EVALUATING HOST PLANT PREFERENCE AND PHEROMONE ATTRACT AND KILL AS STRATEGIES TO MANAGE PEA LEAF WEEVIL *SITONA LINEATUS* (L.) (COLEOPTERA: CURCULIONIDAE) IN MONTANA

by

Pragya Kiju

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Entomology

MONTANA STATE UNIVERSITY
Bozeman, Montana

July 2022

DEDICATION

My work is dedicated to my brothers, mother, father, and my advisors who have pushed to go beyond my limits and supported me through the thick and thins. I would like to thank my friends who has been supporting me endlessly throughout my journey here without whom I won't be able to write this thesis.

ACKNOWLEDGEMENTS

I am grateful to Dr. Kevin Wanner, Dr Michel Ivie, Dr. Gadi VP Reddy, and Dr. Kevin McPhee for guiding, supporting and provide insights for my project. I want to thank Jhon Miller, Mary Ellen Dietz-Holmes, Ruth O’Neill, helping me in the field work. We thank Montana Wheat and Barley Committee for supporting this project. All of these people made this project possible.

TABLE OF CONTENTS

TABLE OF CONTENTS CONTINUED

LIST OF TABLES

LIST OF TABLES CONTINUED

LIST OF FIGURES

LIST OF FIGURES CONTINUED

ABSTRACT

Pea leaf weevil (*Sitona lineatus*) is the most common insect pest of field peas grown in Montana. Montana is the number one producer of field pea in the US. Currently, Montana producers spray insecticides at least once or twice during the spring growing season to avoid leaf damage inflicted by pea leaf weevil adults and larvae. Complete reliance on insecticides may, however, raise the risk of pea leaf weevil populations developing genetic resistance. Therefore, this project focuses on development of alternative pulse insect pest management strategies such as pheromone-based attract and kill and host plant preference. For the attract and kill strategy 6 different treatments compared combinations of aggregate pheromone (4–methyal-3,5-heptanedione) alone in two different forms; septa and pellet, pheromone with granular insecticide (Deltamethrin). To determine the effect of host variety on adult feeding preference, 10 field pea, 2 faba bean, 2 lentil and 2 chickpea varieties were assessed for feeding damage. Crescent shaped notches were counted on 10 individual plants per replicate plot. The average number of larvae within the nitrogen fixing root nodules of each variety was also recorded on 5 randomly selected individual plants per plot. Faba bean was the most preferred host while lentil and chickpea suffered almost no feeding damage. ‘Delta’ and ‘Lifter’ field pea varieties appeared to be preferred over ‘DS Admiral’ and ‘AC Agassiz’ varieties. Given the significant level of feeding on all pea and faba bean cultivars further evaluation of low-cost pheromone traps are essential to establishing an IPM control approach.

CHAPTER ONE

GENREAL INTRODUCTION

Pea Leaf Weevil Systematics

Pea leaf weevil, (*Sitona lineatus* (L.) (Coleoptera: Curculionidae), is of palearctic origin (Rivnay 1962, Velazquez et al. 2010). It belongs to the sub family Curculioninae which is the most speciose insect family of the order Coleoptera (Blatchley and Leng 1916, Arnett 1960, Carcamo and Vankosky 2011).

Sitona belongs to the subfamily Curculioninae, which is characterized by the presence of a scar on mandible marking the location of a deciduous cusp. *Sitona* are easily distinguished from other closely related genera as they lack this mandibular scar (Bright 1994).

The pea leaf weevil is a member of the Entiminae subfamily (i.e., broad nose beetle weevil; Velazquez et al. 2010). Pea leaf weevil was first described by Linnaeus in 1758 (Vankosky et al. 2010). In 1817, Germar proposed the genus name, *Sitona* name simply as “46. Sitona nob. Curc. Gressorius, lineatus, hispidulus” and in 1824 Germar formally proposed the name as a new genus with a full description (Germar 1817, Germar 1824). However, in 1840 Schoenherr modified the genus name to *Sitnoes* (Schoenherr 1840, Bright 1994). In 1840, Westwood was the first to formally use the species name of pea leaf weevil as ‘*Curculio lineatus* L.’ (Westwood 1840).

The classification of pea leaf weevil has changed over time. As such, it has been placed into different families and/or subfamilies like subfamily Sitoninidae (LeConte and Horn 1876), Sitoninae (Casey 1888). It also had been placed in the Sitonina and subfamily Curculioninae

(Champion 1902), tribe Sitonini and subfamily Curculioninae (Batchley and Leng 1920, Arnett 1960), tribe Brachyderinae (Thaylacitniae) (O'Brien and Wibmer 1982), subfamily Sitonini tribe Entiminae (Thompson 1920); finally, subfamily Brachyderinae and tribe Sitonini (Bright 1994). Pea leaf weevil is the only North American *Sitona* species with procoxal cavities touching the narrow groove which is located on the ventral surface of the prosternum (Bright 1994).

Table 1.1. Eleven species of pea leaf weevil in North America with their common name and hosts. (Bright 1994).

Species of *Sitona*	Host crops	Common name
Sitona aquilonius Bright	Unknown	Unknown
Sitona californius Fåhraenus	lupine, alfalfa, plum, apple, peach, sunflower, fruit trees	Unknown
Sitona cylindricollis Fåh	sweet clover, alfalfa seedling, *Cicer* spp, black medic, milkvetch, alfalfa	sweet clover weevil
Sitona desertus Bright	Unknown	Unknown
Sitona flavescens (Marsham)	red clover, white clover	Unknown
Sitona hispidulus (Fabricius)	various species of clovers and alfalfa, forage legumes, lucerne, Lotus, *Trifolium* spp	clover root curculio
Sitona lineatus (Linnaeus.)	pea, faba bean, vetches, beans	pea leaf weevil
Sitona linnellus Bonsdorff	alfalfa, sainfoin, *Cicer spp*, milkvetch, native vetch, pea	alfalfa curculio
Sitona lupinus Sleeper	only on *Lupinus sericeus*	Unknown
Sitona vittatus LeConte	not clearly identified but found under log, under dry cow dung	Unknown
Sitona tanneri Bright	Unknown	Unknown

Pea Leaf Weevil Distribution

Members of the genus *Sitona* are damaging insect pests of legumes, with at least one species associated with every species of legume (Jackson 1920, Velázquez De Castro et. al. 2010). Of the 100 known *Sitona* species, (van Emdem and van Emden 1939), there are only 11 species in North America, with five considered invasive species which were introduced from Europe (Bright 1994, Table 1.1). Pea leaf weevil is native to Europe and North Africa, whereas in North America it is invasive insect pest of field peas (*Pisum sativum* L.) and faba bean (*Vicia faba* L.) (Hoebeke and Wheeler 1985, Olfert et al. 2012, Prochaska et al. 2018).

In Europe, pea leaf weevil is a well-established as insect pest of legumes. (Jackson 1920, Prescott and Reehher 1961). In Germany, significant damage was observed in lupin (*Lupinus albus* L. (Fablaes: Fabaceae)) (Ferguson 1994).

In North America, pea leaf weevil damaged seedlings of peas in 1936 under codling moth band near Victoria in British Columbia, Canada (Downes 1938, Prescott and Reehher 1961, Olfert et al. 2012, Prochaska et al 2018). For example, along the Fraser River of British Columbia, Canada, cannery peas and clover were heavily infested on a 112.65 kilometer (Km) stretch of the Fraser River (Prescott and Reehher 1961). In 1942, pea leaf weevil was first identified in central British Columbia (Hatch 1971) and areas bordering Puget Sound from Vancouver (Prescott and Reehher 1961). Subsequent reports were derived from Lethbridge, southern Alberta, Canada in 1997 (Cárcamo and Vankosky 2011), then northward in Alberta and Saskatchewan in 2007 (Cárcamo and Meers 2007, Hartley 2007, Cárcamo et al. 2010). Pea leaf weevil had become prominent insect pest in Southern Alberta and has rapidly extended to eastern, western Saskatchewan (Olfert et al. 2012). It spread throughout the Canada as there was no geographical barriers to stop movement or flight (Soroka and Cárcamo 2006, Coles et al. 2008). Pea leaf weevil is a prominent insect pest in southern Alberta and western Saskatchewan (Olfert et al. 2012).

