.50	2	0.4724			
				Crop:Lure type		0.47	2	0.7913			
	None-target cutworm	glmer.nb	(Cutworms + 1) ~ Crop + Lure type + (1|Site)	Crop	Wald χ^2	0.73	1	0.3926	422.3	426.9	520.4
		Negative binomial		Lure type		186.83	5	< 0.001			
	Total Pollinator	glmer.nb	(Pollinator) ~ Crop + Lure type + (1|Site)	Crop	Wald χ^2	3.04	1	0.08118	445.9	451.5	468
		Negative binomial		Lure type		40.77	4	< 0.001			
	Total Vespid	glmer.nb	(Vespid) ~ Crop + Lure type + (1|Site)	Crop	Wald χ^2	1.64	1	0.2004	267.2	269.1	312.9
		Negative binomial		Lure type		96.79	4	< 0.001			
Experiment 2 (2014)											
Release rate	Release rate	lmer	(Release rate)1/2 ~ Release rate + (1|Site)	Release rate							
				24-Jun	F-value	69.84	2,30	< 0.001	137.7	145.8	196.8
				08-Jul		50.84	2,30	< 0.001	140.6	141.1	190.6
				22-Jul		63.69	2,30	< 0.001	130.1	133.1	183.1
				05-Aug		109.32	2,30	< 0.001	125.8	128.3	196.8
				18-Aug		113.25	2,30	< 0.001	132.8	135	207.2
				02-Sep		45.39	2,30	< 0.001	136.4	136.4	184.8
				16-Sep		20.11	2,30	< 0.001	123.9	127.7	151.5
				02-Oct		18.9	2,30	< 0.001	108.9	112.2	133.1

Table 4-1. (Continued).

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
Experiment 2 (2014)											
Release rate	Total Noctuid	glmer	Noctuid ~ Release rate + Crop + Sex + Release rate:crop + Release rate:sex + (1|Site)	Release rate	Wald χ^2	316.0	3	< 0.001	860.9	861.0	1584.9
		Poisson		Crop		51.2	1	< 0.001			
				Sex		111.7	1	< 0.001			
				Release rate:Crop		23.5	3	< 0.001			
				Release rate:Sex		10.1	3	0.018			
	Total RBC	glmer	RBC ~ Release rate + Crop + Sex + (1|Site)	Release rate	Wald χ^2	30.83	3	< 0.001	327	334.2	421.2
		Poisson		Crop		19.96	1	< 0.001			
				Sex		18.67	1	< 0.001			
Experiment 3 (2015)											
Release devices	Total Noctuid	glmer	Noctuid ~ Release device + Sex + Release device:Sex + (1|Site)	Release device	Wald χ^2	187.69	3	< 0.001	397.1	397.1	767.1
		Poisson		Sex		3.54	1	0.060			
				Release device:Sex		9.96	3	0.019			
	Total RBC	glmer	RBC ~ Release device + Sex + (1|Site)	Release device	Wald χ^2	23.67	3	< 0.001	184.2	186.5	214.5
		Poisson		Sex		3.12	1	0.077			
Experiment 4 (2015)											
AAMB with additional semiochemicals	Total RBC	glmer.nb	RBC ~ Lure type + Crop + Sex + Lure type:Crop + Lure type:Sex + (1|Site)	Lure type	Wald χ^2	56.78	4	< 0.001	795	802.6	855.8
		Negative binomial		Crop		5.30	1	0.021			
				Sex		3.00	1	0.083			
				Lure type:Crop		10.73	4	0.030			
				Lure type:Sex		27.55	4	< 0.001			
	Total pollinator	glmer.nb	Pollinator ~ Lure type + Crop + (1|Site)	Lure type	Wald χ^2	85.62	8	< 0.001	751.7	759.8	813.6
		Negative binomial		Crop		9.46	1	0.002			
	Total vespid	glmer.nb	(Vespid + 1) ~ Lure type + Crop + (1|Site)	Lure type		542.006	8	< 0.001	782.5	796.2	1010.8
		Negative binomial		Crop		0.068	1	0.7942			

Table 4-1. (Concluded).

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
Experiment 5 (2016)											
Canada thistle lure	Total noctuid	glmer.nb Negative binomial	Noctuid ~ Lure dose + Sex + (1|Site)	Lure dose	Wald χ^2	196.24	5	< 0.001	385.2	394.9	477
				Sex		24.457	1	< 0.001			
	Total RBC	glmer.nb Negative binomial	RBC ~ Lure dose + Sex + (1|Site)	Lure dose	Wald χ^2	57.9	5	< 0.001	307.2	313.6	343.7
				Sex		1.4008	1	0.237			
	Total Honey bees	glmer.nb Negative binomial	Bees ~ Lure dose + (1|Site)	Lure dose	Wald χ^2	101.37	5	< 0.001		166.5	206.8
Experiment 6 (2017)											
RBC Electroantennogram	Acetic acid	lme	Ln (EAG + 1) ~ Sex + Feeding + Concentration, random = ~1|Antenna ID/Concentration	Sex	F-value	4.71	1,35	0.037	-132.5	-47.3	490.3
				Feeding		0.28	1,35	0.597			
				Concentration		562.82	6,210	< 0.001			
	3-methyl-1-butanol	lme	Ln (EAG + 1) ~ Sex + Feeding + Concentration + Sex:Feeding + Sex: Concentration, random = ~1|Antenna ID/Concentration	Sex	F-value	14.59	1,35	< 0.001	-190.8	-131.5	282.0
				Feeding		0.683	1,35	0.414			
				Concentration		346.94	6,210	< 0.001			
				Sex:Feeding		6.53	1,35	0.015			
				Sex:Concentration		7.69	6,210	< 0.001			
	Phenylacetaldehyde	lme	Ln (EAG + 1) ~ Sex + Feeding + Concentration + Sex:Feeding + Sex: Concentration + Concentration:Sex:Feeding, random = ~1|Antenna ID/Concentration	Sex	F-value	26.08	1,35	< 0.001	-187.3	-187.3	329.0
				Feeding		0.39	1,35	0.539			
				Concentration		549.16	6,210	< 0.001			
				Sex:Feeding		7.24	1,35	0.011			
				Sex:Concentration		17.13	6,210	< 0.001			
				Concentration:Sex:Feeding		2.25	6,210	0.039			

Table 4-2. Site coordinates. Seven sites in five counties throughout central Alberta, Canada.

County	Site	Field	Coordinates	2014	2015	2016
Leduc	1	A	53.23790 N 113.34226 W	Canola	Wheat	Canola
		B	53.24722 N 113.34219 W	Wheat	Canola	Wheat
	2	A	53.28640 N 113.87867 W	Canola	Wheat	Canola
		B	53.27595 N 113.85422 W	Wheat	Canola	Wheat
Parkland	3	A	53.44492 N 113.71344 W	Canola	Wheat	Canola
		B	53.43946 N 113.71339 W	Wheat	Canola	Wheat
Barrhead	4	A	54.07452 N 114.37685 W	Canola	Wheat	Canola
		B	54.05627 N 114.34988 W	Wheat	Canola	Wheat
	5	A	54.30392 N 114.47681 W	Canola	Wheat	Canola
		B	54.34530 N 114.47697 W	Wheat	Canola	Wheat
Wainwright	6	A	52.95971 N 111.43202 W	Canola	Wheat	Canola
		B	52.95963 N 111.43922 W	Wheat	Canola	Wheat
	7	A	52.90159 N 110.56340 W	Canola	Wheat	Canola
		B	52.88453 N 110.60859 W	Wheat	Canola	Wheat

Table 4-3. Lure composition and deployment schedule for field experiment in 2014 and 2015

Year	Lure	Components	Ratio	Amount	Time deployed
2014	Redbacked cutworm (RBC; *Euxoa ochrogaster*)	Z5-12Ac,	200	1000 µg	23 Jun – 10 Oct
		Z7-12Ac,	2		
		Z9-12Ac,	1		
		Z5-10Ac	1		
	Bertha armyworm (BAW; *Mamestra configurata*)	Z11-16Ac,	95	500 µg	10 Jun – 02 Sep
		Z9-14Ac	5		
	True armyworm (TAW; *Mythimna unipuncta*)	Z11-16Ac	1	1000 µg	10 Jun – 10 Oct
	Army cutworm (ACW, *Euxoa auxiliaris*)	Z5-14Ac,	100	100 µg	02 Sep – 10 Oct
		Z7-14Ac,	1		
		Z9-14Ac	10		
	AAMB	Acetic acid,	1	10 mL	10 Jun – 10 Oct
		3-methyl-1-butanol	1		
	Unbaited control	-	-	-	10 Jun – 10 Oct
2015	RBC	Z5-12Ac,	200	1000 µg	22 Jun – 15 Sept
		Z7-12Ac,	2		
		Z9-12Ac,	1		
		Z5-10Ac	1		
	BAW	Z11-16Ac,	95	500 µg	22 Jun – 04 Aug
		Z9-14Ac	5		
	TAW	Z11-16Ac	1	1000 µg	22 Jun – 15 Sept
	Pale western cutworm (PWC; *Agrotis orthogonia*)	Z7-12Ac,	2	500 µg	22 Jun – 15 Sept
		Z5-12Ac	1		
	AAMB	Acetic acid,	1	10 mL	22 Jun – 15 Sept
		3-methyl-1-butanol	1		
	AAMB+MP	Acetic acid,	1	10 mL	22 Jun – 15 Sept
		3-methyl-1-butanol,	1		
		2-methyl-1-propanol	1		
	AAMB+PAA	Acetic acid,	1	10 mL	22 Jun – 15 Sept
		3-methyl-1-butanol,	1		
		phenylacetaldehyde	1		
	AAMB+MP+PAA	Acetic acid,	1	10 mL	22 Jun – 15 Sept
		3-methyl-1-butanol,	1		
		2-methyl-1-propanol,	1		
		phenylacetaldehyde	1		
	Unbaited control	-	-	-	22 Jun – 15 Sept

Table 4-4. Lure composition of the floral blend of the Canada thistle lures.

Compounds	Quantities (μg)					
	PAA	CT 0.1×	CT 1.0×	CT 2.0×	CT 4.0×	Control
Benzaldehyde	-	0.3	3.0	6.0	12.0	-
Benzyl Alcohol	-	0.3	3.0	6.0	12.0	-
Phenylacetaldehyde	200.0	10.0	100.0	200.0	400.0	-
Methyl Benzoate	-	0.1	1.0	2.0	4.0	-
Linalool	-	0.3	3.0	6.0	12.0	-
Phenyl ethyl Alcohol	-	0.5	5.0	10.0	20.0	-
Methyl Salicylate	-	2.5	25.0	50.0	100.0	-
P-anisaldehyde	-	0.5	5.0	10.0	20.0	-
Dimethyl Salicylate	-	2.0	20.0	40.0	80.0	-
EE-α-farnesene	-	0.1	1.0	2.0	4.0	-
Benzyl benzoate	-	0.5	5.0	10.0	20.0	-
Total load	200.0	17.1	171.0	342.0	684.0	0.0

Table 4-5. Mean number of the season long capture of cutworm and armyworm moths in AAMB baited traps in Experiment 1, 2014

				Canola		Wheat	
Tribe	**Subtribe**	**Scientific name**	**Common name**	**Female**	**Male**	**Female**	**Male**
Noctuini	Agrotina	*Euxoa ochrogaster*	Redbacked cutworm	2.28 ± 1.17	1.28 ± 0.52	4.86 ± 2.99	2.71 ± 2.06
		Euxoa auxiliaris	Army cutworm	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
		Euxoa scandens	White cutworm	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.14 ± 0.14
		Feltia jaculifera	Dingy cutworm	1.14 ± 0.40	2.29 ± 0.42	1.29 ± 0.74	6.42 ± 5.18
		Agrotis venerabilis	Dusky cutworm	0.14 ± 0.14	0.00 ± 0.00	0.14 ± 0.14	0.29 ± 0.18
		Agrotis orthogonia	Pale wester cutworm	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	Noctuina	*Noctua pronuba*	Winter cutworm	0.14 ± 0.14	0.00 ± 0.00	0.00 ± 0.00	0.14 ± 0.14
Apameini		*Apamea devastator*	Glassy cutworm	0.42 ± 0.30	0.86 ± 0.46	0.57 ± 0.42	2.57 ± 1.04
		Apamea amputatrix	Yellow head cutworm	0.14 ± 0.14	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
		Amphipoea interoceanica	Strawberry cutworm	2.28 ± 0.89	4.0 ± 2.03	3.14 ± 1.26	8.14 ± 4.1
Hadenini		*Xestia c-nigrum*	Spotted cutworm	0.29 ± 0.18	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
		Anarta trifolii	Clover cutworm	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
		Dargida procinctus	Olive green cutwom	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.14 ± 0.14
		Mamestra configurata	Bertha armyworm	0.29 ± 0.18	0.14 ± 0.14	0.28 ± 0.18	0.29 ± 0.18
Eriopygini		*Lacinipolia renigera*	Bristly cutworm	0.28 ± 0.18	0.00 ± 0.00	0.14 ± 0.14	0.42 ± 0.20
Tholerini		*Nephelodes minians*	Bronzed cutworm	0.00 ± 0.00	1.26 ± 0.18	0.28 ± 0.28	1.42 ± 0.52
Leucanii		*Mythimna unipuncta*	True armyworm	0.57 ± 0.42	0.14 ± 0.14	1.71 ± 1.41	1.14 ± 1.14

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Chapter 5: A diversity of noctuid moths (Lepidoptera: Noctuidae) attracted to food-based semiochemical lures in Canadian Prairie agroecosystems

Abstract

Noctuidae is one of the most diverse and abundant lepidopteran families in the Prairie Ecozone. Within this diverse group, a few noctuid species are regarded as agricultural pests in the region. Cutworms and armyworms (Lepidoptera: Noctuidae) are part of a pest complex native to North America that can cause economic damage to multiple crops across the Canadian Prairies. Unless noctuid pest densities are monitored systematically during high and low population phases, population surges will not be detected or predicted. The chemical mixture of two fermented bait by-products, acetic acid and 3-methyl-1-butanol (AAMB), has been used to monitor the diversity and abundance of moths in multiple cropping systems. In this study, I report on the diversity and abundance of pest and non-pest noctuid moths trapped with the AAMB lure in two cropping systems at seven sites in central Alberta, Canada. In two years of trapping, 7,900 noctuid moths were trapped and identified to species. There was no difference in noctuid community composition of moths captured in traps deployed in canola or wheat fields. AAMB-baited traps captured a higher diversity of moths than unbaited traps and explained 15% of the variation in species composition. Noctuinae moths were the most diverse and abundant subfamily attracted to the AAMB lure with 62 species in 8 tribes. AAMB-baited traps captured a higher diversity and abundance of the cutworm and armyworm pests compared to unbaited traps. More noctuid pests were attracted to food bait lures from fermented bait by-products than floral volatiles. AAMB lure can be implemented to monitor the diversity of Noctuinae moths in agroecosystems in Canadian Prairies, and potentially monitor the local density of noctuid pests.

Introduction

The order Lepidoptera is one of the most diverse insect taxa in the Prairie Ecozone, with 2,232 species recorded in 61 families (Pohl et al., 2014). Moths from the families Geometridae, Erebidae and Noctuidae represent 78 % of the total diversity of macro-moth species; and noctuid moths alone, with 693 reported species, make up 28% of the entire lepidopteran fauna in the Canadian Prairies (Pohl et al., 2014). Noctuid moths perform important biological roles in the biotic interactions in prairie habitats. Larvae and adults serve as food sources to higher trophic levels, such as predatory beetles (Frank, 1971, Cárcamo et al., 1995) and spiders (Pearce et al., 2004), grassland birds (Maher, 1979) and insectivorous bats (Vonhof and Hobson, 2001). Although often overlooked, moths also act as generalist nocturnal pollinators in several plant systems, and are capable of dispersing pollen over longer distances than other insects (Reynolds et al., 2009, Winfree et al., 2011). Furthermore, feeding damage by larvae can impact plant community structure, which is dependent on the spatial and temporal variation of moth populations (Crawley, 1989).

The majority of Lepidoptera species in the Canadian Prairie provinces have a neutral effect on agriculture or provide valuable ecosystem services, while only a few species are considered to be pests of several annual crops (Vankosky et al., 2017). Cutworms and armyworms (Lepidoptera: Noctuidae) are part of a pest complex native to North America that can cause economic damage to multiple annual crops grown across the Canadian Prairies (Beirne, 1971, Floate, 2017). The diversity and abundance of the pest complex in a given field is highly variable and it is influenced by differences in regional climate, agricultural practices, the life history traits of the moths and other factors (Floate and Hervet, 2017).

At least 75 % of the grassland habitats in the Canadian Prairie Provinces has been altered for crop cultivation and livestock production (Shorthouse, 2010). Fragmentation of the landscape to support intensive monocultural systems of annual crops and perennial forages is one of the major drivers of reduced arthropod diversity in agroecosystems (Meehan et al., 2013). Agronomic practices result in high levels of habitat disturbance, which have a strong impact on insect community structure and variation in population density of pest species (Shennan, 2008, Evans and Sanderson, 2018). Unless cutworm and armyworm populations are monitored systematically during both high and low population phases, population surges will not be detected or predicted.

Trapping is a useful technique to assess Lepidoptera diversity and abundance in agroecosystems. Light trapping is a common method employed to survey moth diversity and abundance (Ayre and Lamb, 1990, Chey et al., 1997, Beck et al., 2002), however, this tactic requires careful monitoring and is dependent on a power source. Capture of moths in light traps is heavily dependent on the environmental conditions during the trapping period (Yela and Holyoak, 1997, Jonason et al., 2014). Shorter bright nights in the summer may reduce the attraction of moths to light traps in northern latitudes. In addition, surveys with light traps are performed once or few times throughout the summer, and moth community assemblage results may be biased by temporal variation (Lintott et al., 2014).

Food-based semiochemicals have been evaluated as lures to detect, monitor and manage noctuid moths, as these cues attract both sexes of moths (Joyce and Lingren, 1998). In contrast to light trapping, food bait traps can remain in place throughout the growing season to survey moth populations and gather information on seasonal flight patterns. Fermented sugars were some of the first food baits used to monitor the diversity of Lepidoptera. Utrio and Eriksson (1977) trapped several macrolepidopteran species with single chemical and blends of volatile compounds from fermented sources of multiple sugars. The chemical mixture of two fermented sugar by-products, acetic acid and 3-methyl-1-butanol (AAMB), has been used to monitor the diversity and abundance of moths in multiple cropping systems (Landolt et al., 2007, 2011). Several pest species from the cutworm and armyworm complex are attracted to AAMB lures, including the bertha armyworm (*Mamestra configurata* Walker) (Landolt, 2000), true armyworm (*Mythimna unipuncta* [Haworth]) (Landolt and Higbee, 2002) and the redbacked cutworm (*Euxoa ochrogaster* [Guenée])(Landolt et al., 2007). Feeding attractants based on volatiles from flowers visited by noctuid moths as adult food sources have been used to monitor populations of the cabbage looper (*Trichoplusia ni* [Hübner]) (Cantelo and Jacobson, 1979), alfalfa looper (*Autographa californica* [Speyer]) (Guédot et al., 2008) and the soybean looper (*Chrysodeixis ubcludens* [Walker]) (Meagher Jr, 2001a). Although fermented sugar baits and floral volatiles lures attract a broad group of noctuid moths, there may be differences in preference to food-based semiochemicals by different lepidopteran taxa.