In the United States, pea leaf weevil was first recorded infesting peas and vetches on the San Juan Islands of Washington in 1940 followed by Whidbey Island in 1941 (Prescott and Reehher 1961, Hatch 1971). Then, spread southward and became established as a prominent insect pest in California, Florida, Montana, Texas, and Virginia (Hoebeke and Wheeler 1985, Prochaska et al. 2018). Over the last decade in Montana, pea leaf weevil populations have been moving eastward towards the Dakotas (Wanner 2016, Prochaska et al. 2018). Pea leaf weevil was first detected in southwestern North Dakota on field peas in Golden Valley Country during the fall of 2016. Prochaska et al. (2018) additionally reported pea leaf weevil population moving eastward in within the state. North Dakota State University Extension entomologist in 2016 and 2017 reported presence of pea leaf weevil in southwestern counties (e.g., Dunn, Golden Valley and Stark counties), north-central counties (Mountrail and Ward counties) and northwestern counties (Divide County) (Prochaska et al. 2018). In short, once introduced, pea leaf weevil's quickly spread to east and west coast of North America (El-Dessouki 1971, Aeschlimann 1980, Hartley 2007, Cárcamo et al. 2007) and is now present on California, Florida, Idaho, Montana, North Dakota, Northern, Oregon, Virginia, Washington (Prescott and Reeher 1961, El-Dessouki 1971, Hatch 1971, Fisher and O' Keeffe 1979c, Aeschlimann 1980, Hoebeke and Wheeler 1985, Bright 1994, Bloem et al. 2002, Cárcamo et al. 2007, Cárcamo and Vankosky 2011).

Pea leaf weevil is also found in Asian countries like Iran, Israel, Syria, Turkey (Markkulla and Koppa 1960, Melamed-Madjar 1966, Lodos 1971, Boroumand 1975, Plaut 1975, Ahmadi and Alichi 1991, Linke et al. 1991). Pea leaf weevil is also reported in Australia, South Australia (Hawthrone 1987). Pea leaf weevil is also spread across African countries like Algeria, Egypt, Morocco, Tunisia, Uganda (Blaeser 1982, Fam 1983, Hoebeke and Wheeler 1985, Baliddawa 1988).

In short, pea leaf weevil is an important economically damaging insect pest in Africa, Asia, Australia, Europe and North America (Hoebeke and Wheeler 1985, Bloem et al. 2002, Nilsson 1973, Botha 2004).

Pea Leaf Weevil Dispersal and Migration

The introduction of pea leaf weevil across continents may be due to export and import to the movement of agricultural goods (Hoebeke and Wheeler 1958). In recent years, growers in Canada, Montana, and North Dakota are expanding the range of legume production. Therefore, the increased area of legume production and climatic conditions may have contributed to the increase in pea leaf weevil populations in the region (Vankosky et. al. 2009).

Once established in a new region, pea leaf weevil can expand their habitat through flight (Hans 1959, Fisher and O’Keeffe 1979c, Hamon et al. 1987, Nielsen and Jensen 1993). Pea leaf weevil has a migratory behavior as it has two distinct flight periods (Jackson 1920, Hans 1959, Fisher and O’Keeffe 1979c). The first, is a post teneral flight during late summer (Fisher and O’Keeffe 1979a). The second, is a post-diapause flight in the spring (Fisher and O’Keeffe 1979a, Hamon et al 1987). Pea leaf weevil flight is predominantly downwind, as they have migratory flight (Hamon et al 1987). Pea leaf weevil are strong fliers as they can fly long distances (Antonelli 1970, Beniwal et al.1993, Bogdan 2018). Once pea leaf weevil has located their host, redistribution occurs by walking (Fisher and O’Keeffe 1979c, Hamon et al. 1987, Nielsen and Jensen 1993).

Host Plants

During the spring migration, pea leaf weevil is oligophagous and will feed on various plants in the Fabaceae family, the primary hosts for adult pea leaf weevil (Jackson 1920, Grieb and F. K. 1976, Fisher and O’Keeffe 1979, Hamon et al. 1987, Landona et al.1995). For pea leaf weevil larvae, field pea (*Pisum sativum* L.) and faba bean (*Vicia faba* L.) are regarded as the primary hosts for that life stage since these crops allow all life stages (Baliddawa 1984, Schotzko and O’Keeffe 1988, Landona et al. 1995, Bogdan 2018, Cárcamo et al. 2018). Pea leaf weevil are oligophagous during the non-reproductive phase and feed on members of the Fabaceae family before and during overwintering (Jackson 1920, Greib and Klingauf 1976, Fisher and O’Keeffe 1979c, Hamon et al. 1987, Landona et al. 1995). Legumes such as alfalfa (*Medicago sativa* L.), clover (*Trifolium* species), sweet clover (*Trifolium pratense* L.), vetch (*Vicia sativa* L. (Fabales: Fabaceae)), lupin (*Lupinus* species L. (Fabales: Fabaceae)), black medic (*Medicago lupulina* L. (Fabales: Fabaceae)), dry bean (*Phaseolous vulgaris* L), chickpea (*Cicer arietinum* L) and soybean (*Glycine max* (L.) Merr), Siberian pea shrub (*Caragana arborescens* Lam., Fables: Fabaceae) and black locust (*Robinia pseudoacacia* L., Fabales: Fabaceae) are also preferred by adult pea leaf weevil as their secondary hosts (Fisher and O’Keeffe 1979a, Fisher and O’Keeffe 1979b, Bogdan 2018). Secondary host selection occurs in late summer and fall and/or, during overwintering period when there is absence of annual legumes (Jackson 1920, Prescott and Reeher 1961). If oviposited on secondary host plants pea leaf weevil larvae do not develop, and pea leaf weevil adults, maximize their fertility only on pea and faba beans (i.e., primary host plants) (George 1962, Fisher and O’Keeffe 1979a, Schotzko and O’Keeffe 1986, Vankosky et al. 2011a).

Adult pea leaf weevil may feed on plants of different families when primary and secondary hosts are limited abundance (Prescott and Reeher 1961). In Europe, adult pea leaf weevils are considered pest of lupin, field vetch (Cantot and Papineau 1983, Ferguson 1994, Nikolova 2016), faba bean, pea, alfalfa, black medic, all species of clover, tare and wild vetch (Jackson 1920). While larvae are not found on the roots of lupin, peas and vetch are major host in the Pacific Northwest (Ferguson 1994). However, adults may feed on alfalfa and red clovers (*Trifolium pratense* L.) heavily (Prescott and Reeher 1961). Additionally, adult pea leaf weevil can be a major defoliator of buds and flowers of bird’s foot trefoil (*Lotus corniculatus*) (Prescott and Reeher 1961).

In late summer, Markkula and Köppä (1960) reported pea leaf weevil presence at a higher population density on white clover, (*Trifolium repens* L. (Fabales: Fabaceae)) among other *Sitona* species. In England, during the overwintering period, pea leaf weevil can consume as much as 30 % of the photosynthetic area of white clover, causing significant damage to the plant (Murray and Clements 1995). During the harvest season or when crops are drying, pea leaf weevil may feed on certain non-leguminous plants (e.g., Plants from the family Rosaceae, like raspberry, apple, blackberry and rose) (Prescott and Reeher 1961). Sometimes, pea leaf weevil feed on weed species like prostate knotweed (*Polygonum aviculare* L., (Polygonales: Polygonaceae)) if in the absence of legumes (Prescott and Reeher 1961, Grieb and Klingauf 1977, Fisher and O’Keeffe 1979a). Thus, it is theorized that pea leaf weevil exhibits “limited polyphagous behavior” (Grieb and Klingauf 1977).

Pea Leaf Weevil Damage

Adult pea leaf weevil feeds upon the leaf margins and the growing point of legume seedling producing a characteristic distinct notch (Otani 2013). Adult pea leaf weevil can consume on around 40 mm^2 of pea leaves in a single day (Biniaś et al. 2017). When the field peas and faba beans are from 7.3 cm to 15.2 cm high, adult pea leaf weevils make significant damage on these plants (Jackson 1920). When feeding on leaves, adult individuals feed upon the leaf margins making a half-moon or subcircular or U-shaped scalloped notch in the leaf edge/leaf margin (Jackson 1920, Hoebeke and Wheeler 1985, Otani 2013, Wanner 2016). Host plants can compensate and recover from low to moderate levels of damage by feeding adult pea leaf weevils (George 1962, Lee and Upton 1992, Lohaus and Vidal 2010, Vankosky et al. 2011a, b, Cárcamo et al. 2012). Therefore, defoliation is not considered a source of significant economic loss (Williams et al. 1995, Wanner 2016). However, if there is substantial damage to the terminal leaf of the young seedling then, the loss is unrecoverable. Under severe infestations when the population of pea leaf weevil is high, adult feeding can completely destroy the plant and the associated stand count density in the field if damage occurs at the early vegetative growth stage (Jackson 1920). Depending on the timing of weevil establishment and their density, the level of damage to their primary host during adult feeding varies in the spring (Williams et al. 1995). When an adult pea leaf weevil feeds on leaves of leguminous plants, the photosynthetic capacity is limited which will ultimately compromise ability of respective plant to produce reproductive organs or support root nodules (Havlickova 1982, Williams et al. 1995). With the increase in defoliation rate, there will be increase in yield loss too, since the host plant’s reproductive organ will be poor in sequestration of nutrients thus affecting yield (Hodgson and Blackman 1957).

Adult pea leaf weevil feed on legume foliage, however feeding varies at the larval life stage, where preferred host of post-diapause pea leaf weevil are field pea and faba bean (Landona et al. 1995). For pea leaf weevil reproductive potential and larval fitness, the larval stage prefers field pea and faba bean as hosts (Cárcamo and Vankosky 2011). Pea leaf weevil oogenesis is believed to start only if there is post-diapause feeding on peas and faba beans (Hans 1959, Fisher and O'Keeffe 1979a, Schotzko and O'Keeffe 1986, Hamon et al. 1987, Landon et al. 1995). Larval pea leaf weevils only develop in the root nodules of faba beans and field peas, thus rending these crops necessary for the completion of the pea leaf weevil life cycle (Cárcamo et al. 2018). The damage on the main root is more pronounced than on the lateral roots but under severe infestation when larval density is high, it can destroy the majority of nodules (Jackson 1920, Cantot 1986, Verkleij et al. 1992). Damage caused by the larva on the root nodule is considered to be more economically damaging than feeding adults as larval damage results in reduced photosynthetic capacity of the defoliated leaves impacting root nodulation, yellowing of leaves, nitrogen deficiency and reproductive organ development (El- Dessouki 1971, Havlicova 1982, Williams et al. 1995). The larval damage has significant effect on plants during early flowering stage but as the plant matures the impact of larval feeding declines (Jackson 1920, Cárcamo et al. 2018). Similarly, reduction in yield loss in peas are considered to be generally from larval feeding rather than adult feeding or adult defoliation of pea leaf weevil in peas (Hunter 2001, Corre-Hellou and Crozat 2005).

The damage caused by larval feeding is predominantly caused by reduced nitrogen fixation, resulting in nitrogen deficient plants. Due to pea leaf weevil larval infestation, field bean yield reduction can range between 70 to 90 % (Oschman 1984). This reduction in yield makes pea leaf weevil larvae an important pest and therefore requires control tactics to manage their populations (Seidenglanz et al. 2010, Cácamo et al. 2012).

Host Plant Preference and Selection Factors

Adult pea leaf weevil feeds on foliage of several leguminous crops and it feeds on non-legumes to a lesser extent (Jackson 1920, Greib and Klingauf 1977). Depending on the timing of weevil establishment and their density, the level of damage to their primary host during adult feeding varies in the spring (Williams et al. 1995). For pea leaf weevil reproductive potential and larval fitness, the larval stage prefers field pea and faba bean as hosts (Cárcamo and Vankosky 2011). Reproduction of pea leaf weevil is also impacted by host plant preference. Host plant preference, for pea leaf weevil reproduction may be due, in part, to the symbiotic relationship between these host plant species and nitrogen- fixing bacteria *R. leguminosarum* biovar. *viciae* (Spaink 1994 and Mutch and Young 2004). This bacteria species inhabits the root nodules of leguminous plants (e.g., field peas) and provide nutrients to the leghemoglobin within the root nodules (Cárcamo et al. 2015). Leghemoglobin is associated with tendency of every *Sitona* species to feed on nitrogen fixing legume (Danthnarayana 1967).

When adult pea leaf weevils are provided with a choice of cut leaf tissue, they prefer pea over faba bean (Jaworska 1998). However, during oviposition period in May, pea leaf weevils are more attracted to faba bean (Jaworska 1992). If pea and faba bean are planted next to each other, then pea leaf weevil moves to the faba bean during egg laying (Jaworska 1992). Pea leaf weevil nutrient requirements changes as they develop. Thus, to fulfill the changing nutritional requirement, pea leaf weevil can switch between hosts at different stage of its life cycle (Jaworska M.1992). Pea leaf weevil preference also varies with in pea and seems to favor certain pea cultivars (Havlickova 1980, Cantot 1989, Kordan B and Sledz´ 1994, Wojciechowicz-Zytko and Młynarczyk 2002). Many extrinsic resistance factors like epicuticular waxes present on leaves of peas may influence the feeding rate of pea leaf weevil (White and Eigenbrode 2000, Rutledge et al. 2003, Chang et al. 2004). Pea leaf weevil favor thinner epicuticular wax layers coating leaves and stipules over hosts producing thicker epicuticular wax layers (White and Eigenbrode 2000). Due to genotypic variability, field pea has different quantities of wax layer variation, and the modification of these genotypes may have potential to produce resistant varieties against pea leaf weevil (White and Eigenbrode 2000). Adult pea leaf weevils prefer low alkaloid plants while they rarely fed on bitter plants (Cantot and Papineau 1983).

The life span and survival rate of pea leaf weevil also varies by faba bean cultivar (Wojciechowicz-Zytko and Młynarczyk 2002). Carbohydrates, nitrogen, protein content varies among cultivars and plant health, influencing host plant quality for this pest species (Havlickova 1980). Faba bean at its vegetative and late reproductive life stages are considered better hosts than pea, because they offer improved opportunities for egg laying and adult survival (Jaworska 1998). Faba bean host plant preference due, impart, to their prolonged development, thus providing habitat for pea leaf weevil larvae later in the season (Bogdan 2018). Adult pea leaf weevil feeding on faba beans live longer compared to individuals feeding on peas (Bogdan 2018). Therefore, pea leaf weevil host plant may influence their longevity (Jaworska 1998). However, at low densities, Schotzko and O’Keeffe (1988) found that pea leaf weevil longevity was higher on peas than other legumes, contradicting the findings of Bogdan (2018). Additional factors that influence female pea leaf weevil longevity, are populational density and number of eggs that female oviposits over their lifetime (Schotzko and O’Keeffe 1988).

Pea leaf weevil population densities and fecundity may also be closely linked to nitrogen fixation of their host plant. Nitrogen fixation per plant in pea hits maximal amount at or before flowering stage (i.e., early reproductive life stage) and decreases during fruit growth (i.e., late reproductive life stage) (Pate 1958, LaRue and Kurtz 1973, Bethlenfalvay et al. 1978). Faba bean, however, sustains steady nitrogen fixation activity until the time of plant maturity and total bean-plant nitrogen amount also increases into seed maturity (Sprent and Bradford 1977, Dean and Clarke 1980). As the larva of pea leaf weevil feed on the rhizobium bacteria that inhabit the root nodules, faba bean will be able to compensate for pea leaf weevil feeding damage, due to its longer period nitrogen fixation which continues through maturity (Sprent and Bradford 1977, Buttery and Gibson 1990).

The number of pea leaf weevil larvae that a host plant can support is known as carrying capacity (Nielsen 1990). Carrying capacity for peas is low compared to that of capacity of faba bean (Bogdan 2018). Under low pea leaf weevil density of 0.25 weevils per pea plant, larval feeding damage to root nodules was similar to nodule damage under high weevil density of one weevil per plant (Bogdan 2018). This suggests that the economic damage is the similar, regardless of the number of adults or the eggs laid (Bogdan 2018). Therefore, faba beans can support larger pea leaf weevil populations compared to field pea (Bogdan 2018).