The main goal of this project is to develop a food-based semiochemical lure to monitor the cutworm and armyworm pest complex in the Canadian Prairie agroecosystems. First, I determined the attractiveness of AAMB baited traps compared to unbaited traps and sex pheromone-baited traps (Chapter 4). Second, I measured the attraction of the AAMB lure in combination with additional food-based semiochemicals (Chapter 4). Here, I report on the diversity and abundance of noctuid moths trapped with food bait lures based on volatiles from fermented sugar baits by-products. The first objective of the study was to evaluate differences in species composition of moths sampled in two cropping systems, canola (*Brassica napus* L.) (Brassicaceae) and wheat (*Triticum aestivum* L.) (Poaceae), in Alberta. The second objective was to determine differences in lepidopteran taxa, specifically moths within the subfamily Noctuinae, attracted to AAMB lures alone and with additional chemical compounds. Despite the important role of noctuid moths in prairie ecosystems, information on the impact of agronomic practices on the status of moth diversity and abundance in agricultural ecosystems is lacking. Moth community composition can be used as a bioindicator to reflect the state of disturbance of agricultural ecosystems or to improve management strategies (Olfert et al., 2002).

Materials and Methods

Study Area

A series of experiments to develop food-based monitoring tools for noctuid moth diversity were conducted in 2014 and 2015 in wheat and canola fields located in the Aspen Parkland Ecoregion of Alberta, Canada. The landscape in this region is characterised by extensive agricultural plains with discontinuous clusters of trembling aspen (*Populus tremuloides* Michx) (Salicaceae) and balsam poplar (*P. balsamifera* L.) trees (Shorthouse, 2010). Seven sites were selected for moth monitoring across central Alberta, dispersed over an area of approximately 7 350 km² in five counties (Table 5-2). Sites were separated by at least 20 km from other experimental sites. Each site consisted of a canola field paired with a wheat field, separated by a minimum of 500 m. All experiments were conducted at the same seven sites each year. Due to crop rotation practices, a canola field in the first year was rotated to wheat in the second year.

Lures

Two types of lures were used to attract noctuid moths in all experiments: synthetic sex pheromone lures and custom-made food-based semiochemicals. Sex pheromone lures targeting different pest species of cutworm and armyworm moths were used in different experiments (Table 5-3). Sex pheromone blends for each of the target species were prepared and loaded onto pre-extracted red rubber septa; prepared by Contech Enterprise Inc. (Delta, BC). Food bait lures were prepared in the laboratory, following the methods of Landolt et al. (2007). The AAMB lure consisted of acetic acid and 3-methyl-1-butanol in a 50:50 by weight mixture [glacial acetic acid (99.7% purity) Fisher Scientific, Fair Lawn, NJ; 3-methyl-1-butanol (98.5% purity) Sigma Aldrich, St. Louis, MO]. The AAMB chemical mixture was dispensed into a 15 mL narrow-mouth Nalgene HDPE bottle (Thermo Scientific, Rochester, NY) with two cotton balls inserted at the bottom. Each bottle received 10 mL of AAMB chemical mixture. A 3.0 mm diameter hole drilled in the centre of the bottle cap allowed for release of volatiles.

Monitoring and moth identification

Non-saturating green universal moth traps (Unitrap, Contech Enterprise Inc. Delta, BC) were employed in all experiments. Traps were positioned 1.5 m above ground, spaced 25 m apart in a linear transect positioned approximately 5 m from the field edge. Unitraps were baited with either a sex pheromone or a food bait lure. Sex pheromone lures were placed inside baskets positioned under the roof of the unitrap and were replaced every four weeks. Food bait lures were secured to the inside wall of the unitrap buckets with a twist-tie and were replaced every two weeks. An insecticidal strip of Hercon Vaportape II (10% dichlorvos) (Hercon Environmental. Emigsville, PA) was placed inside the bucket of each trap to kill captured insects. Insecticidal strips were replaced every four weeks.

Insect trap catch was collected every week in plastic bags, labelled and frozen at – 20 ^{o}C until it was sorted and identified. In the laboratory, moth trap catch and Hymenoptera by-catch were separated from other arthropods. Moths were separated by sex and pinned. If noctuid moths were in poor condition (i.e. no scales on wings or missing body parts), genitalic dissections were performed following the methods by Hardwick (1950). To dissect the genitalia, abdomens were removed from moths and immersed in 1 mL potassium hydroxide solution (10 % KOH w/v) (Biosev, Frenchtown, NJ) in 1.8 mL glass vials (Fisher Scientific, Fair Lawn, NJ) for 48 hours to dissolve organs and fatty tissue. Moth genitalia were spread and mounted on cardstock (2.0 × 0.5 cm) with Euparal mounting medium (Bioquip Products Inc. Rancho Dominguez, CA). Moths were identified to species through wing maculation and/or morphological characters of genitalia following taxonomic keys from "The Moths of America North of Mexico" book series (Lafontaine, 1987, 1998, 2004, Lafontaine and Robert, 1991, Mikkola et al., 2009). Identifications were verified using comparisons with reference collections at the E. H. Strickland Entomological Museum (University of Alberta, Edmonton, AB).

Pinned moths in the best condition and mounted genitalia dissections from each identified species were selected as voucher specimens and deposited at the E. H. Strickland Entomological Museum, Department of Biological Sciences, University of Alberta, Edmonton.

Experiment 1 – Diversity of moths attracted to food bait (AAMB) lures

Experiment 1 evaluated the diversity and abundance of noctuid moths attracted to AAMB lures. Capture of moths from AAMB-baited traps was compared to that in unbaited control traps. In addition, sex pheromone-baited traps of several cutworm and armyworm pest species were deployed to ensure target moths were present in the field at the time of the experiment. Unitraps were baited with either: redbacked cutworm (RBC) pheromone, bertha armyworm (BAW) pheromone, true armyworm (TAW) pheromone, army cutworm (ACW) pheromone, AAMB lure or left unbaited. The six baited traps were positioned in a linear transect, as described above, in random order in both canola and wheat fields at each of the seven sites. The experiment was conducted from 10 June to 10 October 2014. Sex pheromone-baited traps were deployed in the field according to the flight period of the target moth species (Table 5-3), while the AAMB- and unbaited traps remained in the field throughout the 17-week sampling period. Moths captured in the differently baited traps were identified to species and analyses were conducted on the total number of moths trapped over the sampling season.

First, I determined the specificity of the sex pheromone lures to monitor target moths. Trap catch was separated into two groups: target and non-target moths, and the percentage of target moths captured in sex pheromone-baited traps was calculated from the total moth trap catch ([total number of target moths / total moth trap catch] × 100). Lure specificity was analyzed in a binomial count model in which the response variable is a two-vector object comprised of the count of target moths (success) as the first vector and the count of non-target moths (failure) as the second vector. The two-vector response variable was analyzed in a generalized linear mixed model with binomial family distribution with the ‘glmer’ command in R package ‘lme4’ v.1.1-17 (Bates et al., 2015). Crop and sex pheromone lure were specified as explanatory fixed variables and site as random block factor (Table 5-1).

Several analyses compared the total capture of moths in AAMB- and unbaited traps. A non-metric multidimensional scaling (NMDS, “Bray-Curtis” distance) analysis was conducted to: 1) determine the diversity of moth species attracted to the AAMB lure in comparison to that in unbaited control traps; and 2) to evaluate differences in moth species composition sampled with AAMB-baited traps positioned in canola and wheat fields. A non-parametric permutation analysis of variance (ADONIS, “Bray” distance) was performed to define the variation in moth species composition explained (R^2) by crops and bait treatment (AAMB or unbaited). Additionally, two analyses of similarities (ANOSIM, “Bray” distance) were conducted to determine differences in moth diversity and abundance based on crop and trap bait treatment. The first ANOSIM compared the capture of moths from traps in canola fields to those in wheat fields, while the second ANOSIM compared the moth trap catch in AAMB-baited traps and unbaited traps. ANOSIM analysis compares the mean rank distances between and within the levels of a factor. If the levels of a factor are significantly different, then the dissimilarities between levels is greater than the dissimilarities within levels (ANOSIM statistic: R-value = 1.0; $p < 0.05$). Similar analyses were conducted separately on species from the cutworm and armyworm pest complex to determine the effectiveness of AAMB traps in comparison to unbaited traps.

Moth trap catch in AAMB baited traps was grouped by family and subfamily to compare differences in attraction to food bait lures by moth taxonomic group. An independent analysis was conducted on the total number of Noctuinae moths by tribe that compared the moth trap catch from AAMB to that in unbaited traps. Noctuinae moth trap catch was analyzed in a generalized linear mixed model (Negative binomial family distribution) with the 'glmer.nb' command in the R package 'lme4' v.1.1-17 (Bates et al., 2015). Crop, bait treatment (AAMB or unbaited) and Noctuinae tribe were specified as explanatory fixed variables and site as a random block factor (Table 5-1).

Experiment 2 – Diversity of moths attracted to AAMB lures with additional food-based semiochemicals.

Experiment 2 evaluated the diversity and abundance of moths attracted to AAMB lures with additional chemical compounds. The tested chemicals were an alcohol from fermented sugar bait by-products, 2-methyl-1-propanol (MP) (> 99% purity) (Acros Organics, Fair Lawn, NJ), and a floral volatile, phenylacetaldehyde (PAA) (> 98% purity) (Acros Organics, Fair

Lawn, NJ). Treatments included: AAMB alone, AAMB+MP, AAMB+PAA, AAMB+MP+PAA and an unbaited trap served as control. All lures were prepared in the laboratory in a mixture of equal proportions by weight (Table 5-3). Ten millilitres of the chemical mixtures were loaded in Nalgene HDPE bottles, as previously described, with a 3.0 mm diameter hole in each bottle cap for release of the volatile chemical mixture. Bottles were secured to the inside wall of the unitrap bucket with a twist-tie and were replaced every two weeks. In addition to the different food bait lures, sex pheromone-baited traps targeting RBC, BAW, PWC and TAW were deployed to ensure target moths were present in the field at the time of the experiment (Table 5-3). The nine baited traps were positioned in a linear transect in random order in both canola and wheat fields at the seven sites. The experiment was conducted from 22 June to 15 September 2015. Noctuid moth trap catch per baited trap was identified to species and analyses were conducted on the total number of moths captured over the sampling season. Results focused on comparing the moth trap catch from the different food bait lures and unbaited traps.

A non-metric multidimensional scaling (NMDS, "Bray-Curtis" distance) analysis was conducted to: 1) determine differences in diversity of moths attracted to the AAMB lure with additional chemical compounds; and 2) to evaluate differences in moth species composition sampled in canola and wheat fields. A non-parametric permutation analysis of variance (ADONIS, "Bray" distance) was conducted to define the percentage of variation in moth species composition explained (R^2) by crops and lure types. Additionally, two analyses of similarities (ANOSIM, "Bray" distance) were conducted to determine differences in moth diversity and abundance within two factors: crop and lure type. The first ANOSIM compared the diversity of moth capture in traps deployed in canola fields to that from traps deployed in wheat fields, while the second ANOSIM compared the diversity of moth trap catch among the lure types. Similar analyses were conducted separately on the species from the cutworm and armyworm pest complex to determine the diversity of trap capture in response to AAMB lures with an additional fermented by-product or floral volatile.

Moth trap catch was grouped by family and subfamily to estimate differences in attraction to the AAMB lure with additional chemicals among the moth taxonomic groups. Furthermore, an independent analysis was conducted on the total numbers of Noctuinae moths by tribe that compared moth trap catch in the different food bait lures and unbaited traps. Noctuinae moth trap catch was analyzed with a generalized linear mixed model (Negative binomial family distribution) with the 'glmer.nb' command in the R package 'lme4' v.1.1-17 (Bates et al., 2015). Crop, lure type and Noctuinae tribe were specified as explanatory fixed variables and sites as random block factor (Table 5-1).

Results

Experiment 1 – Diversity of moths captured in AAMB baited traps.

Euxoa ochrogaster, RBC, was the most abundant species among the target pests. Redbacked cutworm sex pheromone baited traps captured on average 1,077.5 ± 407.3 (SE) RBC males per site throughout the sampling period. *Mamestra configurata*, BAW, was the second most abundant target species. Bertha armyworm sex pheromone baited traps captured 89.7 ± 33.9 BAW males per site throughout the sampling period. *Mythimna unipuncta*, TAW, and *E. auxiliaris*, ACW, were the least abundant target species. True armyworm sex pheromone baited trap captured on average 1.4 ± 0.5 TAW males, whereas army cutworm sex pheromone baited traps captured on average 0.4 ± 0.4 ACW males.

Sex pheromone lures had similar specificity in both canola and wheat fields (Wald χ^2 = 0.29, df = 1, p = 0.591). Sex pheromone lure specificity varied with the target species (Wald χ^2 = 242.47, df = 3, p < 0.001) (Figure 5-1). Redbacked cutworm sex pheromone lures had the highest specificity, in which RBC represented 95.2 % of the total moth trap catch. *Plusia putnami* Grote (Lepidoptera: Noctuidae) was the most abundant non-target species in redbacked cutworm sex pheromone baited traps (3%) (Table 5-S1). *Plusia putnami* male moths were captured in RBC sex pheromone baited traps in early summer, from 30 June to 05 August, while *E. ochrogaster* male moths were captured in RBC sex pheromone baited traps later in the summer, from 22 July to 10 October. Bertha armyworm sex pheromone lures were less specific, but 63.3% of the total trap capture was BAW. *Apamea cogitata* (Smith) (Lepidoptera: Noctuidae) was the second most abundant non-target species in BAW sex pheromone baited traps (26 %) (Table 5-S1). *Mamestra configurata* and *A. cogitata* were captured in BAW sex pheromone baited traps from 24 June to 29 July.

Army cutworm sex pheromone traps had low specificity, in which ACW represented only 28.4 % of the total moth trap catch. This low specificity, however, may be influenced by the low population density of the target species across all fields. Army cutworm sex pheromone baited traps captured on average 2.1 ± 1.8 (SE) moths across all sites throughout the season. True armyworm sex pheromone lures had the lowest specificity, as TAW represented 0.3 % of the total moth trap catch. True armyworm sex pheromone-baited traps captured high numbers of RBC (67 %), *Helatropha reniformis* Grote (Lepidoptera: Noctuidae) (12 %), *A. inficita* Walker (10 %) and *Anarta trifolii* (Hugnagel) (Lepidoptera: Noctuidae) (4 %) (Table 5-S1). The low capture of TAW male moths in sex pheromone baited traps may be a result of the low specificity of the synthetic pheromone lure or the low population density of the target species across all fields.

AAMB baited traps captured on average 70.6 ± 18.1 moths per site throughout the sampling period, while unbaited traps captured 18.4 ± 10.3 moths per site. In total 54 macro-Lepidoptera species were captured in AAMB and unbaited traps (Table 5-S2). Crop type explained only 3 % of the variation in species composition (ADONIS $R^2 = 0.03$; $p = 0.34$), while lure type explained 15% of the variation in species composition (ADONIS $R^2 = 0.15$; $p = 0.001$). There was no difference in species composition of moths captured in traps deployed in canola or wheat fields (ANOSIM R = 0.01; p = 0.267), as demonstrated by the overlapping ellipses in the NMDS plot (Figure 5-2). Only one species, *Mythimna oxygala* (Grote) (Lepidoptera: Noctuidae), was more abundant in traps positioned in wheat fields over canola. AAMB-baited traps captured a higher diversity of moths than unbaited traps (ANOSIM R = 0.365; p = 0.001), as shown by the non-overlapping ellipses in the NMDS plot (Figure 5-3).

Moths within the Noctuidae family were the most diverse and abundant group attracted to AAMB-baited traps (47 spp). Other moth families included Drepanidae (1 sp.), Erebidae (1 sp) and Sphingidae (1 sp), however, moths from these families were captured in low numbers in AAMB-baited traps (Table 5-S2). Noctuinae moths were the most diverse and abundant subfamily attracted to the AAMB lure (44 spp), while only a few specimens from Plusiinae (1 sp) and Acronictinae (2 spp) were captured (Table 5-S2). Moths from eight Noctuinae tribes were captured in AAMB-baited traps. Apameini moths were the most diverse and abundant tribe, followed by Noctuini moths (Figure 5-4A & B). Moth from the tribes Leucaniini, Eriopygini, Tholerini and Hadenini were trapped in lowers numbers, while Xylenini and Caradrinini moths were the least represented tribes. The most abundant species were: *Apamea cogitata* (15. 4 %), *Enargia decolor* (Walker) (14 %), *Amphipoea interoceanica* Smith (12.4 %), *Feltia jaculifera* (Guenée) (7.9%), RBC (7.9 %), *Helatropha reniformis* (Grote) (5.3 %) and *Apamea devastator* (Brace) (3.1 %).

An independent analysis compared the total numbers of Noctuinae moths by tribe captured in AAMB- and unbaited traps. AAMB-traps captured more Noctuinae moths in wheat fields than canola, whereas unbaited traps captured similarly low numbers of Noctuinae moths in both crops (crop × lure type, Wald $\chi^2 = 8.78$, df = 1, $p = 0.003$). Noctuinae moths were found in higher numbers in AAMB than unbaited traps, except for moths from the Caradrinini tribe that were found in similarly low numbers in both trap types (lure type × tribe, Wald $\chi^2 = 73.23$, df = 7, $p > 0.001$).

AAMB-baited traps captured a higher diversity and abundance of species of the cutworm and armyworm pest complex compared to unbaited traps (ANOSIM R = 0.400; p = 0.001) (Figure 5-5). These pests represented on average 42.60 % of the total moth trap catch in AAMB-baited traps per site. The most abundant pest species included the strawberry cutworm (*A. interoceanica*), RBC, dingy cutworm (*F. jaculifera*), glassy cutworm (*A. devastator*), TAW and bronzed cutworm (*Nephelodes minians* Guenée). The less abundant species captured were the BAW, bristly cutworm (*Lacinipolia renigera* [Stephens]), spotted cutworm (*Xestia c-nigrum* L.), the invasive pest winter cutworm (*Noctua pronuba* L.), white cutworm (*Euxoa scandens* [Riley]), yellow-headed cutworm (*Apamea amputatrix* [Fitch]) and olive-green cutworm (*Dargida procinctus* Grote). Dusky cutworm (*Agrotis venerabilis* Walker) was also captured in AAMB-baited traps IN low numbers, however, more dusky cutworm moths were found in unbaited than AAMB-baited traps.

Lastly, a large number of pollinators (*Bombus* spp) were captured in the various sex pheromone-baited traps compared to AAMB lure- and unbaited traps, whereas a large number of vespid wasps (Vespidae) were captureD in AAMB-baited traps only (Chapter 3).

Experiment 2 – Diversity of moths attracted to AAMB lures with additional food-based semiochemicals.

Traps baited with AAMB and AAMB+MP lures captured double the total number of moths as traps baited with AAMB+PAA and AAMB+MP+PAA, whereas unbaited traps had the lowest moth trap catch (Wald $\chi^2 = 269.63$, df = 4, $p < 0.001$) (Figure 5-6). AAMB and AAMB+MP-baited traps captured on average 173.4 ± 45.34 and 163.25 ± 46.41 (SE) moths per site, while AAMB+PAA and AAMB+MP+PAA-baited traps captured 82.5 ± 19.4 and 83.1 ± 21.91 moths per site. Unbaited traps captured on average 12.4 ± 1.5 moths per site throughout the sampling period. In total 76 macro-Lepidoptera species were captured in all traps across all sites (Table 5-S3). Crop explained 2 % of the variation in species composition (ADONIS $R^2 = 0.02$; $p = 0.059$), while lure type explained 16% of the variation in species composition (ADONIS $R^2 = 0.16$; $p = 0.001$). The species composition of moths captured in traps was similar in both canola and wheat fields (ANOSIM R = 0.00; $p = 0.282$). Food bait lure traps captured a higher diversity and abundance of moths compared to unbaited traps (ANOSIM R = 0.20; $p = 0.001$), however, the species composition of moths did not vary among the traps baited with the different food bait lures (ANOSIM R = 0.01; $p = 0.287$) (Figure 5-7).