In the absence of pea or faba bean, pea leaf weevil larvae do not complete their lifecycle on other hosts (Fisher and O’Keeffe 1979a, Hoebeke and Wheeler 1985, Ferguson 1994, Murray and Clements 1995). However, chickpeas have emerged as an alternate host as some signs of larval feeding were recorded on root nodules (William et al. 1991). When pea and chickpea are planted side by side and the peas are harvested in the immature stage, weevils migrated to the intercropped chickpea where they fed and lay eggs (William et al. 1991). Another legume crop, lentil (*Lens culinaris* Medik, (Fabales: Fabaceae)) is neither preferred for feeding or oviposition by adult pea leaf weevils (Schotzko and O'Keeffe 1988, Bogdan 2018). In choice tests, adult pea leaf weevil fed on lentils if they were the only available as a food source (Schotzko and O'Keeffe 1988). Similarly, adult pea leaf weevil never preferred common bean (*Phaseolus vulgaris* L. (Fabales: Fabaceae)) for ovipositing nor larvae feeding in green house trials (El-Dessouki 1971). However, damage to common bean by pea leaf weevil was observed in the field (Andersen 1934). Alfalfa, a potential alternative host for pea leaf weevil is longer season crop than field pea. Schotzko and O'Keeffe (1988) reported that alfalfa supported larger populations of pea leaf weevils for a longer time-period than pea. Regardless, further investigation is required to identify potential alternate primary and secondary hosts of pea leaf weevil (Vankosky et al. 2009).

Plant stage also impacts pea leaf weevil larval population density. Larval populational density is lower when adult pea leaf weevil lay eggs on the plants after the 5th node stage compared to adults laying eggs on plants the past at the 2nd node stage (Carcamo et al. 2010). Pea leaf weevil larval populations are influenced by root nodule availability (El Dessouki and Stein 1970, Quinn and Hover 1986, Wolfson 1987) and the carrying capacity of the root nodules (Nielsen 1990). Nodules are an important food source but are limited for pea leaf weevils (Greenwood and Bathurst 1978, Heichel and Vance 1983, Sutton 1983, Quinn and Hover 1986). Thus, root nodule availability is a factor for pea leaf weevil larval development and density (El-Dessouki and Stein 1970, Quinn and Hover 1986, Wolfson 1987). Furthermore, soil conditions such as nitrogen and moisture also influence the larval feeding and amount of nodulation of a plant (Sprent and Bradford 1977, McEwen et al. 1981, Sutton 1983, Wolfson 1987). Under high soil nitrogen levels, pea cultivars produce fewer nodules compared to plants grown under nitrogen deficient conditions (Vankosky et al. 2011a) and may delay peak nodulation in some cases (Gibson and Harper 1985). The larval populations of pea leaf weevil vary by pea cultivar and the quantity of nodules on their host plant (Nouri Ghanbalani 1978).

Origin, Distribution and Production of Affected Host Plants

Field Pea

Field peas is an annual, cool season, herbaceous grain legume and belongs to family Leguminosae (subfamily: Faboideae, tribe: Fabeae, order Fabales) (Smýkal et al. 2012). It is also known as common pea, dry pea, yellow pea or garden pea (Olle and Sooväli 2020). Pea is one of the world's oldest domesticated, and economically important legume crop (Amborse 1995, Clark 2019, Haverson et al. 2021).

Pea was first cultivated over 9,000 years ago, yet there is no record of their exact origin of domestication (Smýkal et al. 2012). Wild representatives of *P. sativum* extends from Iran and Turkmenistan through interior Asia, northern Africa and southern Europe (Makasheva 1979, Maxted and Amborse 2000, Maxted et al. 2010). However, pea plants are believed to be from the Fertile Crescent of southwest Asia due to carbonized remains of peas in archaeological sites of the region (Haverson et al. 2021). An opposing theory is that central Asia, eastern Ethiopia, and Mediterranean countries are believed to be the center of origin of pea based on genetic diversity (Smýkal et al. 2012).

Based on growth rate and flowering behavior, peas are classified into two agronomic classes 1.) winter pea and 2. spring pea (Santra and Saha 2021). In the United States, depending on latitude and altitude, winter pea is sown in early fall, whereas spring pea is sown in mid-March to early May (Santra and Saha 2021).

Similarly, based on use, pea is divided into several classes, garden pea, field pea, green manure and forage types (Maxted et al. 2001, Oelke et al. 1991) The fresh pea is harvested as immature pods or seed and eaten as vegetable (Karkanis et al. 2016). Whereas dried or field peas are mature and consumed by humans and livestock as whole, split, or ground for flour (Oelke et al. 1991). Generally, there are two types of field pea based on leaf type which signifies the pea cultivar’s ability to tolerate harsh conditions (Heath and Hebllethwaite 1985, Endres et al. 2016) that is normal/true leaves and semi-leafless.

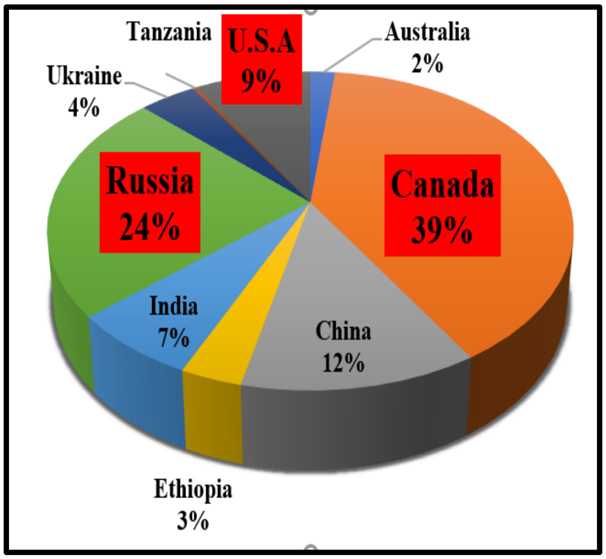
Cousin (1997) and Krall et al. (2006) explained the characteristics of normal and semi leaves. Normal/true leaves have one to three pairs of leaflets, terminal branched tendrils, and stipules with the vine length of 1.22 to 1.83 meters in length. They have higher biomass and yields. Normal leaved field peas are best for forage use for cattle and hogs. In semi-leafless field peas, modified leaflets are reduced to tendrils and normal stipules between 0.61 to 1.22 meters in length. Semi-leafless field peas, have less leaf area, but they are more resistant to lodging. Peas have clam leaf which is recently emerged folded leaf on top part.

Total production area of pea in the world is 9.2 million hectares (ha) with 17.7 million tons of peas produced annually where contribution of the country in the pea production are; Canada (40%), Russian Federation (24%), China (12%), India (7%), Ukraine (4%), the United States (8%), Australia (2%) (FAO STAT 2020) (Figure 1.1). Canada is the highest producer of peas with the acreage of 1,431,200 ha (FAO STAT 2020).

American production of field pea in 2020 was 941,571 metric tons produced on 384,047 hectares (USDA 2020). In 2021, American field pea production was 434,309 metric tons produced on 337,508 hectares (USDA 2021). In short land in dry edible pea production decreased from 384,047 hectares in 2020 to 337,508 hectares in 2021. The top states in the country for field pea production are North Dakota, Montana, Idaho, Washington and Nebraska (Table 1.4) (USDA 2021).

Montanan field pea production is a major component of agricultural production in the state. In 2020, the total Montanan production of edible pea production decreased from 502,689 (2020) metric tons to 168,409 (2021) metric tons (USDA NASS, 2021) (Table 1.4). Acreage of pea production land decreased from 193,440 (2020) hectares to 181,299 (2021) hectares (USDA NASS, 2021) (Table 1.3).

Figure.1.1. Percentage of countries in contributing pea production (tons) among countries with high pea production.



Chickpea

Chickpea is a cool-season and, drought tolerant, annual pulse crop (Rasool et al 2015) grown in arid and semi-arid regions (Maphosa 2020). Chickpea is also referred as garbanzo beans or bengal bean or channa and is a member of the Fabaceae family (Jukanti et al. 2012, Rasool et al. 2015). It is ranked as the third most important pulse crop for food after peas and faba bean (FAO 2008). Chickpea is one of the eight founding crops of agriculture (Zohary and Hopf 2000, Abbo et al. 2003, Rasool et al.2015). The center of origin of chickpea is believed to be southeastern Turkey, with evidence of chickpea consumption from 7,500 years ago (Harlan 1971, Oplinger et al. 1990, Singh and Ocampo 1997, Chen et al. 2011).

Chickpea is regarded as the main source for protein in arid and semi- arid areas (Chen et al. 2011). Chickpea generally contains 20~22 % protein and 60 % carbohydrates, which can provide a good source of protein for humans and livestock (Roy et al. 2001, Gossen et al. 2016) and many minerals and vitamins (Jukanti et al. 2012). There are two main types of chickpea in the market, Kabuli (Mediterranean and Middle Eastern) and Desi types (Indian Origin). These chickpea varieties differ in seed coat morphology, floral coloration, tolerance to abiotic stressors, and seed characteristics (Moreno and Cubero 1978, Purushothaman 2014, Maphosa 2020).

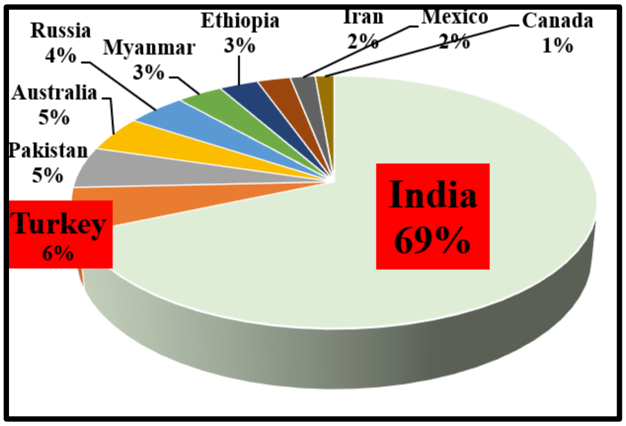
Kabuli chickpeas are characterized by their 0.61 - 0.91-meter height, larger pods and leaves, as well as round, cream-colored seeds averaging 1000 seeds per 0.45 kilograms (van der Masen 1972, Moreno and Cubero 1978, Maphosa 2020). Kabuli is primarily used as an ingredient in hummus or as a whole seed in Central Asia, Mediterranean Basin, the Near East, and America (Margheim et al. 2004, Leport et al. 2006). The desi type is comparatively shorter with smaller leaves and smaller dark brown seeds that average about 2300 seeds per 0.45

kilograms (Maphosa 2020). Desi types are mainly grown in South Asia and are dehulled and split before cooking (Leport et al. 2006).

Both chickpea types provide agronomic benefit to soil as they help maintaining soil fertility through nitrogen fixation at rates of up to 140 kilogram per hector per year (kg/ha/year) (Flowers et al. 2010). Chickpea is grown in over 56 countries with a total global harvested area of 17.2 million tons hectares (Mha) producing 17.2 million tons (FAO 2020). India, the global leader of chickpea production, contributes 69% of global production and is followed by Pakistan which contributes 5% (FAO 2021) (Figure 1.2).

Comparatively, in 2019 the United States ranked seventh with 163,490 hectares of chickpea in production (FAOSTAT, 2019). Since 2001, chickpea production has increased rapidly in the United States as chickpea acreage has increased from 5400 hectares in 2001 to 161,000 hectares in 2018. In 2021, Montana chickpea production was 70,8120 hectares, with a total production of 56,390 metric tons (USDA NASS, 2021).

Figure.1.2. Percentage of countries in contributing chickpea production (tons) among countries with high chickpea production.



Faba bean

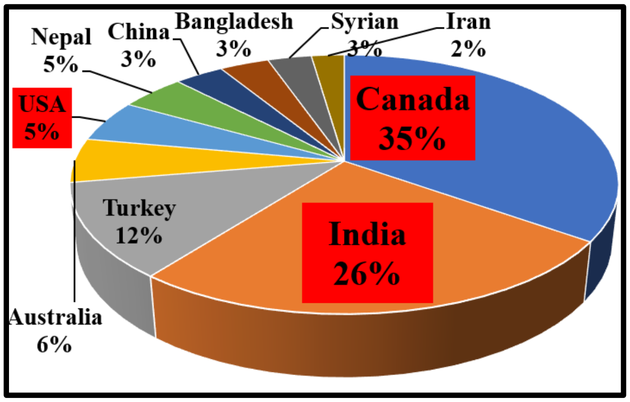
Faba bean is an annual, cool season pulse crop and is member of the Vicia genus in the Fabaceae family (Harlan 1969, Hanelt and Mettin 1989, Juncus 1998, Etemadi et al. 2015, Xiao et al. 2021, Abou-Khater 2022). This crop is also known as faba bean, horse bean and broad bean (Mínguez and Rubiales 2021). Native to the Mediterranean region, faba bean is the oldest cultivated legume crop in the world and was domesticated 10,000 years ago BCE in the Near East (Cuberto 1974, Juncus 1998, Etemadi et al. 2015, Caracuta et al. 2016). Faba bean is considered the fourth most important feed grain legume following pea, lentil and soyabean (Mihailovic et al. 2005, Dhull et al. 2021). Production of faba bean has increased by 2 percent every year over last 3 decades, with the total production of 5.4 million tons in 2019 (Dhull et al. 2021, Abou-Khater 2022).

Major faba bean producing countries include Afghanistan, China, India, Ethiopia, Mediterranean countries, Northern Africa and Northern Europe (Rahate et al. 2020, FAO 2021) (Figure 1.3). 90 % of total production comes from these Asian, European and African countries, where Asia leads by 33% (FAO 2020). North American production of faba bean is higher in Canada than Mexico as faba bean grows well in cool season crop (Etemadi et al. 2015).

Whereas in the United States, faba bean is grown as a seed crop in California, and in other regions of the United States, mostly they are grown as cover crops and/or used as green manure (Etemadi et al. 2015). Faba bean is regarded as the best crop for green manure and the most efficient crop for nitrogen fixation through symbiosis with *Rhizobium* spp (130 to 160 kg N/ha) (Hoffmann et al. 2007, Horst et al. 2007).

Faba bean is a multiuse crop cultivated for human consumption in Africa and Asia, with Europe additionally using it as animal feed or silage (Zhou et al. 2018). If used for human consumption, faba bean is harvested either fresh (as sprouts), cooked or dried (Dhull 2021).

Figure.1.3. Percentage of countries in contributing faba bean production (tons) among countries with high faba bean production.



Lentil

Lentil is an annual cool season legume, grown in subtropical and high-altitude tropical regions of the world (Muehlbauer et al. 1995). It is considered the oldest domesticated pulse crop, as it was amongst human archeological sites dating back to 13,000 years Before Common Era (BCE) (Bahl et al. 1993, Sandhu and Singh 2007). Lentil is originated in eastern and central Asia, with the primary center of diversity found in Middle East (Zohary 1972, Cubero 1981, Sarker and Erskine 2006).

There are two types of lentils that are defined by seed size. small to medium seeded and large seeded (Barulina 1930, Sandhu and Singh 2007). Lentil is grown for mature dry seed and eaten as daal where grain is fried and seasoned as well as being boiled (Yadav et al. 2007).

In lentil producing regions there is high demand of lentil for its high protein content and short cook time (Muehlbauer et al. 1985, Iqbal et al. 2006). Lentil is grown in India, Syria, North

Africa and Europe (Yadav et al. 2007). Lentil translates to “massur” in India, “adas” in Arabic countries, and “messer” in Ethiopia (Sandhu and Singh 2007). In 2020, global production of lentil was 6.5 million metric tons in which, Canada produced the most (35%) followed by India 26% (FAOSTAT 2021) (Figure 1.4).

In the United States, lentil production zones in the U.S. include are the Palouse region of eastern Washington, northern Idaho, northwestern and northeastern Montana, and western North Dakota (Table 1.3, 1.4). In the United States, lentil production increased from 240,000 tons in 2011 to 376,000 tons in 2020 (USDA 2021).

In 2020, lentils were grown primarily in Idaho, Montana, North Dakota, and Washington. Of the states, Montana was the leading produced the most, contributing 72 % of the total production (USDA 2021) (Table 1.4). In 2021, the acreage of lentils in Montana was 214,483 producing 102,316 metric tons (USDA NASS, 2021).

Figure.1.4. Percentage of countries in contributing lentil production (tons) among countries with high lentil production.