Moths within the Noctuidae family were the most diverse and abundant group attracted to food bait lures (67 spp). Other lepidopteran families included Erebidae (3 sp), Sphingidae (2 spp), Cambridae (1 sp), Geometridae (1 sp) and Hesperiidae (1 sp), however, low number of individuals from these families were captured in the traps with different food bait lure combinations (Table 5-S3). Noctuinae moths were the most diverse subfamily attracted to the food bait lures (62 spp), while only a few specimens from Plusiinae (4 spp) and Acronictinae (1 sp) were captured in the baited traps (Table 5-S3). Moths from eight Noctuinae tribes were captured in the different food bait traps. Apameini moths were the most diverse and abundant tribe, followed by Noctuini and Eriopygini moths. Moth from the tribes Leucaniini, Tholerini and Hadenini were trapped in lowers numbers, while Xylenini and Caradrini tribes had the lowest number of species captured (Figure 5-8)

An independent analysis compared the total numbers of Noctuinae moths by tribe between the different food bait traps and unbaited traps. There was a marginally significant interaction between crop and lure type (crop × lure type, Wald $\chi^2 = 9.40$, df = 4, p = 0.052). The different food bait lures captured similar numbers of Noctuinae moths in canola fields, and the trap catch from the different food bait lures was significantly higher than in unbaited traps. In contrast, the different food bait traps caught more Noctuinae moths than unbaited traps in wheat fields. In addition, more Noctuinae moths were captured in AAMB and AAMB+MP baited traps compared to that in AAMB+PAA and AAMB+MP+PAA baited traps. Furthermore, there was a significant interaction between crop and Noctuinae tribe (crop × tribe, Wald $\chi^2 = 17.48$, df = 7, p = 0.016) that impacted moth capture. More Apameini, Eriopygini and Leucaniini moths were captured in traps positioned in wheat fields over canola, while moths from the tribes Noctuini, Hadenini, Tholerini, Xylenini and Caradrini occurred equally in traps positioned in both crops. Lastly, the response of Noctuinae moths to food bait lures was dependent on the tribe (lure type × tribe, Wald $\chi^2 = 130.91$, df = 28, $p < 0.001$). AAMB and AAMB+MB lures attracted more Apameini, Hadenini and Tholerini moths than traps baited with food baits with phenylacetaldehyde (Figure 5-9A, E & F). Noctuini, Eriopygini and Leucaniini moths were similarly captured in all traps baited with food bait lures (Figure 5-9B, C & D). The number of Caradrini and Xylenini moths did not differ between the food bait lure and unbaited traps (Figure 5-9G & F).

Traps baited with AAMB lures with additional food-based chemicals captured a higher diversity of the species in the cutworm and armyworm pest complex compared to unbaited traps (ANOSIM R = 0.16; p = 0.001). Traps baited with AAMB and AAMB+MP lures captured slightly lower proportions of pest species (43.1 % and 46.1 %, respectively) out of the total moth trap catch than traps baited with AAMB+PAA and AAMB+MP+PAA lures (41.7% and 37.2%, respectively) (Wald $\chi^2 = 17.36$, df = 3, $p < 0.001$). Several cutworm species, however, were more attracted to AAMB and AAMB+MP lures than lures with phenylacetaldehyde, including the dingy cutworm, RBC, glassy cutworm, strawberry cutworm and bronzed cutworm (Figure 5-10).

Lastly, the addition of phenylacetaldehyde to AAMB lures increased pollinators (*Bombus* spp.) by-catch in baited traps, whereas traps baited with AAMB and AAMB+MP capture a large number of vespid wasps (Vespidae) by-catch (Chapter 3).

Discussion

The vast majority of noctuid female-produced sex pheromones are a blend of straight-chain (*Z*)-alkneols, -alkenals or -alkenyl acetates of even carbon numbers (10 through 16) (Steck et al., 1982b). Depending on the species, noctuid females can produce complex blends of up to seven chemical compounds (Badeke et al., 2016). Although individual components of sex pheromone blends may be similar in some Noctuid species, specificity of the chemical signal is achieved by the specific ratio of the individual components or single structural alteration of one or more chemical components (Steck et al., 1982b).

Female-produced sex pheromones have been identified for most cutworm and armyworm pest species in the Canadian Prairies (Steck et al., 1982b). Differences in specificity of the sex pheromone lures tested here can be explained by the profile of the synthetic pheromone blends of the commercial lures. The standard four-component RBC sex pheromone lure had the highest specificity (95 %) in baited traps in central Alberta. A similar RBC lure specificity (> 99%) was reported in a noctuid pest survey in southern Alberta from 1978 to 1983 (Byers and Struble, 1987). Therefore, the four-component lure is an optimum synthetic pheromone blend to attract *E. ochrogaster* male moths (Struble, 1981). Furthermore, *P. putnami*, the most dominant non-target species captured in RBC sex pheromone baited traps (3%), shares the same components of the female sex pheromone blend of RBC at different ratios (Steck et al., 1982a) (Table 5-4), and thus, *P. putnami* is attracted to RBC sex pheromone baited traps. Differences in flight phenology may be a more important reproductive isolating mechanism than sex pheromone blend for both species. *Plusia putnami* flies early in the summer, while RBC flies from mid-summer to early-fall (Lafontaine, 1987, Lafontaine and Robert, 1991).

The standard two-component BAW sex pheromone lure has relatively low specificity (63 %) in baited traps in central Alberta. In addition, *Apamea cogitata*, the most dominant non-target species captured in BAW sex pheromone baited traps (26%), shares the same components of the female sex pheromone blend as BAW (Steck et al., 1982b) (Table 5-4); and thus, *A. cogitata* is attracted to BAW sex pheromone baited traps. A noctuid pest survey in southern Alberta reported a similar specificity of the standard two-component BAW sex pheromone lure (68 %) and the presence of *A. cogitata* as the dominant non-target species (Byers and Struble, 1987). Two additional trace components of BAW female sex pheromone blend were identified to enhance the attraction of male moths (Struble et al., 1984). The four-component blend increased

BAW attraction by 1.5-fold and reduced the *A. cogitata* by-catch, however, the four-component blend attracted other non-target species in similar numbers as the standard two-component blend (Byers and Struble, 1987). The two-component BAW sex pheromone lure remains as the standard lure for monitoring BAW across the Prairie Provinces.

The standard three-component ACW sex pheromone lure has very low specificity (28 %) in baited traps in central Alberta. In contrast, a noctuid pest survey in southern Alberta reported a high specificity (> 99 %) of the standard three-component ACW sex pheromone (Byers and Struble, 1987). Army cutworm sex pheromone baited traps captured very low numbers of moths (2.1 moths ± 1.8 SE per site), and thus, the low specificity may reflect a low population density of ACW in central Alberta in 2014 and not a low efficiency of the synthetic pheromone lure.

Four components have been identified in TAW female sex pheromone blend (Steck et al., 1982c) (Table 5-4), however, the TAW sex pheromone commercial lure used in the current study contained only the main component of the sex pheromone blend, (*Z*)-11-hexadecenyl acetate. The one-component TAW sex pheromone lure has extremely low specificity (0.3 %) and baited traps captured very low numbers of TAW male moths in central Alberta. Non-target species were capture at high numbers, including RBC (67 %), *H. reniformis* (12 %), *A. inficita* (10 %) and *A. trifolii* (4 %). The main component of the female sex pheromone lure in *H. reniformis* and *A. trifolii* is the same as TAW (Steck et al., 1982b) (Table 5-4), and thus, both noctuid moths are attracted to the one-component TAW sex pheromone baited trap. Although the sex pheromone blend of RBC is different from the blend of TAW, RBC was the most abundant the most abundant non-target species in TAW sex-pheromone baited traps. *Mythimna unipuncta* is rarely a common species in Alberta and sporadic infestations occur from moths that migrate from the south in spring (Fields and McNeil, 1984), however, I cannot conclude that the low trap catch of

TAW in sex pheromone baited traps reflects a low population density in central Alberta in 2014. In contrast, the large number of non-target noctuid moths captured in TAW sex pheromone baited traps indicate a low efficiency of the synthetic pheromone lure to monitor the target pest. Therefore, the single-component TAW sex pheromone lure is not an optimum synthetic pheromone lure to attract *M. unipuncta* male moths (Turgeon et al., 1983).

In total, 67 lepidopteran species were captured in traps baited with a food bait lure based on volatiles from fermented sugar bait by-products. Although more moths were captured in wheat fields compared to canola, there was no difference in the species composition of moths sampled in canola and wheat fields, which suggests a common moth species diversity in agroecosystems in central Alberta and/or significant dispersal capacity across agricultural landscape. A biodiversity survey in several farms in Sweden showed that species richness of butterflies and rove beetles did not differ by cropping system, but species richness generally increased with landscape heterogeneity at a farm scale level (Weibull et al., 2003). Noctuid moths are strong flyers and are capable of dispersing over long distances. For instance, marked individuals of *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) were recaptured at a maximum distance of 806 m for males and 608 m for females across corn (*Zea mays* L.) (Poaceae) fields (Vilarinho et al., 2011). Similarly, a mark-recapture experiments of *Heliothis virescens* (Fabricious) (Lepidoptera: Noctuidae), showed that moths can disperse up to 30 km from the release point (Schneider, 1999).

Moths from the family Noctuidae were the most diverse and abundant lepidopteran taxa captured in AAMB-baited traps, whereas only a few species from the families Erebidae, Geometridae, Sphingidae and Cambridae were captured in low numbers. The lack of capture of other lepidopteran taxa, outside Noctuidae, may be because taxa are not present or are not attracted to AAMB lures. The distribution of lepidopteran taxa sampled with AAMB-baited traps is representative of the proportion of species in each family of Lepidoptera present in grassland habits within the Prairie Ecozones. Noctuidae represents 80 % of the total macro-Lepidoptera diversity in grasslands habitats in the Canadian Prairies, followed by Erebidae with 10 % and Geometridae with 9 % (Pohl et al., 2014). Furthermore, the range of lepidopteran taxa captured in AAMB baited traps in the Canadian prairie agroecosystems is similar to that of the lepidopteran taxa captured in AAMB-baited traps in apple orchards in Washington (Landolt and Hammond, 2001) and horticultural gardens in Alaska (Landolt et al., 2007). Moths from different families differ in their attraction to specific compounds from fermented sugar bait by-products. For instance, more Geometridae moths were captured in traps baited with ethyl alcohol, acetoin or β-phenyl alcohol, while Noctuidae moths were captured at low numbers (Utrio and Eriksson, 1977). In contrast, a large number Noctuidae moths were captured with food baits based on acetic acid and 3-methyl-1-methanol, while Geometridae moths were captured at low numbers (Utrio and Eriksson, 1977). The monitoring experiment in central Alberta in 2014 shows a similar distribution of lepidopteran taxa in traps baited with AAMB lure.

Noctuinae moths were the most diverse and abundant noctuid subfamily attracted to AAMB lures, with the majority of species and the highest number of captured moths were represented in the tribes Apameini and Noctuini. The most abundant species captured in AAMB-baited traps in 2014, *A. cogitata*, was also reported as the most abundant noctuid species attracted to AAMB lure in baited traps in Alaska (Landolt et al., 2007). Several cutworm and armyworm pest species were captured in AAMB-baited traps in comparison to unbaited traps in 2014. The RBC, dingy cutworm, glassy cutworm, spotted cutworm, yellow-head cutworm and the olive-green cutworm have also been captured in AAMB-baited traps in noctuid moth survey in Washington and Alaska (Landolt and Hammond, 2001, Landolt et al., 2007), however, these surveys did not include an unbaited control trap to determine if these cutworm species are significantly attracted to AAMB lures.

A second experiment evaluated the addition of other food-based semiochemicals to AAMB lures to enhance the attraction of cutworm and armyworm pests in 2015. The distribution of lepidopteran taxa sampled in traps baited with the different food baited lures in 2015 shows a similar pattern as the survey in 2014. The large difference in the total number of moths captured in traps with AAMB alone and additional alcohol compared to baited traps with additional phenylacetaldehyde was mainly influenced by the lack of capture of *A. cogitata* moths in baited traps with the additional floral volatile. Likewise, more *A. cogitata* were captured in AAMB-baited traps compared to floral volatile-baited traps (Landolt et al., 2011).

A similar number of cutworm and armyworm species were found in traps baited with different food bait lure types, however, more noctuid pests were attracted to food bait lures from fermented by-products than floral volatiles, specifically the dingy cutworm, RBC, glassy cutworm, strawberry cutworm, bronzed cutworm and yellow-head cutworm. Similar patterns have been reported for the glassy cutworm and dingy cutworm (Landolt et al., 2011)

In summary, the AAMB lure has advantages and disadvantages as a potential tool to surveys and monitor noctuid moths. This study shows the broad attraction of acetic acid and 3-methyl-1-butanol to a large number of noctuid moths, and thus, food baits based on fermented by-products can be used to determine diversity of moth within the Noctuinae subfamily in agroecosystem (Süssenbach and Fiedler, 1999). Several noctuid pest species are attracted to AAMB lure, and therefore, this food bait can be implemented as a general lure to monitor the presence, abundance and flight activity of cutworm and armyworm in the Canadian Prairies. The addition of phenylacetaldehyde did not enhance the attraction of noctuid pest species, and some cutworm species were less attracted to food baits with floral volatiles. The general response of noctuid moths to AAMB-baited traps may pose a concern for monitoring noctuid pests because non-target Lepidoptera will increase the time sorting specimens and require specialized knowledge to identify individuals.

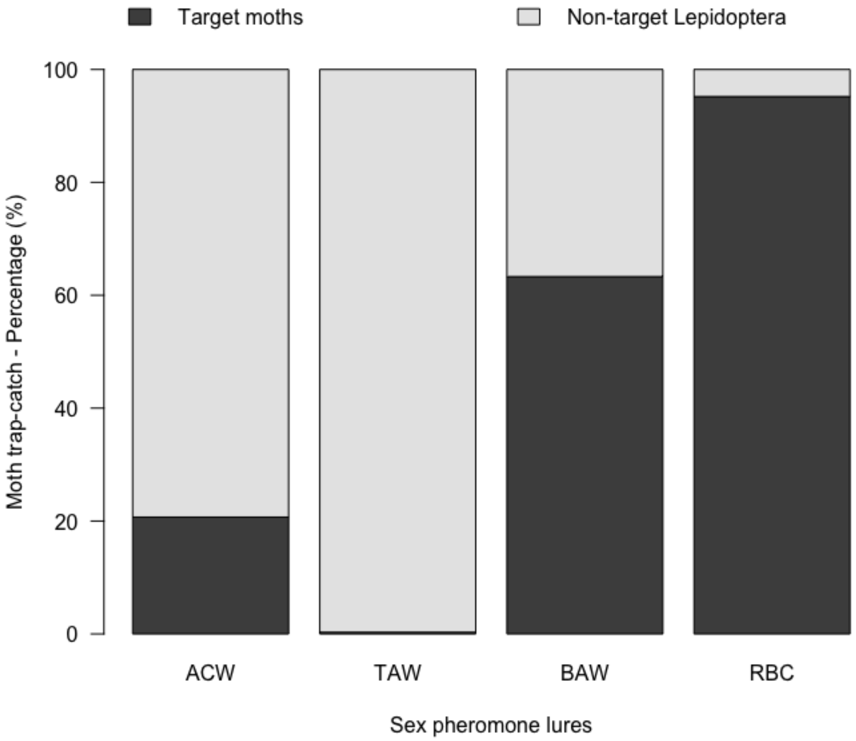

Figure 5-1. Sex pheromone lure specificity (Experiment 1) expressed as percentage (%) of target species captured in sex pheromone-baited traps from the total moth trap catch. RBC = redbacked cutworm (*Euxoa ochrogaster*); BAW = bertha armyworm (*Mamestra configurata*); TAW= true armyworm (*Mythimna unipuncta*); ACW = army cutworm (*Euxoa auxiliaris*).

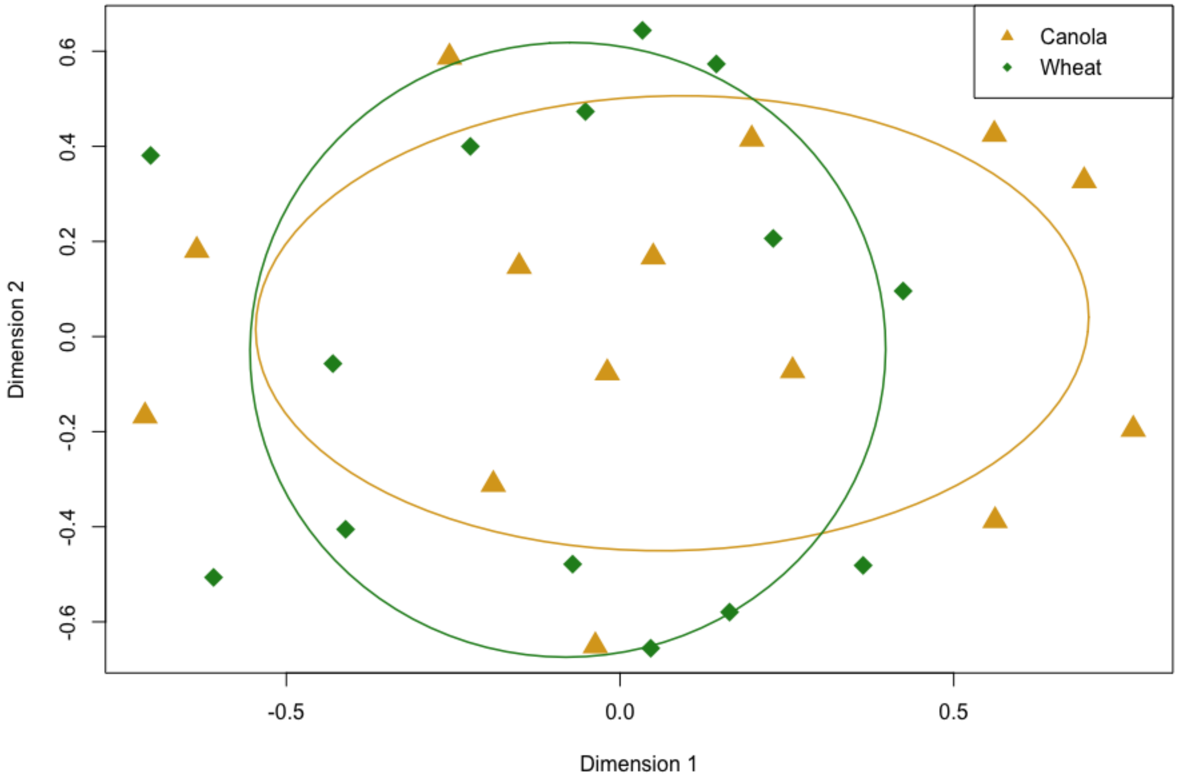

Figure 5-2. Non-metric multidimensional scaling (NMDS) for the diversity of moths sampled in canola and wheat fields at seven sites in central Alberta (Stress = 0.265; R^2 = 0.511).