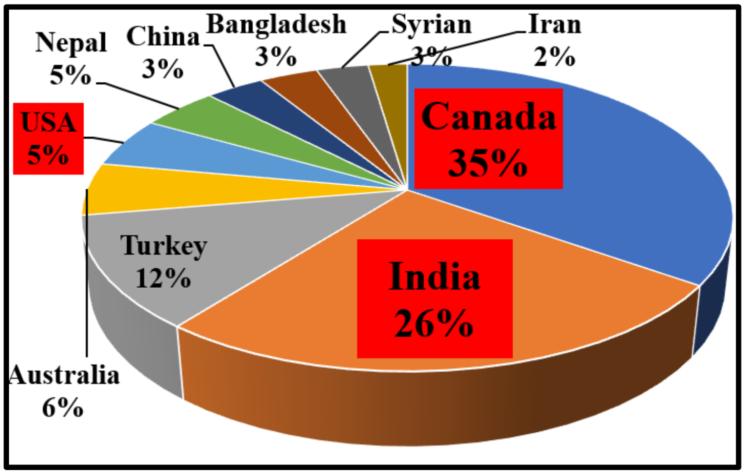


Table 1.2. Total acreage (hectare), production (metric ton), value per ton and total value of (dollar) field pea, lentil, chickpea in different states and provinces of U.S and Canada.

Pulse crops	North America States/ Province	Acreage (hectare)	Production (metric ton)	Value per ton (dollar)	Total value (1000 USD dollar)
Field pea	Montana	230676	168411	331	55692
	North Dakota	103198	181975	364	66267
	Alberta	667800	1799100	352	633283
	Saskatchewan	380251	2477700	361	894450
Lentil	Montana	214489	102317	620	63441
	North Dakota	48563	48059	703	33772
	Alberta	69243	370500	643	238232
	Saskatchewan	623513	2497200	1055	2634546
Chickpea	Montana	70822	56391	764	43068
	North Dakota	6597	10313	872	8993
	Alberta	17240	12973	-	-
	Saskatchewan	56980	56155	609	34198

Table 1.3. Total acreage (in 1000 hectare) of dry pea, lentil, chickpea in different states of U.S in 2019, 2020 and 2021.

Crops	States	Acreage in hectare in different years		
		2019	2020	2021
Field pea	Nebraska	13	15	12
Field pea	Idaho	11	14	12
Field pea	Montana	215	200	231
Field pea	North Dakota	172	132	103
Field pea	Washington	29	32	28
Field pea	South Dakota	7	12	11
Field pea (Total)	USA	446	404	396
Lentil	Idaho	14	11	9
Lentil	Montana	120	150	215
Lentil	North Dakota	39	33	49
Lentil	Washington	25	19	15
Lentil (Total)	USA	197	212	287
Chickpea	California	5	4	1
Chickpea	Idaho	36	24	32
Chickpea	Montana	81	43	71
Chickpea	North Dakota	17	6	7
Chickpea	Washington	45	27	39
Chickpea (Total)	USA	184	103	149

Table 1.4. Total yield (in 1000 metric ton) of field pea, lentil, chickpea in different states of U.S in 2019, 2020 and 2021.

Crops	States	Yield of pulse crops (1000 MT)		
		2019	2020	2021
Field pea	Idaho	26	44	15
Field pea	Montana	516	499	168
Field pea	Nebraska	33	18	18
Field pea	North Dakota	465	390	182
Field pea	South Dakota	17	21	7
Field pea	Washington	72	119	44
Field pea (Total)	USA	1128	1090	434
Lentil	Idaho	18	17	4
Lentil	Montana	170	271	10
Lentil	North Dakota	47	57	48
Lentil	Washington	34	30	14
Lentil (Total)	USA	270	376	169
Chickpea	California	18	12	4
Chickpea	Idaho	63	44	36
Chickpea	Montana	124	78	56
Chickpea	North Dakota	19	14	10
Chickpea	Washington	93	60	39
Chickpea (Total)	USA	318	208	145

Biology of Pea Leaf Weevil

Adult pea leaf weevil feeds on most leguminous plants, however, reproductive phase can only be completed on either field pea or faba bean (Baliddawa 1984, Schotzko and O’Keeffe 1988, Landona et al. 1995, Bogdan 2018, Cárcamo et al. 2018). Larvae of pea leaf weevil primarily feed on pea and faba bean root nodules (George 1962, Fisher and O’Keeffe 1979a, Schotzko and O’Keeffe 1986, Vankosky et al. 2011a.). Pea leaf weevil is univoltine in North America and England (Jackson 1920, Hoebeke and Wheeler 1985) but in some geographical regions they can be also bivoltine (Hans 1959, Hoebeke and Wheeler 1985). Pea leaf weevil undergoes complete metamorphosis with stages passing through egg, larva, pupae and adult

(Jackson 1919). In the western region of North America, oviposition occurs between February and May and in Idaho, USA it occurs in May (Prescot and Reheer 1961, Fisher 1997). Humidity and temperature influences hatching of egg of pea leaf weevil (Vankosky 2010). Twenty to 21 days after oviposition, eggs hatch (Jackson 1920). Pea leaf weevil egg incubation period may be as short as 18 days, depending on abiotic factors like temperature (Prescott and Reeher 1961, Hoebeke and Wheeler 1985).

Eggs

Eggs are sub -spherical in shape measuring 0.36 mm in diameter (Prescott and Reehher 1961, Jia et al. 2019). Pea leaf weevil eggs are glossy (Prescott and Reehher 1961) and their color changes from white to black within 48 hours (Wanner 2016). Females oviposit eggs singly on the soil surface and in cracks near the seedlings of plants (Schotzko and O’Keefe 1988). After two to three weeks, eggs hatch and newly hatched larvae burrow into the soil near the host plant (Prochaska et al. 2018). Jackson et.al (1920), noted that females lay on average 354 to 1655 eggs on the soil over their life span (Wanner 2016). If the optimal ovipositing temperature (12 -22 °C) is met the ovipositing period that starts after 7 days, extends to 3 months which will make availability of pea leaf weevil of all stages during the crop season (Cárcamo et al. 2010, Wanner 2016).

Larvae

First instar pea leaf weevil larvae burrow into soil and feed on Rhizobium bacteria in the root nodules, where they make a hole in the nodule and inhabit the nodule (Johnson and O’Keeffe 1981). Larvae are 0.5 mm in length when they hatch, but once they are grown, they can grow to 5.5 mm. Larvae are white in color, have a fleshy, cylindrical body covered with long setae protruding vertically from each segment, and curl to a “c” shape when exposed (Prescott 1961, Wanner 2016). It takes four to eight weeks, depending on soil temperature and other abiotic factors to pass through the five larval instar stages and pupate (Jackson 1920, Hoebeke and Wheeler 1985, Landona et al. 1985, Prochaska et al. 2018). Pea leaf weevil larvae feed predominantly on *Rhizobium leguminosarum* Frank (Rhizobiales: Rhizobiaceae) in root nodules (Johnson and O’Keeffe 1981).

Pupae

Pupae are found in oval shaped earthen pupation cells within the soil and are exarate in form (Jackson 1920). They are white in color with hairs protruding from head and thorax that resemble like a small horn (Prescott 1961). Pupae require 14 to 19 days to complete their development, a period occurring between early July to early August (Fisher 1977). However, in Europe this period is lengthened to 16 to 19 days. Whereas in North America, this period takes approximately 15-days (Prescott and Reeher 1961, Hoebeke and Wheeler 1985).

Adult

In late July to August, a new generation of adult pea leaf weevils emerge (Prochaska et al. 2018). The adult remains in the soil until their exoskeleton is fully sclerotized (Jackson 1920). Adult pea leaf weevils are slender and grayish color ranging 3.6 to 5.4 mm in length, and have a broad shaped snout (Jackson 1920, Wanner 2016). Adult pea leaf weevils are distinguished by three light longitudinal stripes in their pronotum that extends to the abdomen on the dorsal side of their greyish body (Jackson 1920). These stripes are due to ochreous scales that generate the grey and black color and fade away as the adult ages (Jackson 1920). Male and female pea leaf weevil can be differentiated from each other based on the shape and size of the pygidium, the last segment of the abdomen (Jackson 1920).

Adult pea leaf weevils can survive up to 11- months and depending on variable physiological state, shows different period of activity throughout the year (Schotzko and O'Keeffe 1988). The overwintering generation upon emergence in August, are sexually immature and search for sites to feed (e.g., perennial legumes) before overwintering (Jackson 1920, Cárcamo and Vankosky 2011). Pea leaf weevil overwinter in field margins, shelter belts, or in surrounding perennial legumes (e.g., clover or vetch) (Jackson 1920, Schotzko and O'Keeffee 1988, Murray 1992). Overwintering adults are still reproductively immature and migrate in the early spring when average daily temperature starts to increase and reaches to 12.5 ºC to fields of field pea and faba beans (Hans 1959, Hamon et al. 1987). In these field, they feed, becomes reproductively mature, mate and lay eggs (Evenden 2018).

Semiochemicals and Their Use in Management of Pea leaf weevil

Integrated pest management (IPM) is a popular practice in agricultural systems. Integrated pest management can be an effective management practice focusing on the biology of the target pest, while minimizing the impact on non-target species and the environment (St. Onge 2017). IPM focuses on the diversification of control tactics, including the application of chemical control tactics. The three main component of IPM are cultural, biological and chemical control. Programs utilizing IPM strategies focus on the utilization of insect pest biology knowledge, as well as knowledge pertaining to their host plants and related natural enemies to reduce non-target effects of management while maintaining pest activity below economically damaging levels (Kogan 1998, Witzgall et al. 2010, Barzman et al. 2015). There are many tools, strategies, and tactics utilized in IPM. Semiochemical monitoring trap is an efficient tool used in IPM programs to monitor specific insect pest populations (Bjostad et al. 1993, Baker 2008, Witzgall et al. 2010).

Semiochemicals are organic compounds that act as signals that enable specific communication within the same (intra) or amongst different species (inter) (Landolt et al. 1991). Semiochemicals are also known as message bearing chemicals which carry important biological signals for organisms in the vicinity of the individuals producing them, and can modify their behavior, thus are important for altering the behavior of insects (Law and Regnier 1971). Pheromones and allomones are the most important semiochemicals for IPM. Pheromones are released by individuals of one species to alter or modify the behavior of other individuals of the same species (Shorey 1977, Mori and Evenden 2014, Pickett et al. 2014). Whereas allelochemicals are produced by one species to modify behavior, physiological condition, or ecological welfare of members of a different species (Scriber 1984, Sharma et al. 2019). Sex and aggregation pheromones, alarm pheromones are some examples of semiochemicals. When used in IPM, humans are able to modify or control insect activity and monitor populations by manipulating semiochemicals in a selected location (Law and Regnier 1971, Bjostad et al. 1993, Baker 2008, Vankosky et al. 2009, Witzgall et al. 2010).

Semiochemicals play a crucial role in biological management of arthropods and can be used in monitoring, mass trapping, mating disruption, attract and kill, push and pull of pest species (Bjostad et al. 1993, Baker 2008, Witzgall et al. 2010, Bakthavatsalam 2016). Semiochemical monitoring traps are baited with pheromones of the target insect species to lure and trap them (Landolt 1997, Baker 2008, Witzgall et al. 2010). In moths, sex pheromones act as a signal to attract potential mates over long distances (Agelopoulos et al. 1999, Tewari 2014). Aggregation pheromones are intraspecific signals that signal location of conspecifics to both male and female usually for group formation, such as mating and overwintering aggregations (Landolt 1997, Agelopoulos et al. 1999, Tinzaara et al. 2002). Aggregation pheromones are mostly used in trap lures for use in IPM of beetles (Coleoptera: Curculionidae). When there is low density of the target species, semiochemical based management tools are the most effective as insect behavior is heavily tied to olfaction (El-Sayed et al. 2006, El-Sayed et al. 2009, Witzgall et al. 2010).

One of the initial studies conducted by Blight and Wadhams (1987), found that bait consisting of male pea leaf weevil feeding on faba bean attracted both male and female pea leaf weevil in a 1:1 ratio, while traps baited with only faba bean or faba bean with female pea leaf weevil, attracted low number of pea leaf weevil. These findings suggest that male pea leaf weevils can communicate intraspecifically via semiochemicals, mainly aggregation pheromones attractive to both male and female individuals. Blight et al. (1984) after conducting analysis by gas chromatography-mass spectrometry (GC-MS) of volatile emissions from male pea leaf weevil feeding on faba beans, identified a compound 4-methyl-3,5-heptanedione. According to Blight et al. (1991) only reproductively active male pea leaf weevils produce the aggregate pheromones (Blight et al 1991). 4-methyl-3,5-heptanedione is an aggregation pheromone which is produced by male pea leaf weevil when they feed on faba bean (Blight et al. 1984, Blight and Wadhams 1987).

Furthermore, there is no clear indication of need of faba bean or pea for pea leaf weevil to produce this compound as volatiles emissions of unfed male pea leaf weevil was not recorded

(Bright et al. 1984, Blight et al. 1991). Electrophysiological analysis showed that both male and female antennae as well as newly emerged, reproductively inactive individuals were sensitive to 4-methyl-3,5-heptanedione (Blight et al. 1991). Therefore, 4-methyl-3,5-heptanedione attract all pea leaf weevil adult individuals (Blight et al. 1984).

Host Plant Volatiles

Host plant volatiles are semiochemical signals which are used by phytophagous insects to locate the host (Bojstad et al.1993, Landolt and Phillips 1997, Szendrei and Rodriguez-Saona 2010). Host plant volatiles are less specific semiochemicals than pheromones (Landolt and Phillips 1997, Szendrei and Rodriguez-Saona 2010). Field pea releases volatile compounds, and during spring migration, *cis*-3-hexen-1-yl is the main volatile released as it accounts for 87% of total volatiles released (Landona et al. 1997). Compared to pea, other legumes have less of this compound and pea leaf weevil are sensitive to these host plant odors (Leroy et al. 1999, Landona et al. 1997). Pea leaf weevils also respond, both electrophysiologically and behaviorally, to compounds like (Z)-3-hexen-1-yl acetate, (Z)-3-hexen-1-ol, 2-hexenal, and 3-octanone both of which are released by leguminous plants (Landona et al. 1997).

Management of Pea Leaf Weevil

Adult pea leaf weevils are not easily monitored as their color makes them hard to notice when in the soil and they drop dead to ground when threatened (Cárcamo and Vankosky 2011). Pea leaf weevil larvae are more economically damaging than adults, making the larval life stage the focus of pea leaf weevil management (Seidenglanz et al. 2010, Cárcamo et al. 2012).

Use of Nitrogen

Nitrogen plays an important role in the development of plants and determination of pea leaf weevil status (Cárcamo et al. 2018). In nitrogen fixing plants, nitrogen is not pulled out from the atmosphere but rather fixed by bacteria located in the root nodules of their host plants. Available soil nitrogen fertility influences nodulation of the roots (Cárcamo et al. 2015) as high nitrogen content in soil hinders nodulation (George 1962, Vankosky et al. 2011a). With less nodulation due to the higher nitrogen content, food for the larvae will be scarce and which in turn decreases the weevil recruitment (Quinn and Hower 1986, Lohaus and Vidal 2010, Carcamo et al. 2015).

Furthermore, the nitrogen fixation rate is reduced in soil of pea plants when female pea leaf weevils feed on them and/or eggs are laid near its vicinity, compared to plants subjected to male feeding or control plants without weevils (Jansen et al. 1989). Thus, larval damage in the root nodules impacts pea plant and soil nitrogen (Corre-Hellou and Crozat 2005, Lohaus and Vidal 2010, Cárcamo et al. 2015).

When nitrogen is applied early in pea development, it limits nodule development and can delay peak nodulation, than pea plants grown under nitrogen deficient conditions (Gibson and Harper 1985, Jensen et al 1989, Vankosky et al. 2011a). Thus, limiting pea leaf weevil larval food resources (Vankosky et al. 2011a) resulting in limited larval accumulation, therefore reducing root nodule injury of their host (Cárcamo et al. 2015). In pea plants, reduced nitrogen fixation rates in soil results in higher female herbivory and egg laying comparatively to the control one which does not include any weevils (Jensen et al. 1989). Depending on pea leaf weevil density, high nitrogen might increase in yield too. Therefore, high rates nitrogen fertilizer may be an alternative management tool to synthetic insecticides. However, the increased application rate of nitrogen may increase the cost of production and it is not considered an economical and environmentally friendly management option (Vankosky et al. 2011b, Cárcamoa et al. 2018, Willsey et al. 2021). Organic farmers may apply manure to a field as a mitigating strategy against yield loss due to pea leaf weevil damage (Cárcamo et al. 2018). Further research efforts are needed to understand the impact of soil nitrogen on plant yield and pea leaf weevil populations since little research has been done in this area (Cárcamo et al. 2018).