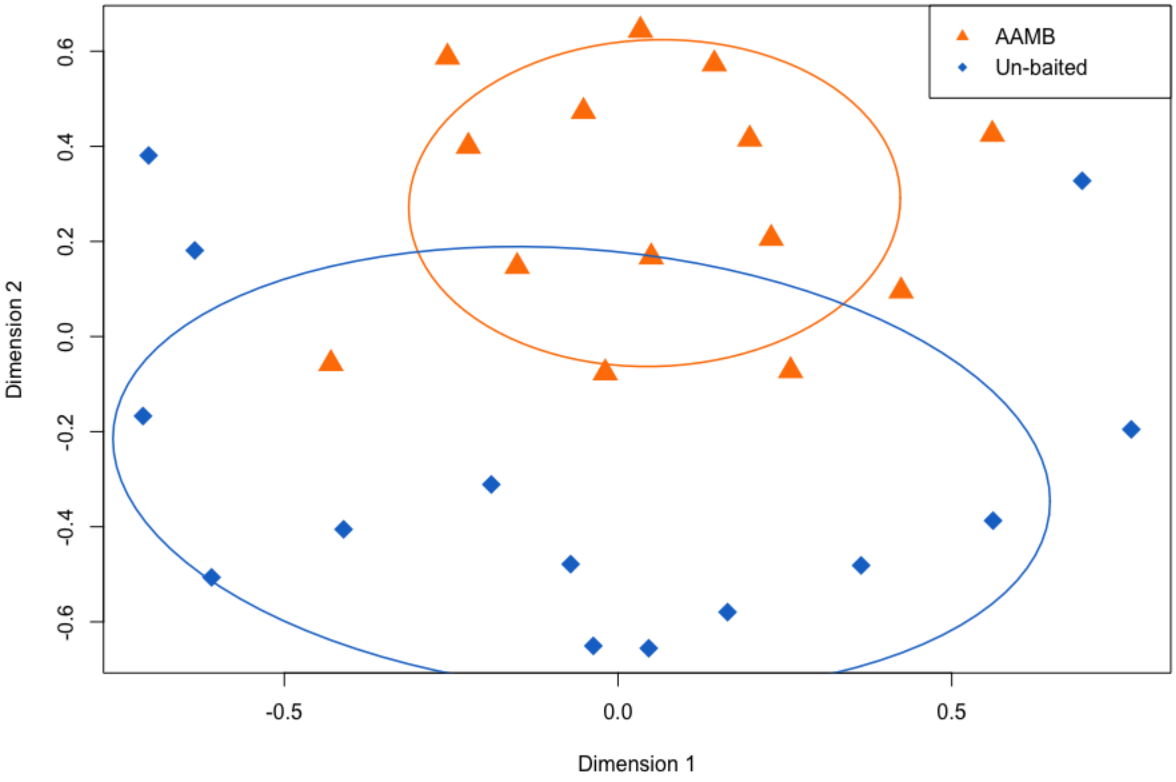

Figure 5-3. Non-metric multidimensional scaling (NMDS, Stress = 0.265; $R^2 = 0.511$) for the diversity of moths attracted to AAMB lure (acetic acid and 3-mehtyl-1-butanol) compared to unbaited traps.

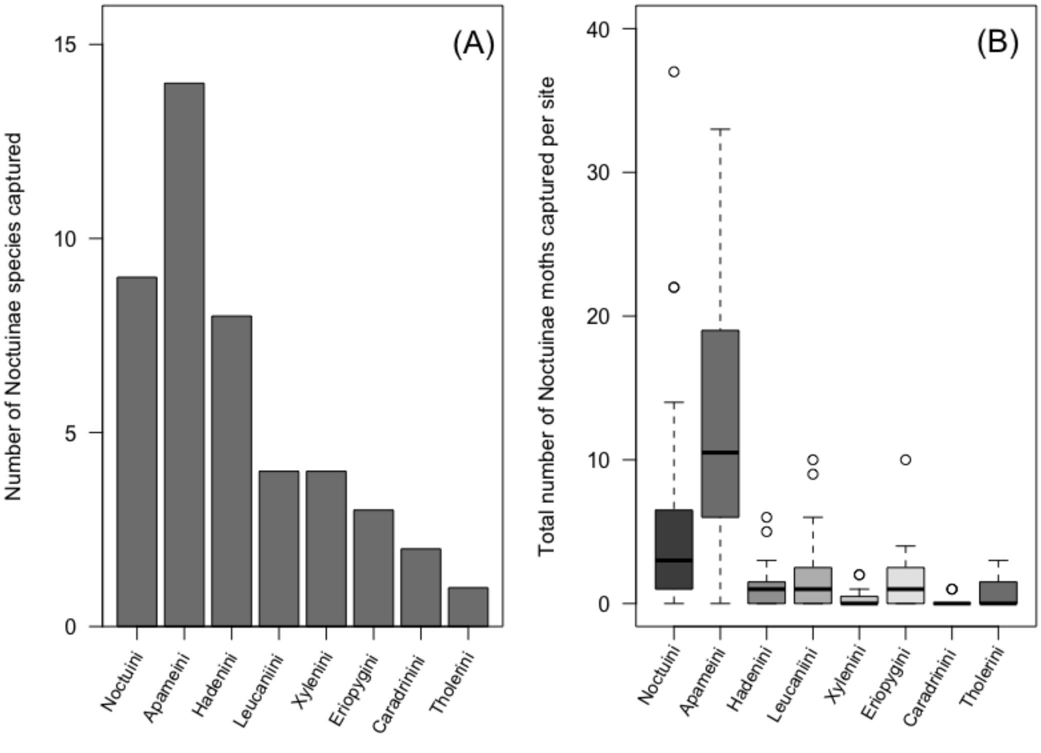

Figure 5-4. Diversity and abundance of Noctuinae moth by tribe captured in AAMB (Acetic acid and 3-methyl-1-butanol) baited traps. (A) Barplot of the total number of Noctuinae species by tribe. (B). Boxplot of the total number of Noctuinae moths by tribe. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range.

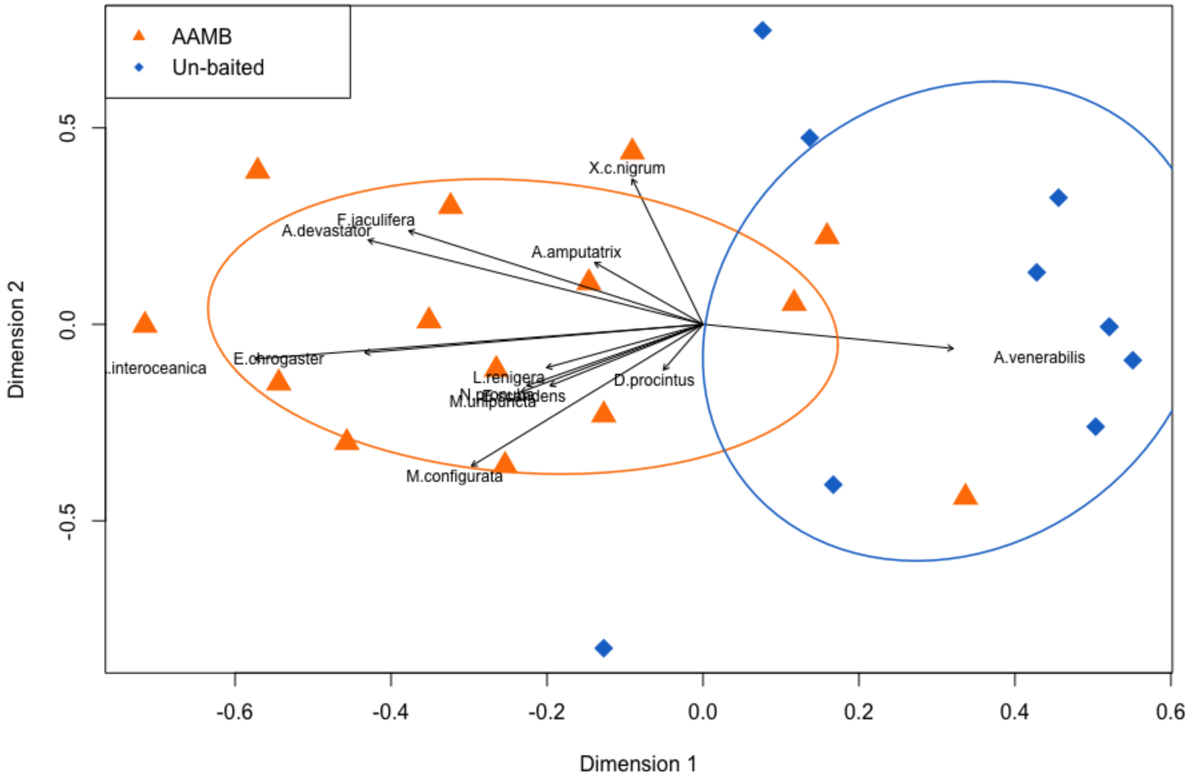

Figure 5-5. Non-metric multidimensional scaling (NMDS, Stress = 0.209; R^2 = 0.656) for the diversity of cutworm and armyworm species attracted to AAMB lure (acetic acid and 3-mehtyl-1-butanol) compared to unbaited traps.

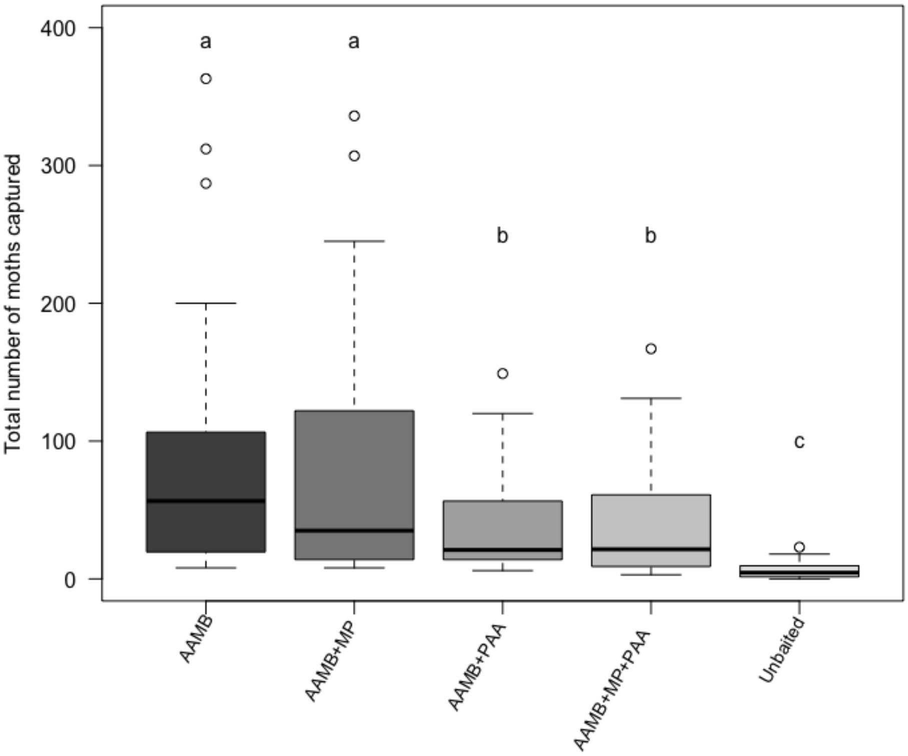

Figure 5-6. Boxplots of the total number of moths captured in AAMB lures with and without additional chemical compounds. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. The tested chemicals were an alcohol from fermented by-products, 2-methyl-1-propanol (MP), and a floral volatile, phenylacetaldehyde (PAA). Treatments included: AAMB alone, AAMB+MP, AAMB+PAA, AAMB+MP+PAA and an unbaited trap that served as control. Means comparisons were performed for difference in moth trap catch in traps baited with the different food bait lures. Boxplots marked with different letters are statistically different (Tukey method, α = 0.05).

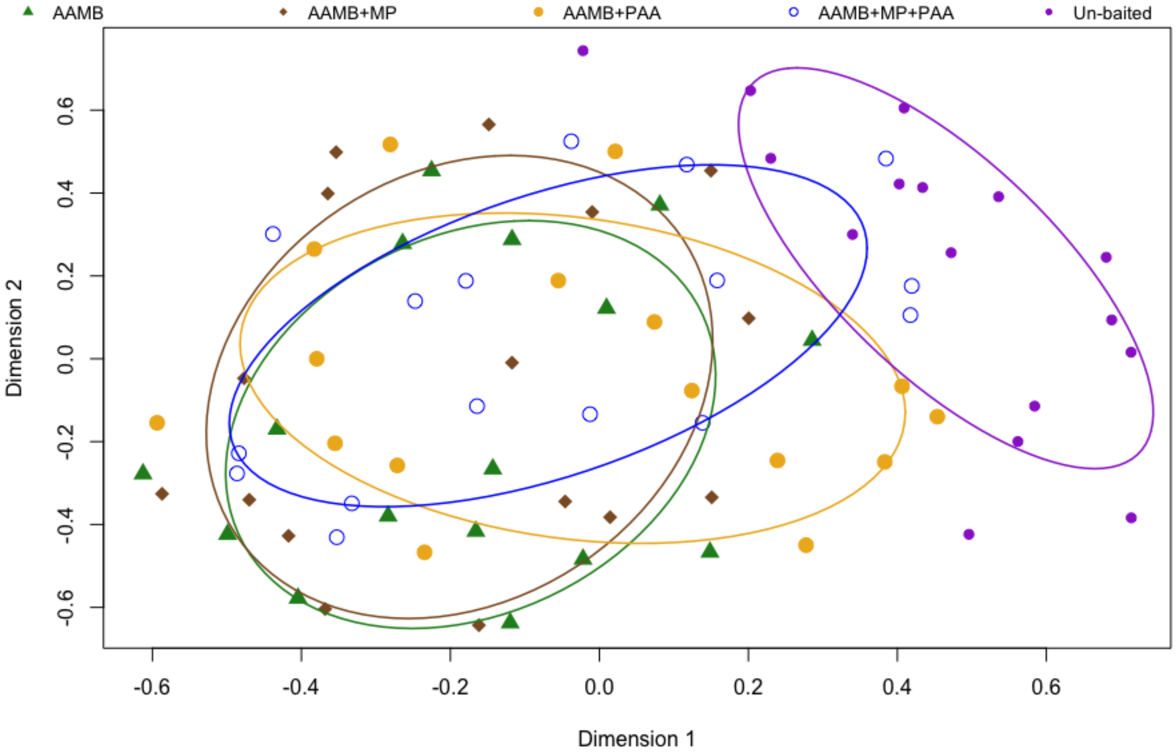

Figure 5-7. Non-metric multidimensional scaling (NMDS, Stress = 0.214; R^2 = 0.7182) for the diversity of moths attracted to AAMB lure with and without additional chemical compounds. The tested chemicals were an alcohol from fermented by-products, 2-methyl-1-propanol (MP), and a floral volatile, phenylacetaldehyde (PAA). Treatments included: AAMB alone, AAMB+MP, AAMB+PAA, AAMB+MP+PAA and an unbaited trap that served as control.

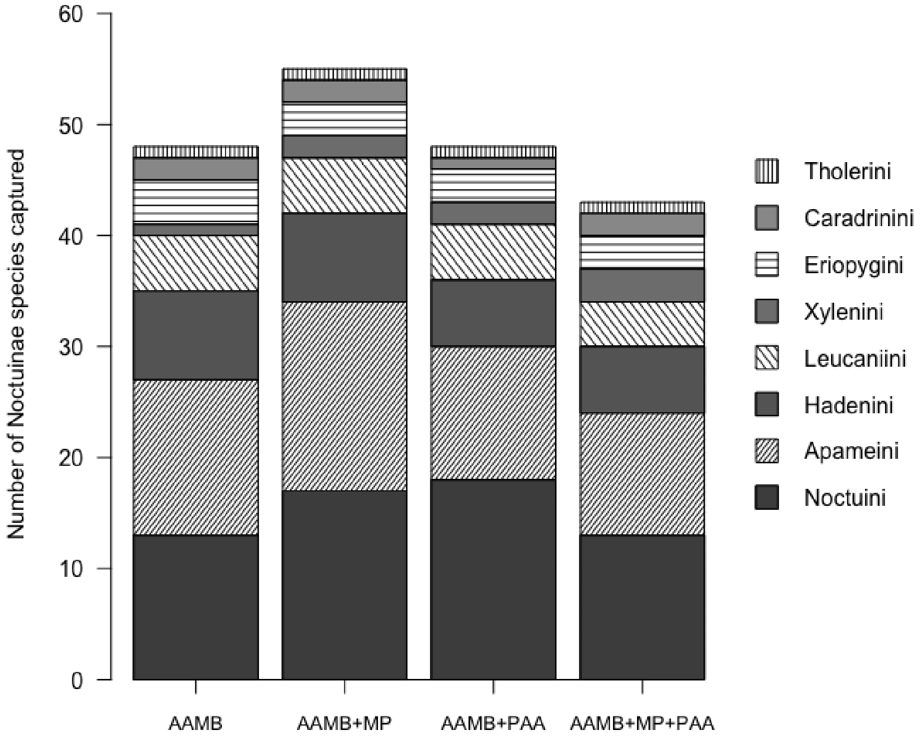

Figure 5-8. Barplot of the total number of species of Noctuinae moth by tribes captured in traps baited with AAMB lures with and without additional chemical compounds. The tested chemicals were an alcohol from fermented by-products, 2-methyl-1-propanol (MP), and a floral volatile, phenylacetaldehyde (PAA). Treatments included: AAMB alone, AAMB+MP, AAMB+PAA, AAMB+MP+PAA.

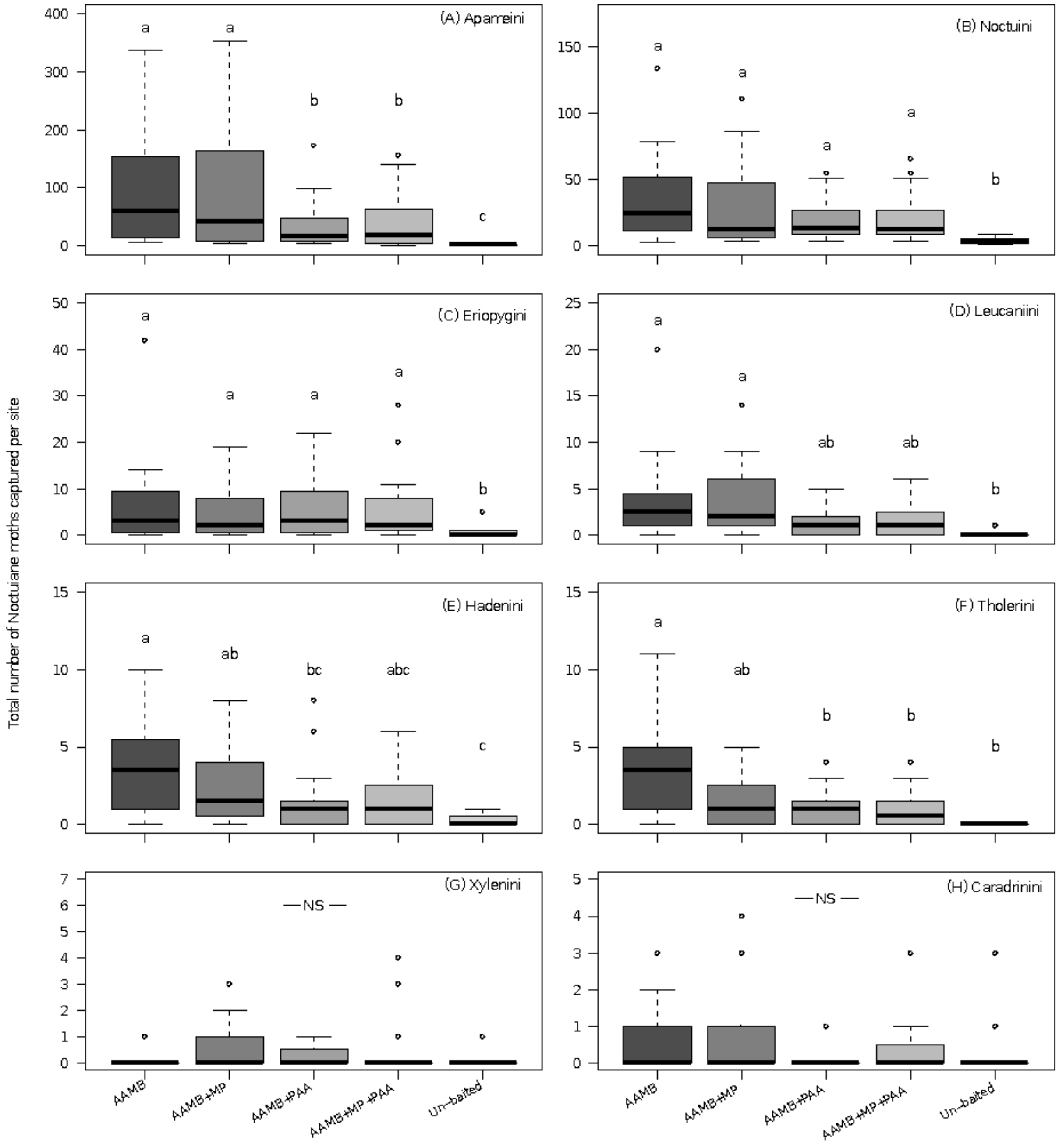

Figure 5-9. Boxplots of the total number of Noctuinae moths by tribe captured in traps baited with AAMB lures with and without additional chemical compounds. Midline indicates the median; the top and bottom of the box indicates the first and third quartiles, respectively; vertical line or whiskers represent the 1.5 interquartile range of the data or the maximum value; open circles represent points more than 1.5 times the interquartile range. The tested chemicals were an

alcohol from fermented by-products, 2-methyl-1-propanol (MP), and a floral volatile, phenylacetaldehyde (PAA). Treatments included: AAMB alone, AAMB+MP, AAMB+PAA, AAMB+MP+PAA. Means comparisons were performed for difference in moth trap catch by Noctuinae tribe in traps baited with the different food bait lures. Boxplots marked with different letters within the panel are statistically different (Tukey method, $\alpha = 0.05$).

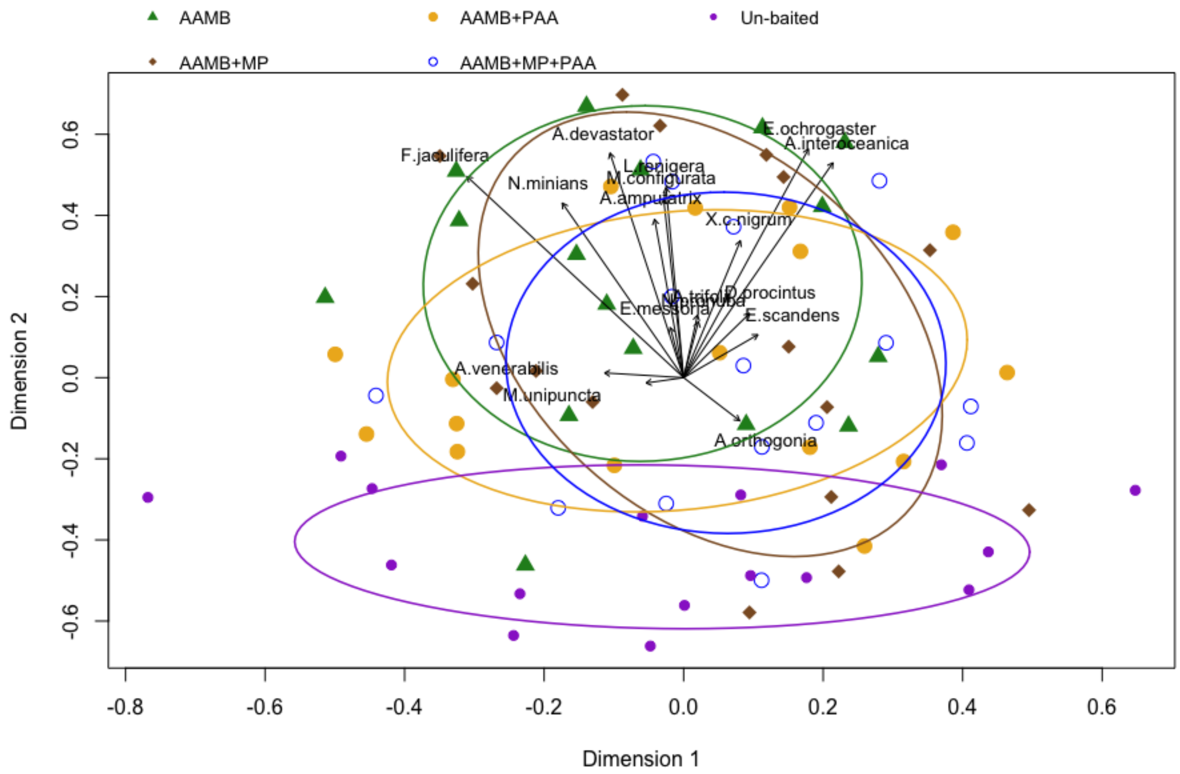

Figure 5-10. Non-metric multidimensional scaling (NMDS, Stress = 0.193; R^2 = 0.765) for the diversity of cutworm and armyworm species attracted to AAMB lure with and without additional chemical compounds. The tested chemicals were an alcohol from fermented by-products, 2-methyl-1-propanol (MP), and a floral volatile, phenylacetaldehyde (PAA). Treatments included: AAMB alone, AAMB+MP, AAMB+PAA, AAMB+MP+PAA and an unbaited trap that served as control.

Table 5-1. Results of the optimal statistical models used in the several experiments to determine the diversity of noctuid moths (Lepidoptera: Noctuidae) attracted to food-based semiochemicals lures in Canadian Prairies agroecosystems.

Experiment	**Response variable**	**Function**	**Optimal Model**	**Explanatory varaible**	**Statistic**		**df**	**P-value**	**Optimal model AIC**	**Full model AIC**	**Null Model AIC**
Experiment 1 (2014)											
Diversity of moths attracted to AAMB	Sex pheromone specificty	glmer	(Target, non-target) ~ Sex pheromone + Crop + (1|Site)	Sex pheromone	Wald χ^2	242.47	3	< 0.001	340	340.8	577.7
		Binomial		Crop		0.29	1	0.591			
	NMDS, AAMB vs. Unbaite	NMDS	nmds (Bray Curtis, mindim = 2, maxdim = 2)		Stress	0.265	.	.	.	.	.
	All species				R^2	0.511	.	.	.	.	.
		ADONIS	Data ~ Crop + Bait treatment, distance = "Bray"	Crop	R^2	0.039	1	0.123	.	.	.
				Bait treatment	R^2	0.149	1	0.001	.	.	.
		ANOSIM	anosim (data, crop)	Crop	R	0.018	.	0.267	.	.	.
			anosim (data, Bait treatment)	Bait treatment	R	0.365	.	0.001	.	.	.
	NMDS, AAMB vs. Unbaite	NMDS	nmds (Bray Curtis, mindim = 2, maxdim = 2)		Stress	0.209	.	.	.	.	.
	Pest species only				R^2	0.656	.	.	.	.	.
		ADONIS	Data ~ Bait treatment, distance = "Bray"	Bait treatment	R^2	0.183	1	0.001	.	.	.
		ANOSIM	anosim (data, Bait treatment)	Bait treatment	R	0.4	.	0.001	.	.	.
	Noctuinae tribes	glmer.nb	Count ~ Crop + Bait treatment + Tribe + Crop:Bait treatment + Crop:Tribe + Bait treatment:Tribe + (1|Site)	Crop	Wald χ^2	2.11	1	0.146	967	977	1191.4
		Negative binomial		Bait treatment		68.83	1	< 0.001			
				Tribe		181.25	7	< 0.001			
				Crop:Bait treatment		8.78	1	0.003			
				Crop:Tribe		15.73	7	0.028			
				Bait treatment:Tribe		73.23	7	< 0.001			

Table 5-1. (Concluded).

Experiment	Response variable	Function	Optimal Model	Explanatory varaible	Statistic		df	P-value	Optimal model AIC	Full model AIC	Null Model AIC
Experiment 2 (2015)											
Diversity of moths attracted to AAMB with additional semiochemicals	NMDS, AAMB vs. Unbaitec	NMDS	nmds (Bray Curtis, mindim = 2, maxdim = 2)		Stress	0.214	.	.	.	.	.
	All species				R^2	0.718	.	.	.	.	.
		ADONIS	Data ~ Crop + Lure type, distance = "Bray"	Crop	R^2	0.015	1	0.059	.	.	.
				Lure type	R^2	0.156	4	0.001	.	.	.
		ANOSIM	anosim (data, crop)	Crop	R	0.007	.	0.282	.	.	.
			anosim (data, Lure type)	Lure type	R	0.199	.	0.001	.	.	.
	NMDS, AAMB vs. Unbaitec	NMDS	nmds (Bray Curtis, mindim = 2, maxdim = 2)		Stress	0.196	.	.	.	.	.
	Pest species only				R^2	0.757	.	.	.	.	.
		ADONIS	Data ~ Lure type, distance = "Bray"	Lure type	R^2	0.161	4	0.001			
		ANOSIM	anosim (data, Lure type)	Lure type	R	0.156	.	0.001			
	Noctuinae tribes	glmer.nb	Count ~ Crop + Lure type + Tribe + Crop:Lure type + Crop:Tribe + Lure type:Tribe + (1|Site)	Crop	Wald χ^2	7.64	1	0.005		31258	4050.6
		Negative binomial		Lure type		263.59	4	< 0.001			
				Tribe		1656.75	7	< 0.001			
				Crop:Lure type		9.4	4	0.052			
				Crop:Tribe		17.48	7	0.014			
				Lure type:Tribe		130.91	28	< 0.001			

Table 5-2. Site coordinates. Seven sites in five counties throughout central Alberta, Canada.

County	Site	Field	Coordinates	2014	2015	2016
Leduc	1	A	53.23790 N 113.34226 W	Canola	Wheat	Canola
		B	53.24722 N 113.34219 W	Wheat	Canola	Wheat
	2	A	53.28640 N 113.87867 W	Canola	Wheat	Canola
		B	53.27595 N 113.85422 W	Wheat	Canola	Wheat
Parkland	3	A	53.44492 N 113.71344 W	Canola	Wheat	Canola
		B	53.43946 N 113.71339 W	Wheat	Canola	Wheat
Barrhead	4	A	54.07452 N 114.37685 W	Canola	Wheat	Canola
		B	54.05627 N 114.34988 W	Wheat	Canola	Wheat
	5	A	54.30392 N 114.47681 W	Canola	Wheat	Canola
		B	54.34530 N 114.47697 W	Wheat	Canola	Wheat
Wainwright	6	A	52.95971 N 111.43202 W	Canola	Wheat	Canola
		B	52.95963 N 111.43922 W	Wheat	Canola	Wheat
	7	A	52.90159 N 110.56340 W	Canola	Wheat	Canola
		B	52.88453 N 110.60859 W	Wheat	Canola	Wheat

Table 5-3. Lure composition and deployment schedule for field experiment in 2014 and 2015

Year	Lure	Components	Ratio	Amount	Time deployed
2014	Redbacked cutworm (RBC; *Euxoa ochrogaster*)	Z5-12Ac, Z7-12Ac, Z9-12Ac, Z5-10Ac	200 2 1 1	1000 µg	23 Jun – 10 Oct
	Bertha armyworm (BAW; *Mamestra configurata*)	Z11-16Ac, Z9-14Ac	95 5	500 µg	10 Jun – 02 Sep
	True armyworm (TAW; *Mythimna unipuncta*)	Z11-16Ac	1	1000 µg	10 Jun – 10 Oct
	Army cutworm (ACW, *Euxoa auxiliaris*)	Z5-14Ac, Z7-14Ac, Z9-14Ac	100 1 10	100 µg	02 Sep – 10 Oct
	AAMB	Acetic acid, 3-methyl-1-butanol	1 1	10 mL	10 Jun – 10 Oct
	Unbaited control	-	-	-	10 Jun – 10 Oct
2015	RBC	Z5-12Ac, Z7-12Ac, Z9-12Ac, Z5-10Ac	200 2 1 1	1000 µg	22 Jun – 15 Sept
	BAW	Z11-16Ac, Z9-14Ac	95 5	500 µg	22 Jun – 04 Aug
	TAW	Z11-16Ac	1	1000 µg	22 Jun – 15 Sept
	Pale western cutworm (PWC; *Agrotis orthogonia*)	Z7-12Ac, Z5-12Ac	2 1	500 µg	22 Jun – 15 Sept
	AAMB	Acetic acid, 3-methyl-1-butanol	1 1	10 mL	22 Jun – 15 Sept
	AAMB+MP	Acetic acid, 3-methyl-1-butanol, 2-methyl-1-propanol	1 1 1	10 mL	22 Jun – 15 Sept
	AAMB+PAA	Acetic acid, 3-methyl-1-butanol, phenylacetaldehyde	1 1 1	10 mL	22 Jun – 15 Sept
	AAMB+MP+PAA	Acetic acid, 3-methyl-1-butanol, 2-methyl-1-propanol, phenylacetaldehyde	1 1 1 1	10 mL	22 Jun – 15 Sept
	Unbaited control	-	-	-	22 Jun – 15 Sept

Table 5-4. Sex pheromone blends of target cutworm and armyworm species and the respective most abundant non-target species capture in sex pheromone-baited traps.

Target species	Components	Ratio	Non-target species	Components	Ratio
Redbacked cutworm	Z5-12: Ac,	200	*Plusia putnami*	Z5-12: Ac,	100
(*Euxoa ochrogaster*)	Z7-12: Ac,	2		Z7-12: Ac	1
	Z9-12: Ac,	1			
	Z5-10: Ac	1			
Bertha armyworm	Z11-16: Ac,	95	*Apamea cogitata*	Z11-16: Ac,	20
(*Mamestra configurata)*	Z9-14: Ac,	5		Z9-14: Ac	1
	Z7-12: Ac,	10			
	Z7-12: OH	1			
Army cutworm	Z5-14: Ac,	100			
(*Euxoa auxiliaris*)	Z7-14: Ac,	1			
	Z9-14: Ac	10			
True armyworm	Z11-16: Ac,	5000	*Celaena reniformis*	Z11-16: Ac	20
(*Pseudaletia unipuncta*)	Z11-16: OH,	10		Z7-16: Ac	1
	Z11-16: Ald,	2	*Anarta tifolii*	Z11-16: Ac,	9
	Z9-14: Ac	1		Z11-16: OH	1

Supplementary tables.

Table 5-S1. Species, average ± SE, and percentage of females and males (♀, ♂) for moths captured at seven sites in central Alberta, Canada, in green Unitraps baited with cutworm and armyworm sex pheromone lures: RBC = redbacked cutworm (*Euxoa ochrogaster*); BAW = bertha armyworm (*Mamestra configurata*); TAW= true armyworm (*Mythimna unipuncta*); ACW = army cutworm (*Euxoa auxiliaris*). Average ± SE represents the total number of moths captured over the monitoring period (17 weeks) per species per site.

	Canola							
Species	RBC		BAW		TAW		ACW	
Target								
Euxoa ochrogaster	933.1 ± 221.9	(0,100)	0.6 ± 0.2	(50,50)	299.0 ± 85.0	(0,100)	0	-
Mamestra configurata	0.4 ± 0.3	(0,100)	92.9 ± 34.9	(0,100)	0	-	0	-
Mythimna unipuncta	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	0	-
Euxoa auxiliaris	0	-	0	-	0	-	0.7 ± 0.7	(0,100)
Non-target								
Noctuidae								
Noctuinae: Noctuini								
Agrotis orthogonia	0	-	0	-	0	-	0	-
Cryptocala acadiensis	0.4 ± 0.3	(0,100)	0.4 ± 0.2	(0,100)	0.1 ± 0.1	(0,100)	0	-
Euxoa albipennis	0		0	-	0	-	0	-
Euxoa declarata	0.1 ± 0.1	(100,0)	0	-	0.1 ± 0.1	(0,100)	0	-
Euxoa divergens	0	-	0	-	0	-	0	-
Euxoa ridingsiana	0.1 ± 0.1	(0,100)	0	-	0	-	0	-

Table 5-S1. (continued)

	Canola							
Species	RBC		BAW		TAW		ACW	
Feltia jaculifera	0.1 ± 0.1	(0,100)	0.4 ± 0.2	(0,100)	0.6 ± 0.3	(0,100)	0	-
Feltia mollis	0	-	0	-	0	-	0	-
Pseudohermonassa tenuicula	0.6 ± 0.3	(0,100)	0	-	0.4 ± 0.4	(0,100)	0	-
Xestia c nigrum	0.1 ± 0.1	(100,0)	0	-	0	-	0	-
Xestia smithii	0		0	-	0	-	0	-
Noctuinae: Apameini								
Amphipoea americana	0		0	-	0.3 ± 0.2	(50,50)	0	-
Apamea cogitata	0	-	39.1 ± 14.2	(0,100)	0.4 ± 0.2	(33,67)	0	-
Apamea devastator	0	-	0	-	0.9 ± 0.5	(0,100)	0	-
Apamea inficita	0	-	0.7 ± 0.6	(0,100)	28.4 ± 9.3	(0,100)	0	-
Apamea niveivenosa	0	-	0	-	0	-	0	-
Celaena reniformis	0		0	-	53.6 ± 25.4	(0,100)	0	-
Oligia egens	0	-	0	-	2.6 ± 1.3	(0,100)	0	-
Resapamea passer	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Noctuinae: Hadenini								
Anarta trifolii	0	-	0.3 ± 0.2	(0,100)	20.9 ± 12.6	(3,97)	0	-
Dargida difussa	0		1.3 ± 0.8	(0,100)	0.3 ± 0.2	(0,100)	0	-
Lacanobia atlantica	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	3.6 ± 2.3	(0,100)	0	-
Lacanobia radix	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Melanchra assimilis	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Polia nimbosa	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Noctuinae: Leucaniini								
Leucania commoides	0.1 ± 0.1	(0,100)	1.0 ± 0.5	(0,100)	1.0 ± 1.0	(0,100)	0	-
Leucania multilinea	0	-	0	-	0	-	0	-
Mythimna oxygala	0.3 ± 0.2	(0,100)	0	-	0.1 ± 0.1	(0,100)	0	-

Table 5-S1. (continued)

	Canola							
Species	RBC		BAW		TAW		ACW	
Noctuinae: Eriopygini								
Lacinipolia lorea	0.1 ± 0.1	(0,100)	0.3 ± 0.2	(0,100)	0	-	0	-
Lacinipolia olivacea	0.4 ± 0.3	(67,33)	0	-	0.1 ± 0.1	(0,100)	0	-
Lacinipolia renigera	0.7 ± 0.6	(0,100)	0	-	0	-	0	-
Noctuinae: Xylenini								
Enargia decolor	11.1 ± 10.0	(3,97)	2.0 ± 1.8	(43,57)	2.9 ± 2.7	(5,95)	1.6 ± 1.6	(0,100)
Enargia infumata	15.4 ± 15.4	(1,99)	2.1 ± 1.5	(0,100)	1.0 ± 0.7	(14,86)	0.9 ± 0.9	(17,83)
Noctuinae: Pseudeustrotiini								
Pseudeustrotia carneola	0.3 ± 0.2	(0,100)	0.1 ± 0.1	(100,0)	0	-	0	-
Plusiinae: Plusiini								
Anagrapha falcifera	0		0	-	0.1 ± 0.1	(0,100)	0	-
Plusia putnami	25.4 ± 9.9	(0,100)	0	-	0	-	0	-
Acronictinae								
Acronicta grisea	0.3 ± 0.2	(0,100)	0	-	0	-	0	-
Erebidae								
Arctiinae: Arctiini								
Apantesis virgo	0	-	0	-	0.1 ± 0.1	(100,0)	0	-
Ctenucha virgina	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Cambridae								
Glaphyriinae								
Evergestis pallidata	0	-	0	-	0	-	0	-

Table 5-S1. (continued)

	Canola							
Species	RBC		BAW		TAW		ACW	
Pieridae								
Pierinae: Pierini								
Pieris rapae	0	-	0	-	0	-	0.1 ± 0.1	(0,100)
Unidentified	0.7 ± 0.5	(0,100)	1.7 ± 0.9	(8,92)	7.0 ± 1.6	(4,96)	0.1 ± 0.1	(100,0)
Total	990.4 ± 228.0	(0,100)	143.7 ± 43.1	(1,99)	424.0 ± 96.9	(0,100)	3.4 ± 3.4	(8,92)

Table 5-S1. (continued)

	Wheat							
Species	RBC		BAW		TAW		ACW	
Target								
Euxoa ochrogaster	1221.9 ± 182.7	(0,100)	0.1 ± 0.1	(0,100)	245.4 ± 53.9	(0,100)	0	-
Mamestra configurata	0.3 ± 0.2	(50,50)	86.6 ± 35.1	(0,100)	0.1 ± 0.1	(100,0)	0	-
Mythimna unipuncta	0.4 ± 0.4	(0,100)	0	-	2.6 ± 1.5	(0,100)	0	-
Euxoa auxiliaris	0	-	0	-	0	-	0.1 ± 0.1	(0,100)
Non-target								
Noctuidae								
Noctuinae: Noctuini								
Agrotis orthogonia	0	-	0	-	0.3 ± 0.3	(0,100)	0	-
Cryptocala acadiensis	0.1 ± 0.1	(0,100)	0		0.1 ± 0.1	(0,100)	0	-
Euxoa albipennis	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Euxoa declarata	0.4 ± 0.2	(67,33)	0		0.1 ± 0.1	(0,100)	0	-
Euxoa divergens	0	-	0	-	0	-	0	-
Euxoa ridingsiana	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Feltia jaculifera	0.7 ± 0.3	(0,100)	0.6 ± 0.2	(0,100)	1.4 ± 1.3	(0,100)	0	-
Feltia mollis	0	-	0.3 ± 0.2	(0,100)	0	-	0	-
Pseudohermonassa tenuicula	1.3 ± 0.3	(0,100)	0.4 ± 0.3	(0,100)	0	-	0	-
Xestia c nigrum	0	-	0		0	-	0	-
Xestia smithii	0.1 ± 0.1	(0,100)	0		0	-	0	-

Table 5-S1. (continued)

	Wheat							
Species	RBC		BAW		TAW		ACW	
Noctuinae: Apameini								
Amphipoea americana	0.3 ± 0.3	(0,100)	0.4 ± 0.2	(0,100)	0.4 ± 0.3	(33,67)	0	-
Apamea cogitata	0	-	33.7 ± 7.8	(0,100)	0.7 ± 0.2	(0,100)	0	-
Apamea devastator	0	-	0.4 ± 0.2	(0,100)	0.7 ± 0.6	(0,100)	0	-
Apamea inficita	0	-	1.3 ± 0.2	(0,100)	50.0 ± 12.2	(0,100)	0	-
Apamea niveivenosa	0	-	0.3 ± 0.1	(0,100)	0	-	0	-
Celaena reniformis	0.3 ± 0.2	(50,50)	0.1 ± 0.1	(0,100)	46.9 ± 19.0	(0,100)	0	-
Oligia egens	0	-	0.1 ± 0.1	(0,100)	1.7 ± 0.6	(0,100)	0	-
Resapamea passer	0	-	0	-	0	-	0	-
Noctuinae: Hadenini								
Anarta trifolii	0	-	1.4 ± 1.3	(0,100)	10.1 ± 3.9	(1,99)	0	-
Dargida difussa	0.7 ± 0.6	(20,80)	1.0 ± 0.3	(14,86)	1.1 ± 0.4	(13,88)	0	-
Lacanobia atlantica	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	4.9 ± 1.9	(6,94)	0	-
Lacanobia radix	0	-	0	-	0	-	0	-
Melanchra assimilis	0	-	0	-	0	-	0	-
Polia nimbosa	0	-	0		0	-	0	-
Noctuinae: Leucaniini								
Leucania commoides	0	-	0		0.4 ± 0.3	(0,100)	0	-
Leucania multilinea	0	-	0.9 ± 0.3	(17,83)	0	-	0	-
Mythimna oxygala	0.9 ± 0.3	(0,100)	0.9 ± 0.3	(0,100)	0.1 ± 0.1	(0,100)	0	-
Noctuinae: Eriopygini								
Lacinipolia lorea	0.4 ± 0.2	(0,100)	0.3 ± 0.3	(0,100)	0.3 ± 0.3	(50,50)	0	-
Lacinipolia olivacea	0	-	0.7 ± 0.2	(40,60)	0.6 ± 0.3	(25,75)	0	-
Lacinipolia renigera	0.1 ± 0.1	(0,100)	0.3 ± 0.2	(0,100)	0.6 ± 0.2	(50,50)	0	-

Table 5-S1. (concluded)

	Wheat							
Species	RBC		BAW		TAW		ACW	
Noctuinae: Xylenini								
Enargia decolor	1.4 ± 1.1	(0,100)	1.0 ± 0.7	(0,100)	3.9 ± 3.4	(0,100)	0.3 ± 0.3	(50,50)
Enargia infumata	1.3 ± 0.5	(0,100)	6.9 ± 4.6	(0,100)	3.6 ± 3.1	(0,100)	0	-
Noctuinae: Pseudeustrotiini								
Pseudeustrotia carneola	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Plusiinae: Plusiini								
Anagrapha falcifera	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	0	-	0	-
Plusia putnami	40.3 ± 15.8	(0,100)	0	-	0.6 ± 0.3	(25,75)	0	-
Acronictinae								
Acronicta grisea	0.3 ± 0.2	(0,100)	0.1 ± 0.1	(0,100)	0	-	0	-
Erebidae								
Arctiinae: Arctiini								
Apantesis virgo	0	-	0	-	0	-	0	-
Ctenucha virgina	0	-	0	-	0	-	0	-
Cambridae								
Glaphyriinae								
Evergestis pallidata	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Pieridae								
Pierinae: Pierini								
Pieris rapae	0	-	0	-	0	-	0	-
Unidentified	1.4 ± 0.4	(10,90)	1.3 ± 0.4	(22,78)	5.1 ± 1.6	(11,89)	0.3 ± 0.3	(50,50)
Total	1273.1 ± 180.0	(0,100)	139.7 ± 139.7	(1,99)	382.0 ± 69.2	(1,99)	0.7 ± 0.7	(40,60)

Table 5-S2. Species, average ± SE, and percentage of females and males (♀, ♂) for moths captured at seven sites in central Alberta, Canada, in green Unitraps baited with AAMB (acetic acid and 3-methyl-1-butanol) or unbaited. For each species, average ± SE represents the total number of moths captured over the monitoring period (17 weeks) per site.

	Canola				Wheat			
Species	AAMB		Unbaited		AAMB		Unbaited	
Noctuidae:								
Noctuinae: Noctuini								
Agrotis venerabilis	0.1 ± 0.1	(100,0)	0.3 ± 0.2	(50,50)	0.4 ± 0.2	(33,67)	0.4 ± 0.2	(33,67)
Cryptocala acadiensis	0	-	0.3 ± 0.2	(50,50)	0	-	0.1 ± 0.1	(0,100)
Eurois occulta	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(0,100)	0.3 ± 0.2	(50,50)	0.1 ± 0.1	(0,100)
Euxoa declarata	0	-	0.1 ± 0.1	(0,100)	0.7 ± 0.6	(80,20)	0.1 ± 0.1	(0,100)
Euxoa divergens	0	-	0	-	0	-	0.1 ± 0.1	(0,100)
Euxoa ochrogaster	3.6 ± 1.6	(64,36)	1.0 ± 0.6	(43,57)	7.6 ± 5.0	(64,36)	0.6 ± 0.2	(50,50)
Euxoa scandens	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Feltia jaculifera	3.4 ± 0.6	(33,67)	0.3 ± 0.2	(50,50)	7.7 ± 5.8	(17,83)	0.3 ± 0.2	(0,100)
Noctua pronuba	0.1 ± 0.1	(100,0)	0	-	0.1 ± 0.1	(0,100)	0	-
Paradiarsia littoralis	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Xestia c nigrum	0.3 ± 0.2	(100,0)	0.4 ± 0.3	(0,100)	0	-	0	-
Xestia smithii	0.1 ± 0.1	(0,100)	0.4 ± 0.3	(0,100)	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)
Noctuinae: Apameini								
Amphipoea interoceanica	6.3 ± 2.8	(36,64)	0	-	11.3 ± 5.2	(28,72)	0.3 ± 0.3	(100,0)
Apamea alia	0.1 ± 0.1	(100,0)	0	-	0.1 ± 0.1	(100,0)	0	-
Apamea amputatrix	0.1 ± 0.1	(100,0)	0	-	0	-	0	-
Apamea centralis	0	-	0	-	0.1 ± 0.1	(100,0)	0	-
Apamea cogitata	9.9 ± 6.0	(48,52)	0.1 ± 0.1	(0,100)	11.9 ± 3.9	(41,59)	0.3 ± 0.2	(0,100)

Table 5-S2. (continued.)

	Canola				Wheat			
Species	AAMB		Unbaited		AAMB		Unbaited	
Apamea commoda	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Apamea devastator	1.3 ± 0.6	(33,67)	0.1 ± 0.1	(0,100)	3.1 ± 1.4	(18,82)	0.6 ± 0.2	(0,100)
Apamea inficita	0.9 ± 0.3	(0,100)	0.3 ± 0.2	(50,50)	0.3 ± 0.2	(0,100)	0	-
Apamea lignicolora	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Apamea niveivenosa	1.4 ± 0.5	(10,90)	0.3 ± 0.2	(50,50)	2.6 ± 1.3	(11,89)	0	-
Apamea scoparia	0.4 ± 0.4	(100,0)	0.1 ± 0.1	(0,100)	0	-	0	-
Celaena reniformis	2.9 ± 1.2	(55,45)	0	-	4.6 ± 2.0	(47,53)	0	-
Oligia egens	0	-	0	-	0.1 ± 0.1	(100,0)	0	-
Resapamea passer	0	-	0		0	-	0.1 ± 0.1	(0,100)
Noctuinae: Hadenini								
Dargida difussa	0	-	0.6 ± 0.3	(0,100)	0.3 ± 0.2	(0,100)	0.7 ± 0.5	(20,80)
Dargida procinctus	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Lacanobia atlantica	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	0.6 ± 0.3	(0,100)	0	-
Lacanobia radix	0	-	0		0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)
Mamestra configurata	0.4 ± 0.3	(67,33)	0.3 ± 0.3	(50,50)	0.6 ± 0.3	(50,50)	0	-
Melanchra assimilis	0	-	0	-	0.1 ± 0.1	(100,0)	0	-
Polia nimbosa	0.6 ± 0.3	(50,50)	0.1 ± 0.1	(0,100)	0.6 ± 0.4	(50,50)	0	-
Trichordestra lilacina	0.1 ± 0.1	(0,100)	0		0.4 ± 0.3	(0,100)	0.1 ± 0.1	(0,100)
Noctuinae: Leucani								
Leucania commoides	0.4 ± 0.3	(0,100)	0.1 ± 0.1	(100,0)	0.7 ± 0.4	(0,100)	0	-
Leucania multilinea	0.3 ± 0.3	(0,100)	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(0,100)
Mythimna oxygala	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	2.1 ± 0.6	(20,80)	0.6 ± 0.3	(0,100)
Mythimna unipuncta	0.7 ± 0.6	(80,20)	0	-	2.9 ± 2.5	(60,40)	0	-

Table 5-S2. (continued.)

	Canola				Wheat			
Species	AAMB		Unbaited		AAMB		Unbaited	
Noctuinae: Xylenini								
Enargia decolor	18.1 ± 17.3	(35,65)	18.9 ± 18.2	(5,95)	1.6 ± 0.6	(27,73)	0.3 ± 0.3	(0,100)
Enargia infumata	0.9 ± 0.7	(17,83)	2.4 ± 2.4	(6,94)	0	-	0	-
Lithophane innominata	0.3 ± 0.3	(100,0)	0	-	0.3 ± 0.2	(50,50)	0	-
Sunira bicolorago	0.7 ± 0.3	(20,80)	0	-	0	-	0	-
Noctuinae: Eripygini								
Lacinipolia lorea	1.3 ± 0.5	(22,78)	0.6 ± 0.2	(25,75)	2.9 ± 1.4	(50,50)	0.1 ± 0.1	(0,100)
Lacinipolia olivacea	0.4 ± 0.3	(100,0)	0.1 ± 0.1	(0,100)	1.1 ± 0.5	(75,25)	0	-
Lacinipolia renigera	0.3 ± 0.2	(100,0)	0.1 ± 0.1	(100,0)	0.6 ± 0.3	(25,75)	0.1 ± 0.1	(0,100)
Noctuinae: Caradrinini								
Caradrina montana	0	-	0	-	0.3 ± 0.3	(50,50)	0	-
Caradrina morpheus	0	-	0		0.1 ± 0.1	(100,0)	0.1 ± 0.1	(0,100)
Noctuinae: Tholerini								
Nephelodes minians	1.3 ± 0.2	(0,100)	0.1 ± 0.1	(0,100)	1.7 ± 0.6	(17,83)	0	-
Plusiinae: Plusiini								
Anagrapha falcifera	0	-	0.1 ± 0.1	(0,100)	0.3 ± 0.3	(0,100)	0	-
Acronictinae								
Acronicta americana	0	-	0	-	0.1 ± 0.1	(100,0)	0	-
Acronicta superans	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Drepanidae								
Thyatiinae: Habrosynini								
Habrosyne scripta	0.4 ± 0.3	(33,67)	0	-	0	-	0	-

Table 5-S2. (concluded.)

Species	Canola				Wheat			
	AAMB		Unbaited		AAMB		Unbaited	
Erebidae								
Arctiinae: Arctiini								
Ctenucha virgina	0	-	0	-	0.1 ± 0.1	(100,0)	0	-
Sphingidae								
Macroglossinae: Macroglossini								
Darapsa choerlus	0.1 ± 0.1	(100,0)	0	-	0	-	0	-
Unidentified	5.9 ± 0.9	(41,59)	2.0 ± 0.6	(43,57)	8.0 ± 2.3	(46,54)	0.9 ± 0.5	(17,83)
Pest species	18.0 ± 4.5	(44,56)	1.3 ± 0.6	(44,56)	36.3 ± 13.0	(34,66)	0.6 ± 0.2	(50,50)
Total	63.9 ± 19.9	(40,60)	30.1 ± 20.4	(12,88)	78.6 ± 17.5	(37,63)	6.6 ± 0.8	(15,85)

Table 5-S3. Species, average ± SE, and percentage of females and males (♀, ♂) for moths captured at seven sites in central Alberta, Canada, in green Unitraps baited with different food baits: AAMB = acetic acid and 3-methyl-1-butanol; AAMB+MP = AAMB plus 2-methyl-1-propanol; AAMB+PAA = AAMB plus phenylacetaldehyde and AAMB+MB+PAA. For each species, average ± SE represents the total number of moths captured over the monitoring period (17 weeks) per site.

	Canola									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Noctuidae										
Noctuinae: Noctuini										
Agrotis orthogonia	0	-	0	-	0	-	0	-	0	-
Agrotis venerabilis	0.6 ± 0.4	(40,60)	0.4 ± 0.3	(33,67)	0.8 ± 0.3	(33,67)	0.4 ± 0.3	(0,100)	0.5 ± 0.4	(0,100)
Cryptocala acadiensis	0.4 ± 0.3	(33,67)	0.3 ± 0.2	(0,100)	0	-	0.3 ± 0.2	(0,100)	0.1 ± 0.1	(0,100)
Eurois astricta	0	-	0	-	0	-	0.1 ± 0.1	(100,0)	0	-
Eurois occulta	0.3 ± 0.2	(100,0)	0.1 ± 0.1	(100,0)	0.3 ± 0.2	(100,0)	0	-	0	-
Euxoa albipennis	0	-	0.1 ± 0.1	(0,100)	0.4 ± 0.2	(0,100)	0	-	0	-
Euxoa campestris	2.1 ± 1.3	(47,53)	0.9 ± 0.5	(86,14)	0.5 ± 0.2	(25,75)	0.8 ± 0.4	(67,33)	0	-
Euxoa castanea	0	-	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Euxoa declarata	0.1 ± 0.1	(0,100)	0.3 ± 0.3	(0,100)	2.0 ± 0.8	(25,75)	0.6 ± 0.2	(0,100)	0	-
Euxoa divergens	0	-	0	-	0.1 ± 0.1	(0,100)	0	-	0.1 ± 0.1	(0,100)
Euxoa messoria	0.1 ± 0.1	(0,100)	0	-	0	-	0	-	0	-
Euxoa ochrogaster	18.1 ± 7.5	(61,39)	13.8 ± 6.3	(52,48)	10.9 ± 3.6	(64,36)	15.5 ± 4.8	(44,56)	2.0 ± 0.5	(19,81)
Euxoa ridingsiana	0.1 ± 0.1	(0,100)	0.3 ± 0.2	(100,0)	0.4 ± 0.3	(33,67)	0.1 ± 0.1	(0,100)	0	-
Euxoa scandens	0	-	0	-	0	-	0	-	0	-
Feltia jaculifera	6.1 ± 2.1	(39,61)	6.0 ± 2.7	(35,65)	3.9 ± 1.4	(29,71)	4.6 ± 1.6	(35,65)	1.6 ± 0.8	(8,92)
Feltia nigrita	0	-	0	-	0.8 ± 0.5	(50,50)	0	-	0	-
Feltia subgothica	0	-	0	-	0.1 ± 0.1	(100,0)	0	-	0	-

Table 5-S3. (continued)

	Canola									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Graphiphora augur	0.1 ± 0.1	(0,100)	0.4 ± 0.2	(67,33)	0.3 ± 0.2	(0,100)	0.4 ± 0.3	(33,67)	0	-
Noctua pronuba	0	-	0	-	0.1 ± 0.1	(0,100)	0.3 ± 0.2	(100,0)	0	-
Paradiarsia littoralis	0.3 ± 0.3	(0,100)	0	-	0	-	0	-	0	-
Noctuinae: Apameini										
Amphipoea interoceanica	9.9 ± 4.2	(42,58)	9.0 ± 2.9	(31,69)	9.8 ± 4.8	(41,59)	3.4 ± 1.2	(44,56)	0.4 ± 0.3	(33,67)
Apamea alia	0.3 ± 0.3	(50,50)	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(100,0)	0	-	0.1 ± 0.1	(100,0)
Apamea amputatrix	0.9 ± 0.6	(57,43)	0.5 ± 0.3	(50,50)	0	-	0.5 ± 0.4	(50,50)	0	-
Apamea centralis	0.1 ± 0.1	(100,0)	0.3 ± 0.3	(0,100)	0	-	0	-	0	-
Apamea cogitata	31.5 ± 14.0	(40,60)	37.0 ± 20.3	(38,62)	16.6 ± 10.8	(38,62)	15.5 ± 8.4	(45,55)	0.1 ± 0.1	(0,100)
Apamea commoda	0.8 ± 0.3	(0,100)	0.9 ± 0.5	(29,71)	1.1 ± 0.6	(44,56)	0.6 ± 0.3	(60,40)	0	-
Apamea devastaor	8.6 ± 2.5	(19,81)	12.4 ± 5.3	(12,88)	3.0 ± 1.2	(25,75)	5.0 ± 2.9	(25,75)	0.5 ± 0.3	(0,100)
Apamea dubitans	0	-	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Apamea impulsa	0	-	0.3 ± 0.2	(0,100)	0	-	0	-	0	-
Apamea inficita	1.0 ± 0.5	(38,63)	1.1 ± 0.5	(44,56)	1.5 ± 0.6	(8,92)	1.6 ± 0.8	(15,85)	0.3 ± 0.2	(0,100)
Apamea lignicolora	0.1 ± 0.1	(0,100)	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Apamea niveivenosa	4.6 ± 1.5	(30,70)	3.6 ± 1.4	(14,86)	1.3 ± 0.7	(10,90)	0.8 ± 0.3	(17,83)	0	-
Apamea plutonia	0	-	0.1 ± 0.1	(100,0)	0	-	0	-	0	-
Apamea scoparia	0	-	0	-	0.3 ± 0.3	(50,50)	0	-	0	-
Celaena reniformis	9.6 ± 6.3	(53,47)	10.9 ± 6.3	(45,55)	6.6 ± 3.2	(53,47)	6.3 ± 2.7	(44,56)	0.1 ± 0.1	(0,100)
Hypocoena rufostrigata	0.5 ± 0.4	(0,100)	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Mesapamea fractilinea	0	-	0	-	0	-	0	-	0	-
Noctuinae: Hadenini										
Anarta trifolii	0	-	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	0	-	0	-
Dargida diffusa	0.1 ± 0.1	(0,100)	0	-	0.4 ± 0.3	(0,100)	0	-	0.1 ± 0.1	(0,100)
Dargida procinctus	0.1 ± 0.1	(100,0)	0	-	0	-	0	-	0	-
Lacanobia atlantica	0.9 ± 0.6	(29,71)	0.8 ± 0.4	(33,67)	0.3 ± 0.2	(0,100)	0.1 ± 0.1	(0,100)	0	-

Table 5-S3. (continued)

	Canola									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Lacanobia radix	1.0 ± 0.6	(63,38)	0.8 ± 0.4	(83,17)	0.5 ± 0.3	(75,25)	0.8 ± 0.4	(33,67)	0	-
Polia nimbosa	0.9 ± 0.4	(14,86)	0.1 ± 0.1	(100,0)	0.5 ± 0.3	(25,75)	0.1 ± 0.1	(100,0)	0	-
Trichordestra lilacina	0	-	0	-	0	-	0	-	0	-
Xestia c-nigrum	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(0,100)	0.3 ± 0.2	(50,50)	0	-	0	-
Xestia smithii	1.0 ± 0.4	(13,88)	0.6 ± 0.5	(20,80)	0.3 ± 0.2	(0,100)	1.0 ± 0.7	(50,50)	0.1 ± 0.1	(0,100)
Noctuinae: Leucaniini										
Leucania anteroclara	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	0	-	0.4 ± 0.3	(67,33)	0	-
Leucania commoides	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	0.5 ± 0.3	(50,50)	0	-	0	-
Leucania multilineata	0.6 ± 0.4	(0,100)	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(0,100)	0	-	0	-
Mamestra configurata	0.9 ± 0.5	(29,71)	0.5 ± 0.3	(50,50)	0.8 ± 0.5	(33,67)	0.5 ± 0.3	(75,25)	0	-
Mythimna oxygala	1.6 ± 0.7	(54,46)	1.3 ± 0.6	(20,80)	0.4 ± 0.3	(67,33)	1.3 ± 0.4	(40,60)	0	-
Mythimna unipuncta	0.1 ± 0.1	(0,100)	0	-	0.4 ± 0.4	(0,100)	0	-	0	-
Noctuinae: Eriopygini										
Lacinipolia lorea	2.3 ± 1.2	(44,56)	1.1 ± 0.7	(33,67)	1.3 ± 1.0	(40,60)	0.6 ± 0.5	(40,60)	0	-
Lacinipolia meditata	0.1 ± 0.1	(100,0)	0	-	0	-	0	-	0	-
Lacinipolia olivacea	0.5 ± 0.4	(0,100)	0.3 ± 0.2	(50,50)	1.4 ± 0.7	(45,55)	3.1 ± 1.4	(40,60)	0.1 ± 0.1	(0,100)
Lacinipolia renigera	0.9 ± 0.5	(71,29)	1.4 ± 0.6	(27,73)	1.4 ± 0.7	(36,64)	1.5 ± 0.7	(50,50)	0	-
Noctuinae: Xylenini										
Enargia spp.	0	-	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Sunira bicolorago	0.3 ± 0.2	(0,100)	0.1 ± 0.1	(100,0)	0.3 ± 0.2	(50,50)	0	-	0.1 ± 0.1	(0,100)
Xanthia tatago	0	-	0	-	0	-	0	-	0	-
Noctuinae: Caradrinini										
Caradrina montana	0.1 ± 0.1	(100,0)	1.3 ± 0.5	(30,70)	0.1 ± 0.1	(0,100)	0.3 ± 0.2	(50,50)	0.5 ± 0.4	(25,75)
Caradrina morpheus	0.4 ± 0.3	(0,100)	0	-	0	-	0.3 ± 0.3	(0,100)	0	-
Noctuinae: Tholerini										
Nephelodes minians	4.3 ± 1.0	(0,100)	2.4 ± 0.7	(5,95)	1.1 ± 0.5	(0,100)	1.1 ± 0.5	(0,100)	0	-

Table 5-S3. (continued)

	Canola									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Plusiinae: Plusiini										
Anagrapha falcifera	0	-	0	-	0	-	0	-	0	-
Autographa californica	0	-	0	-	0.5 ± 0.3	(100,0)	0.3 ± 0.2	(100,0)	0	-
Plusia putnami	0	-	0	-	0.6 ± 0.6	(100,0)	0	-	0	-
Plusiinae: Pseudeustrotiini										
Pseudeustrotia carneola	1.9 ± 0.8	(80,20)	1.1 ± 0.5	(56,44)	0.9 ± 0.6	(43,57)	0.6 ± 0.4	(80,20)	0	-
Acronictiane										
Acronicta americana	0	-	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Sphingidae										
Macroglossinae: Macroglossini										
Darapsa choerilus	0.5 ± 0.4	(50,50)	0.1 ± 0.1	(100,0)	0	-	0	-	0	-
Smerinthinae: Smerinthini										
Smerinthus jamaicensis	0.1 ± 0.1	(100,0)	0	-	0	-	0	-	0	-
Crambidae										
Glaphyriinae										
Evergestis pallidata	0	-	0	-	0	-	0.1 ± 0.1	(100,0)	0	-
Erebidae										
Arctiinae: Arctiini										
Ctenucha virginica	0.4 ± 0.3	(67,33)	0	-	0	-	0.3 ± 0.3	(100,0)	0	-
Arctiinae: Lithosiini										
Hypoprepia miniata	0	-	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Erebidae										
Erebinae: Euclidiini										
Caenurgina erechtea	0	-	0	-	0	-	0	-	0	-

Table 5-S3. (continued)

	Canola									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Geometridae										
Ennominae: Ourapterygini										
Sicya macularia	0	-	0	-	0	-	0	-	0	-
Larentiinae: Hydriomenini										
Rheumaptera undulata	0	-	0	-	0	-	0	-	0	-
Hesperiidae										
Hesperiinae: Thymelicini										
Thymelicus lineola	0	-	0	-	0	-	0	-	0	-
Unidentified	11.1 ± 2.3	(53,47)	17.1 ± 5.4	(32,68)	11.1 ± 2.6	(40,60)	10.8 ± 3.3	(21,79)	3.8 ± 0.7	(7,93)
Total	126.6 ± 42.0	(42,58)	128.5 ± 48.6	(35,65)	83.9 ± 28.1	(41,59)	79.8 ± 28.1	(39,61)	10.6 ± 1.8	(11,89)

Table 5-S3. (continued)

	Wheat									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Noctuidae										
Noctuinae: Noctuini										
Agrotis orthogonia	0	-	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Agrotis venerabilis	0.6 ± 0.2	(40,60)	0.4 ± 0.2	(0,100)	0.4 ± 0.2	(33,67)	0.3 ± 0.3	(0,100)	0.1 ± 0.1	(0,100)
Cryptocala acadiensis	0.4 ± 0.3	(100,0)	0.3 ± 0.2	(0,100)	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(100,0)	0.3 ± 0.3	(100,0)
Eurois astricta	0	-	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Eurois occulta	0.3 ± 0.2	(50,50)	0	-	0	-	0	-	0	-
Euxoa albipennis	0	-	0.1 ± 0.1	(0,100)	0.3 ± 0.2	(0,100)	0.1 ± 0.1	(0,100)	0	-
Euxoa campestris	1.4 ± 0.7	(82,18)	1.6 ± 0.8	(62,38)	0.6 ± 0.3	(100,0)	0.4 ± 0.3	(33,67)	0	-
Euxoa castanea	0	-	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Euxoa declarata	0.5 ± 0.2	(25,75)	0.3 ± 0.2	(50,50)	0.3 ± 0.2	(0,100)	0.3 ± 0.3	(0,100)	0	-
Euxoa divergens	0	-	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Euxoa messoria	0	-	0	-	0	-	0	-	0	-
Euxoa ochrogaster	18.0 ± 8.1	(69,31)	15.8 ± 8.3	(47,53)	7.4 ± 2.9	(64,36)	7.9 ± 3.5	(63,37)	2.5 ± 0.8	(25,75)
Euxoa ridingsiana	0.5 ± 0.3	(50,50)	0.6 ± 0.5	(20,80)	0.3 ± 0.2	(50,50)	0.4 ± 0.3	(100,0)	0	-
Euxoa scandens	0	-	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Feltia jaculifera	18.1 ± 6.4	(51,49)	12.9 ± 5.8	(51,49)	8.4 ± 2.2	(39,61)	8.4 ± 2.4	(45,55)	1.3 ± 0.5	(10,90)
Feltia nigrita	0	-	0.3 ± 0.3	(50,50)	0.1 ± 0.1	(0,100)	0	(50,50)	0	-
Feltia subgothica	0	-	0.1 ± 0.1	(100,0)	0	-	0	-	0	-
Graphiphora augur	0.5 ± 0.3	(50,50)	0	-	0.1 ± 0.1	(100,0)	0	-	0	-
Noctua pronuba	0	-	0	-	0	-	0	-	0	-
Paradiarsia littoralis	0.1 ± 0.1	(0,100)	0.3 ± 0.2	(50,50)	0.1 ± 0.1	(0,100)	0	-	0	-
Xestia c-nigrum	0.5 ± 0.3	(50,50)	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Xestia smithii	0	-	0.3 ± 0.2	(0,100)	0.3 ± 0.3	(100,0)	0.1 ± 0.1	(100,0)	0	-

Table 5-S3. (continued)

	Wheat									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Noctuinae: Apameini										
Amphipoea interoceanica	12.9 ± 5.1	(25,75)	10.9 ± 4.8	(33,67)	6.1 ± 3.3	(43,57)	11.3 ± 6.0	(34,66)	1.1 ± 0.5	(11,89)
Apamea alia	0.4 ± 0.2	(33,67)	0.3 ± 0.3	(50,50)	0	-	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(100,0)
Apamea amputatrix	1.0 ± 0.3	(88,13)	0.3 ± 0.2	(100,0)	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(100,0)	0	-
Apamea centralis	0	-	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Apamea cogitata	51.0 ± 24.5	(42,58)	46.3 ± 21.8	(53,47)	12.9 ± 5.9	(53,47)	22.3 ± 12.7	(44,56)	0	-
Apamea commoda	1.6 ± 0.8	(54,46)	1.4 ± 0.7	(55,45)	0.4 ± 0.2	(33,67)	0.3 ± 0.3	(50,50)	0	-
Apamea devastaor	19.5 ± 7.5	(37,63)	21.8 ± 10.8	(39,61)	5.9 ± 3.1	(49,51)	4.5 ± 2.2	(22,78)	0.8 ± 0.4	(0,100)
Apamea dubitans	0	-	0	-	0	-	0	-	0	-
Apamea impulsa	0	-	0	-	0	-	0	-	0	-
Apamea inficita	4.1 ± 1.7	(58,42)	2.4 ± 1.1	(42,58)	1.1 ± 0.5	(44,56)	1.5 ± 0.4	(25,75)	0.1 ± 0.1	(100,0)
Apamea lignicolora	0.1 ± 0.1	(100,0)	0.5 ± 0.3	(50,50)	0	-	0	-	0	-
Apamea niveivenosa	22.3 ± 10.5	(13,87)	17.6 ± 10.5	(15,85)	4.3 ± 1.9	(12,88)	3.4 ± 1.5	(22,78)	0.1 ± 0.1	(0,100)
Apamea plutonia	0.1 ± 0.1	(0,100)	0	-	0	-	0	-	0	-
Apamea scoparia	0.3 ± 0.2	(0,100)	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(0,100)
Celaena reniformis	5.3 ± 1.6	(52,48)	6.0 ± 2.5	(56,44)	2.0 ± 1.1	(31,69)	3.1 ± 1.9	(40,60)	0.1 ± 0.1	(100,0)
Hypocoena rufostrigata	0.9 ± 0.6	(14,86)	0.8 ± 0.5	(0,100)	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	0	-
Mesapamea fractilinea	0	-	0.1 ± 0.1	(0,100)	0	-	0	-	0	-
Noctuinae: Hadenini										
Anarta trifolii	0.1 ± 0.1	(0,100)	0	-	0	-	0	-	0	-
Dargida diffusa	0.4 ± 0.3	(0,100)	0.4 ± 0.2	(0,100)	0.3 ± 0.2	(50,50)	0.1 ± 0.1	(100,0)	0.4 ± 0.2	(0,100)
Dargida procinctus	0	-	0.1 ± 0.1	(100,0)	0	-	0	-	0	-
Lacanobia atlantica	0.8 ± 0.5	(0,100)	0.6 ± 0.3	(60,40)	0	-	0.3 ± 0.2	(50,50)	0	-
Lacanobia radix	0.3 ± 0.2	(50,50)	0.1 ± 0.1	(100,0)	0	-	0.3 ± 0.2	(50,50)	0	-
Polia nimbosa	0.5 ± 0.2	(0,100)	0.3 ± 0.2	(50,50)	0.1 ± 0.1	(0,100)	0.1 ± 0.1	(0,100)	0	-

Table 5-S3. (continued)

	Wheat									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Trichordestra lilacina	0.8 ± 0.4	(0,100)	0.8 ± 0.4	(33,67)	0	-	0.1 ± 0.1	(0,100)	0	-
Noctuinae: Leucaniini										
Leucania anteroclara	0	-	0	-	0.3 ± 0.2	(50,50)	0.1 ± 0.1	(0,100)	0	-
Leucania commoides	1.1 ± 0.4	(22,78)	1.0 ± 0.6	(25,75)	0.4 ± 0.3	(0,100)	0.5 ± 0.3	(25,75)	0.1 ± 0.1	(0,100)
Leucania multilineata	0.4 ± 0.2	(33,67)	0.3 ± 0.2	(50,50)	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(0,100)	0	-
Mamestra configurata	1.1 ± 0.9	(78,22)	0.8 ± 0.6	(83,17)	0.1 ± 0.1	(100,0)	0.5 ± 0.2	(25,75)	0	-
Mythimna oxygala	3.6 ± 1.9	(10,90)	4.1 ± 1.6	(30,70)	0.3 ± 0.2	(0,100)	0.9 ± 0.4	(0,100)	0.1 ± 0.1	(0,100)
Mythimna unipuncta	0	-	0.1 ± 0.1	(100,0)	0	-	0	-	0	-
Noctuinae: Eriopygini										
Lacinipolia lorea	3.3 ± 1.7	(38,62)	2.3 ± 0.8	(28,72)	0.9 ± 0.7	(43,57)	1.0 ± 0.9	(13,88)	0	-
Lacinipolia meditata	0	-	0	-	0	-	0	-	0	-
Lacinipolia olivacea	1.8 ± 1.3	(57,43)	0.9 ± 0.5	(43,57)	3.0 ± 1.5	(58,42)	2.6 ± 1.4	(48,52)	0.6 ± 0.5	(0,100)
Lacinipolia renigera	4.6 ± 2.0	(49,51)	4.9 ± 1.8	(72,28)	4.3 ± 1.5	(50,50)	2.9 ± 1.2	(70,30)	0.4 ± 0.2	(33,67)
Noctuinae: Xylenini										
Enargia spp.	0	-	0.5 ± 0.4	(25,75)	0.1 ± 0.1	(0,100)	0.5 ± 0.4	(0,100)	0.3 ± 0.2	(0,100)
Sunira bicolorago	0.1 ± 0.1	(100,0)	0.4 ± 0.3	(67,33)	0	-	0.4 ± 0.3	(0,100)	0	-
Xanthia tatago	0	-	0	-	0	-	0.1 ± 0.1	(0,100)	0	-
Noctuinae: Caradrinini										
Caradrina montana	0.4 ± 0.3	(67,33)	0.4 ± 0.4	(33,67)	0	-	0.5 ± 0.5	(25,75)	1.0 ± 1.0	(0,100)
Caradrina morpheus	0.3 ± 0.2	(0,100)	0.1 ± 0.1	(0,100)	0	-	0.6 ± 0.5	(40,60)	0	-
Noctuinae: Tholerini										
Nephelodes minians	3.3 ± 1.4	(4,96)	0.8 ± 0.4	(0,100)	0.9 ± 0.3	(29,71)	0.8 ± 0.3	(0,100)	0	-

Table 5-S3. (continued)

	Wheat									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Plusiinae: Plusiini										
Anagrapha falcifera	0	-	0	-	0	-	0	-	0.1 ± 0.1	(0,100)
Autographa californica	0	-	0.1 ± 0.1	(100,0)	0.6 ± 0.3	(100,0)	0.4 ± 0.2	(67,33)	0	-
Plusia putnami	0.1 ± 0.1	(100,0)	0	-	0	-	0	-	0	-
Plusiinae: Pseudeustrotiini										
Pseudeustrotia carneola	1.0 ± 0.7	(25,75)	0.5 ± 0.4	(25,75)	0.4 ± 0.3	(33,67)	0.8 ± 0.5	(50,50)	0.1 ± 0.1	(0,100)
Acronictiane										
Acronicta americana	0	-	0	-	0	-	0	-	0	-
Sphingidae										
Macroglossinae: Macroglossini										
Darapsa choerilus	0	-	0.1 ± 0.1	(100,0)	0	-	0	-	0	-
Smerinthinae: Smerinthini										
Smerinthus jamaicensis	0.1 ± 0.1	(100,0)	0	-	0	-	0	-	0	-
Crambidae										
Glaphyriinae										
Evergestis pallidata	0.1 ± 0.1	(100,0)	0	-	0	-	0	-	0.1 ± 0.1	(100,0)
Erebidae										
Arctiinae: Arctiini										
Ctenucha virginica	0	-	0.1 ± 0.1	(100,0)	0.8 ± 0.6	(100,0)	0.1 ± 0.1	(100,0)	0.1 ± 0.1	(100,0)
Arctiinae: Lithosiini										
Hypoprepia miniata	0	-	0	-	0	-	0	-	0	-
Erebidae										
Erebinae: Euclidiini										
Caenurgina erechtea	1.1 ± 0.5	(67,33)	0.6 ± 0.4	(60,40)	0	-	0.1 ± 0.1	(100,0)	0	-

Table 5-S3. (concluded)

	Wheat									
Species	AAMB		AAMB+MP		AAMB+PAA		AAMB+MP+PAA		Unbaited	
Geometridae										
Ennominae: Ourapterygini										
Sicya macularia	0	-	0	-	0.1 ± 0.1	(0,100)	0	-	0	-
Larentiinae: Hydriomenini										
Rheumaptera undulata	0	-	0	-	0.1 ± 0.1	(100,0)	0	-	0	-
Hesperiidae										
Hesperiinae: Thymelicini										
Thymelicus lineola	0.1 ± 0.1	(100,0)	0.3 ± 0.3	(100,0)	0.5 ± 0.5	(100,0)	0.4 ± 0.3	(100,0)	0.1 ± 0.1	(100,0)
Unidentified	34.8 ± 19.5	(37,63)	36.1 ± 17.0	(36,64)	16.5 ± 6.5	(43,57)	7.5 ± 2.3	(42,58)	4.0 ± 1.0	(22,78)
Total	220.3 ± 80.1	(40,60)	198.0 ± 80.8	(42,58)	81.1 ± 28.8	(47,53)	86.4 ± 35.5	(41,59)	14.1 ± 2.5	(20,80)

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Chapter 6 General Conclusion

Cutworms and armyworms (Lepidoptera: Noctuidae) are part of a pest complex, native to North America, that affect multiple annual crops grown across the Canadian Prairies (Floate, 2017). These pests are generalist herbivores on a wide range of hosts from different plant families (Lafontaine, 2004). Furthermore, adults are large, robust-bodied moths that can disperse over long distances (McNeil, 1987, Showers et al., 1989, Hendrix III and Showers, 1992). In this study, I identify knowledge gaps in crop-cutworm interactions to enhance Integrated Pest Management (IPM) of this group in the Prairie Provinces.

The first component of this study focused on crop-cutworm interactions at the individual level. I examined how agricultural practices influence the performance and fitness of three focal pest species: the true armyworm, *Mythimna unipuncta* (Haworth); the redbacked cutworm, *Euxoa ochrogaster* (Guenée); and the pale western cutworm, *Agortis orthogonia* (Morrison). First, I assessed the influence of crop variety and fertilization regime on the relationship between oviposition preference and larval performance of the true armyworm (Chapter 2). Second, I evaluated the effect of crop variety and fertilization regime on the larval performance and larval feeding preference of the redbacked cutworm and pale western cutworm (Chapter 3).

The second component of this study focused on crop-cutworm interactions at the population level, specifically on the adult stage of cutworms and the chemical ecology of feeding attractant volatiles. A series of field experiments were conducted to develop a food-based semiochemical to monitor the cutworm and armyworm pest complex with a single lure in Canadian Prairie agroecosystems (Chapter 4). The chemical mixture of acetic acid and 3-methyl-1-butanol (AAMB) is attractive to several noctuid pests in multiple cropping systems (Landolt, 2000, Landolt and Higbee, 2002, Landolt et al., 2007). My approach was to enhance the attractiveness of the AAMB lure to monitor the most common cutworm species across the Prairies, the redbacked cutworm, in canola (*Brassica napus* L.) (Brassicaceae) and wheat (*Triticum aestivum* L.) (Poaceae) fields in central Alberta. Lastly, I report on the diversity and abundance of noctuid moths trapped with food bait lures based on the volatile by-products of microbial fermented sugar baits (Chapter 5).

Preference-performance relationship in generalist herbivores

The ‘mother knows best’ principle predicts that natural selection favours females with an oviposition preference for host plants on which offspring will have the highest performance (Levins and MacArthur, 1969, Courtney and Kibota, 1990). Insect diet breadth is a factor that highly influences the preference-performance relationship, in which specialist herbivores have a stronger preference for suitable hosts plants compared to generalist herbivores (Gripenberg et al., 2010). For instance, a study of six vinegar fly species (Diptera: Dorsophilidae) illustrates the preference-performance relationship differs according to the degree of host specialization; with a strong positive correlation for specialist species and no relationship for generalists (de la Masselière et al., 2017). Similarly, the specialist *Helicoverpa armigera* (Hübner) prefers high-quality host plants on which offspring perform best, whereas the generalist sister species *H. assulta* (Gueéne) equally accepts high- and low-quality hosts (Liu et al., 2012). Despite the overall support for the ‘mother knows best' principle, there are numerous studies for which preference and performance are not strongly coupled (Berdegue et al., 1998, Jallow and Zalucki, 2003, Wist and Evenden, 2016, Hufnagel et al., 2017). Female oviposition behaviour may be modified by ecological factors (i.e. predator avoidance) and/or life history traits of the herbivore (Gripenberg et al., 2010). For example, some herbivorous larvae disperse within and among plants during development. Weak selection for a preference-performance relationship would be expected in herbivores with highly mobile larvae (Thompson, 1988, Craig and Itami, 2008). For example, neonate larvae of the generalist *Spodoptera littoralis* (Boisduval) (Lepidoptera: Noctuidae) feed *in situ* for about five days on young leaves of cotton (*Gossypim arboretum* L.) (Malvaceae) selected by female moths for oviposition. As larvae grow, they gradually move to feed on mature leaves of the same plant or neighbouring plants (Sadek, 2011).

Many generalist insect herbivores can discriminate between hosts within their accepted host-range and exercise some degree of preference at host selection for oviposition (Schoonhoven et al., 2005). In the true armyworm, my work shows that females prefer the lowest quality host, feed barley (Xena), that supported the lowest larval performance. Furthermore, the addition of fertilizer increased the nutrition quality of the host plants and enhanced the larval performance, however, females failed to assess the nutritional quality of the host and equally accepted fertilized and unfertilized hosts. Although oviposition preference for both cutworm species was not evaluated in this study, it is known that redbacked and pale western cutworm females do not oviposit directly on larval host plants but lay eggs in loose-dry soil under crop stubble or in fallow fields (Beirne, 1971). It is possible that this oviposition strategy may weaken the preference-performance relationship in both cutworm species, although preference for oviposition choice in soil with different species of crop stubble has not been tested. In multiple-choice larval feeding preference experiments, redbacked and pale western cutworm prefer to feed on the host plant that promotes high performance. For both cutworm species, larvae assess the suitability of a host plant and may have a more active role in host selection than the adult females that lay eggs in the soil.

Schäpers et al. (2016) suggest a negative relationship between herbivore diet breadth and larval dispersal abilities. The strength of the preference-performance relationship in a nymphalid system (Lepidoptera: Nymphalidae) depends on larval host-range and the larval dispersal abilities (Schäpers et al., 2016). A series of experiments tests the oviposition preference and neonate larval performance between high- and low-quality hosts, and neonate larval dispersal abilities. The generalist nymphalids (*Polygonia c-album* L. and *Vanessa cardui* L.) equally prefer both hosts, neonate larvae have similar performance and survival rate on both hosts, and are highly mobile. In contrast, the specialist nymphalids (*Aglais urticae*, *A. io* and *V. atalanta*) prefer the high-quality host, neonate larvae have a higher performance and survival rate on only the high-quality host, and they are less mobile than the generalist nyphalids.

From my results, I infer that the true armyworm, redbacked and pale western cutworm do not follow the 'mother knows best' principle. This study provides evidence in favour of Schäpers et al. (2016) prediction, as larvae of the three focal species feed on a wide host plant-range and are highly mobile, and therefore, female oviposition behaviour may be less specific as larvae can disperse to find hosts. Cutworms and armyworms may employ a bet-hedging strategy to spread the risk of mortality among offspring by the spatial distribution of eggs across the landscape (Hopper, 1999).

Effect of agricultural practices on cutworm performance

Crop rotation and fertilizer input are common agricultural practices across the Prairie Provinces. Crop rotation aims to exploit the feeding habits of herbivores with narrow diet breadth to prevent pest density buildup through substitution with non-host crops (Bullock, 1992). Crop rotation can cause larvae to feed on less than optimal host plants, which can affect the performance and adult fitness of the target pest. Fertilizer input increases nitrogen content in plants (Mattson, 1980, López-Bellido et al., 1996, Jackson, 2000), and therefore, enhances larval performance of herbivores (Chen et al., 2004, Chen et al., 2010, Weeraddana and Evenden, 2018). This bottom-up effect on herbivore growth and reproduction can, in turn, impact population density and contribute to outbreaks of pest species.

Redbacked and pale western cutworm adults fly in late summer and early fall after crop harvest (Beirne, 1971), so that assessment of the plant community available for offspring the following spring is not possible. Cutworm larvae are restricted to feed, at least initially, on the current crop, which may differ from that selected by the adult female. Generalist herbivores are able to feed and complete larval development on hosts from different plant families, however, their performance and fitness varies among host plants species. In larval performance experiments with different host species, redbacked cutworm performs best on canola and field peas, whereas pale western cutworm performs well on spring wheat seedlings. Field peas are not a suitable host for pale western cutworm as there is low larval survival on this host. In larval performance experiments under two fertilization regimes, redbacked cutworm perform better on canola than on spring wheat, whereas pale western cutworms do better on spring wheat than canola. The nutritional quality of canola and spring wheat seedlings was enhanced through fertilization. Both cutworm species perform better on fertilized seedlings, regardless of the crop species.

Canola-cereal crops is a common crop rotation schedule in the Canadian Prairie Provinces, however, this IPM tactic will not negatively impact cutworm performance. First, redbacked and pale western cutworm have a wide host plant range and larvae have high dispersal capacity, and thus, larvae will be able to cope with low-quality hosts or search for a better host. Second, although crop rotation alters female host selection and cutworm larval performance varies with the crop species, fertilizer input at seeding will enhance host plant suitability for both cutworm species.

Noctuidae moth response to food-based semiochemicals

Cutworm and armyworm moths, like many lepidopterans, use volatile organic compounds for orientation towards food sources, and females may also use these cues to select oviposition sites (Schoonhoven et al., 2005). Furthermore, insects may be sensitive to cues produced by microbes associated with their food sources and oviposition sites, referred to as microbial volatile organic compounds (MVOC) (Davis et al., 2013). The MVOC hypothesis states that microbial emissions serve as semiochemicals that provide cues regarding suitability and nutritional quality of hosts (Davis et al., 2013). Overall, food-based semiochemicals are classified into three groups: host plant volatiles, floral volatiles and MVOCs from fermented sugars.

Redbacked cutworm and the pale western cutworm females do not oviposit directly on larval host plants (Beirne, 1971), and thus, host plant volatiles cues may not be involved in location of food sources or oviposition sites. Furthermore, specialist herbivores may be more attracted to food bait lures based on host plant volatiles than generalist moths, as specialist females are more efficient and accurate in selecting host plants for offspring development than generalist herbivores (Bernays and Funk, 1999, Bernays, 2001). For instance, traps baited with ethyl (*E,Z*)-2,4-decadienoate, a pear-derived host volatile, equally attracts males and females of the specialist codling moth (*Cydia pomonella* L.) (Lepidoptera: Tortricidae) in similar numbers to sex pheromone baited traps (Light et al., 2001).

Phenylacetaldehyde and benzaldehyde are among the most dominant floral volatiles identified from several plants visited by noctuid moths (Cantelo and Jacobson, 1979, El-Sayed et al., 2008, Guédot et al., 2008, Landolt and Smithhisler, 2003). Interestingly, noctuid pest from the subfamily Plusiinae and Heliothinae are more attracted to traps baited with phenylacetaldehyde alone or complete floral blends than noctuid pest from the Noctuinae (Meagher Jr, 2001a, Guédot et al., 2008, Stringer et al., 2008, Tóth et al., 2010).

Several insects rely specifically on microbial volatile organic compounds as cues to locate food sources (Davis et al., 2013). For instance, over 90 % of moth species captured in traps baited with different sources of fermented sugar baits are noctuids (El-Sayed et al., 2005). The chemical mixture of two fermented sugar by-products, acetic acid and 3-methyl-1-butanol (AAMB), has been used to monitor the diversity and abundance of moths in multiple cropping systems (Landolt, 2000, Landolt and Higbee, 2002, Landolt et al., 2007). In field experiments in central Alberta, Noctuinae are the most diverse and abundant subfamily attracted to AAMB-baited traps, including several cutworm and armyworm pest species. The majority of Noctuinae moths attracted to AAMB-baited traps represent the tribes Apameini and Noctuini. The addition of phenylacetaldehyde and 2-methyl-1-propanol to AAMB lures did not enhance the attraction of cutworm and armyworm pests. More cutworm pests were attracted to food bait lures from fermented by-products than floral volatiles.

Overall, moths from the subfamily Noctuinae may rely on microbial volatile organic compounds for location of food source, whereas moths form the subfamilies Plusiinae may rely on floral volatiles. Similar patterns were found by Landolt et al. (2011), who compared noctuid moth diversity in traps baited with AAMB and floral lures.

Development of food bait lures to monitor cutworm and armyworm moths in the Canadian Prairie agroecosystem

My approach was to enhance the attractiveness of the AAMB lure to monitor cutworm and armyworm pests in canola and wheat fields in central Alberta. Overall, AAMB-baited traps deployed in wheat fields captured more noctuid moths than baited traps in canola fields.

Furthermore, there was no difference in the species composition of noctuid moths sampled in canola and wheat fields, which might indicate that noctuid moths have high dispersal capacity across agricultural landscapes. Noctuid moths are strong flyers and are capable of dispersing over long distances. For instance, marked individuals of *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) were recaptured at a maximum distance of 806 m for males and 608 m for females across corn (*Zea mays* L.) (Poaceae) fields (Vilarinho et al., 2011). Similarly, *Heiothis virescens* (Fabricious) (Lepidoptera: Noctuidae) males can disperse up to 30 km from the release point in mark-recapture experiment (Schneider, 1999).

It is possible that variation in response to AAMB lure is influenced by host plant volatiles from crops in the background where baited traps were positioned. For example, a food bait lure based on benzaldehyde to monitor the tea leafhopper (*Empoasca onukii* [Matsuda]) (Hemiptera: Cicadellidae) was highly attractive in wind-tunnel laboratory assays, however, low numbers of tea leafhoppers were captured in field experiments due to the high concentration of benzaldehyde in the background odours of tea plantations (Cai et al., 2017). Acetic acid is one of the most prominent volatile organic compounds emitted by canola plants at the flowering stage (Veromann et al., 2013), whereas acetic acid is not part of the volatile profile in wheat plants (Piesik et al., 2010, Piesik et al., 2011). Background odours can interfere with the attraction of food baits if their components overlap (Cai et al., 2017). Therefore, the AAMB lure may be more efficient at monitoring cutworm pests if traps are deployed near wheat fields than canola fields.

In an attempt to enhance the attractiveness of the AAMB lure to target noctuid species, especially redbacked cutworm, different AAMB release rates and release devices were tested. Although the amount of AAMB (mg/day) delivered from Nalgene bottles differed among the release rate treatments (low: 1.0 mm; standard: 3.0 mm; high: 5.0 mm), equal numbers of redbacked cutworm moths were captured among the three release treatments. Likewise, spotted cutworm (*Xestia c-nigrum* L.) and bertha armyworm (*Mamestra configurata* Walker) moths were captured in similar numbers in AAMB delivered from Nalgene bottles with 1.0 and 3.0 mm holes in the bottle cap (Landolt and Alfaro, 2001). In the release device experiment, more redbacked cutworm moths were captured in traps baited with AAMB delivered in Splat™ than from Nalgene bottles, while capture in traps baited with polyethylene bags was intermediate. Although release rates of AAMB from the different devices were not recorded in this experiment, it is likely that the AAMB Splat™ mixture has a different release rate than Nalgene bottles and polyethylene bags. For example, phenylacetaldehyde incorporated into the wax developed for dispensing semiochemicals has a higher release compared to that from rubber stopper lures, and thus, attracts more moths to baited traps (Meagher Jr, 2002). Splat™ may be a more effective release device to deliver the AAMB lure than Nalgene bottles or polyethylene bags to monitor cutworm and armyworm pests in prairie agroecosystems.

The addition of two food-based semiochemicals, phenylacetaldehyde and 2-methyl-1-propanol, to AAMB lures were evaluated to enhance the attraction to redbacked cutworm. More female redbacked cutworm moths are attracted to AAMB lures with the additional alcohol from fermented by-products than AAMB lures with phenylacetaldehyde. Furthermore, capture of more cutworm moths is greater in traps baited with food bait lures from fermented by-products than floral volatiles, specifically the dingy cutworm (*Feltia jaculifera* [Guenée]), glassy cutworm (*Apamea devastator* [Brace]), strawberry cutworm (*Amphipoea interoceanica* Smith), bronzed cutworm (*Nephelodes minians* Guenée) and yellow-head cutworm (*Apamea amputatrix* [Fitch]). Similar patterns were previously reported for the glassy cutworm and dingy cutworm in apple orchards (Landolt et al., 2011). Overall, food bait lures based on fermented sugar by-products, AAMB or AAMB plus 2-mehtyl-1-propanol, are more efficient for monitoring the redbacked cutworm and other cutworm pests than AAMB with floral volatiles.

AAMB-baited traps have a low pollinator by-catch but high numbers of vespid wasp by-catch. The impact of capturing pollinators in baited traps targeting cutworm-moths on the population of native pollinators has not been assessed, however, a high by-catch of pollinators or vespid wasps will increase the efforts to process and identify the target cutworm moths. An efficient cutworm monitoring tool should limit attraction of non-noctuid moth by-catch. The addition of phenylacetaldehyde to food bait traps, however, attracts more *Bombus* spp. by-catch. Food bait lures based on microbial volatile organic compounds may be especially suitable for monitoring cutworm and armyworm moths because pollinators do not appear to be attracted to these compounds. Further studies should evaluate food bait lures with longer chain alcohols to reduce the attraction of vespid wasps (Landolt et al., 2000).

Final thoughts

Polyphagy and high dispersal capability allow cutworm and armyworms to adapt to annual disturbances inflicted by farming practices in prairie agroecosystems, and therefore, cause sporadic economic damage across the Prairie Provinces. On crop-cutworm interactions at the individual level, this study demonstrates that redbacked cutworm larvae have a higher performance and preference in canola over wheat, whereas pale western cutworm larvae have higher performance and preference on wheat over canola. Although cutworm larval performance varies with the crop species, fertilizer input at seeding will enhance host plant suitability for both cutworm species. Agricultural practices like monoculture systems and fertilizer inputs allow cutworms to have a high performance and fitness, and in turn, potentially lead to an increase population density to infestation levels.

On crop-cutworm interactions at the population level, the AAMB lure is a potential tool to survey and monitor cutworm and armyworm pests. This study shows the broad attraction of acetic acid and 3-methyl-1-butanol to a large number of noctuid moths, and thus, food baits based on fermented sugar by-products can be used to determine diversity of moths within the Noctuinae subfamily in agroecosystems. The general response of noctuid moths to AAMB-baited traps, however, may pose a concern for monitoring cutworms as non-target Lepidoptera will increase the time sorting specimens and require specialized knowledge to identify individuals.

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