Chemical Control

Insecticide seed treatment Cruiser^{TM} (active Ingredient Thiamethoxam), cyhalothrin-lambda, permethrin reduce oviposition and larval feeding on the root nodules, as well as adult feeding on the leaves (Bardner et al. 1983, Steene et al. 1999, Wanner 2016). Thiamethoxam, is an effective neonicotinoid seed treatment based on reduced foliar feeding of pea leaf weevil (Cárcamo et al. 2012). In one study, it was found that thiamethoxam killed less than 30 % of adults (Cárcamo et al. 2010). Also, thiamethoxam when applied to seeds delays the oviposition by one week as it was found to reduce the oviposition in critical periods of crop growth (second to fifth node stage) (Cárcamo et al. 2012). Furthermore, thiamethoxam when applied on pea field reduce half of larval pea leaf feeding (Cárcamo et al. 2012). Therefore, thiamethoxam when applied has a negative impact on adult fecundity and foliar feeding, as well as egg viability (Cárcamo et al. 2012).

Systemic insecticides, like thiamethoxam, applied in furrow at planting or as seed coatings are believed to be more effective against pea leaf weevil than foliar treatments (Vankosky et al. 2009, Seidenglaz et al. 2010). Foliar insecticides can reduce foliar damage caused by adult pea leaf weevil; however, it may not protect yield (Vankosky et al. 2009). To maximize the efficacy of foliar insecticides, the timing of application is important but difficult to determine since the application should occur soon after the first detection of pea leaf weevil invasion (King 1981, Bardner et al. 1983, Ester and Jeuring 1992). By applying foliar insecticides as soon as first invasion of pea leaf weevil occurs one can hope to mitigate egg laying in the host crop, thus limiting yield loss due to larval feeding (Prochaska et al. 2018). Depending on the residual time of the insecticide and rainfall, multiple applications (three to four) of foliar insecticides may be preferred to ensure protection of plant over the pea leaf weevil dispersal period (Prochaska et al. 2018).

As foliar insecticides do not inhibit root nodule damage due to larval feeding, the management of pea leaf weevil populations is a challenging (King 1981, Bardner et al. 1983, Ester and Jeuring 1992). Pea leaf weevil migrate to field peas in over the course of several weeks, thus foliar insecticides have little residual activity to inhibit invasions of pea leaf weevil (Hamon et al. 1987). It is for these reasons, that growers prefer systemic insecticide over foliar insecticides for the control of pea leaf weevil populations.

Foliar insecticides like permethrin (McEwan et al. 1981, Bardner et al. 1983, Griffiths et al. 1986), cypermethrin carbosulfan, phorate (King 1981, Bardner et al. 1983), cyhalothrin-lambda (also known as lambda-cyhalothrin; Steene et al. 1999) and imidacloprid (Steene et al. 1999) has been used to manage pea leaf weevil populations for decades (Cárcamo and Vankosky. 2011). Permethrin, a pyrethroid insecticide, only reduces pea leaf weevil larval populations by 50% (Bardner et al. 1983). Since contact foliar insecticides have no direct impacts on pea leaf weevil eggs or larvae, the decrease in larval populations might be caused by mortality of adult females prior to oviposition (Steene et al. 1999). Carbamates (e.g., furathiocarb) when applied mitigates pea leaf weevil larval feeding damage and, therefore, helps to increase yield in comparison to untreated plots in Europe (Taupin 1994, Steene et al. 1999). Similarly, imidacloprid, a neonicotinoid seed treatment, reduces adult feeding damage by 50 % (Steene et al. 1999). Lambda cyhalothrin, a type II pyrethroid kills 56% of adult pea leaf weevils (Steene et al. 1999). Since these products are environmentally risky and pose threat to natural enemies, they have been deregistered (Cárcamo and Vankosky 2011). In North America and Europe, lambda-cyhalothrin is registered in some jurisdictions (Seidenglanz et al. 2010).

Biological Control

Biological control is one of the integral parts of integrated pest management strategies. Biocontrol agents like predators, parasitoids, entomopathogenic fungi, and entomopathogenic nematodes are used as effective measure to control pea leaf weevil (Vankosky et al 2009). There are numerous insect biocontrol agents for the control of pea leaf weevil like generalist ground beetles, such as: *Pterosticus melanarius* (Illiger) and *Bembidion quadrimaculatum* (L.) (Coleoptera: Carabidae) feed on pea leaf weevil eggs and adults in laboratory and in field pea experiments (Vankosky et al. 2011, Prochaksa et al. 2018). These generalist ground beetle species, have a proclivity for attacking newly emerged pea leaf weevil adults rather than other life stages (Hamon et al. 1980).

Under laboratory conditions, *Bembidion* species, are a voracious predator of pea leaf weevil eggs (Vankosky et al. 2010). To support in-field natural enemy populations, foliar applications in field pulse crops should be limited. A parasitoid wasp *Microctonus aethiopoides* (Hymenoptera: Braconidae), is an important natural enemy of *Sitona* weevils in the Mediterranean (Aeschlimann 1980). Additional biological control agents include fungus species

Beauveria globulifera, which are known to be efficacious on controlling the weevil populations. Some nematode species may devour pea leaf weevil larvae in root nodules with variability in their efficacy (Jaworska 1998, Vankosky et al. 2009). There is a need for further research efforts is required to identify additional biocontrol agents of pea leaf weevil and to determine the efficacy of these species.

Host Plant Resistance

Host plant resistance is also important tool of integrated pest management strategies of pea leaf weevil. For the management of pea leaf weevil populations, host plant resistance is often derived from the thickness of the wax layer on field pea leaves (White and Eigenbrode 2000, Chang et al. 2004). In field pea plots, pea leaf weevil consumed foliage and stipules of pea varieties that have thinner wax layer than thicker one (White and Eigenbrode 2000). New resistant varieties are produced by manipulation of these genotypes. There are less studies done on management of pea leaf weevil populations based on crop plant resist ance in last 20 years. Given the limited amount of research on the subject, future research efforts should focus on host plant volatiles, trichome densities, and leaf wax layers as source for host plant resistance that can be utilized by producers for the control of pea leaf weevil populations.

Cultural Control

Planting field pea seed 10- days earlier reduces pea leaf weevil incidence on plant foliage as emergence of pea does not coincide with peak emergence and dispersal of pea leaf weevil in spring. Damage to host plant foliage is the least during peak emergence and dispersal of pea leaf weevil as these events do not coincide with the pea emergence. Additionally, the use of no till systems is another efficacious cultural control method. Historically, for the cultural control of insect pests, crop rotation has largely been considered an important cultural control strategy (Yates 1954, Bullock 1992). However, for management of pea leaf weevil populations, it seems to be ineffective since pea leaf weevil population during their dispersal period (i.e., fall-spring) are highly mobile (Fisher and O’Keeffe 1979c, Hamon et al. 1987, Vankosky et al. 2009). Trap cropping is also a key part of pea leaf weevil cultural control strategies in pulse crops (Hokkanen 1991). Trap crops are the plants that are cultivated to protect the target crops from pest damage which attracts insect or other organisms like nematodes (Hokkanen 1991).

Austrian winter peas were used as a trap crop and were planted in autumn around the periphery of field of spring pea, which was the main crop in the coming spring, resulting in little to no feeding damage in spring pea (Cárcamo et al. 2010**)**. Therefore, the use of trap crops may reduce adult and larval damage to the main crop (Prochaska et al. 2018). Combining trap crops with a pheromone increases effectiveness as it attracts more pea leaf weevil to the trap crops (Cárcamo et al. 2018). The push and pull strategy of cultural control strategies reduce adult and larval pea leaf weevil feeding damage in faba bean plots (Smart et al. 1994). Utilizing faba bean as a trap crop for first generation pea leaf weevil is very promising as pea leaf weevil are attracted to faba beans, thus protecting from yield damage (Cárcamo et al. 2018). It is important to note that faba beans, in less humid or low irrigation regions, can serve as a late season host and requires timely monitoring of pea leaf weevil to prevent them from moving to the main crops (Cárcamo et al. 2018).

Cultural control tactics of integrated pest management also exploit pea leaf weevil preferences. For example, pea leaf weevil larvae are not tolerant to soils that are consistently wet, therefore, proper irrigation can reduce pea leaf weevil larval populations (McEwan et al. 1981).

Furthermore, conservation tillage and no tillage, are two forms of tillage used during field preparation in the spring. Studies show that there is a difference in the population size of pea leaf weevil, larval populations, and colonization of pea leaf weevils in plots with no-tillage vs plots with conventional tillage (Hanavan and Bosque-Pérez 2012). Pea leaf weevil populations moving into emerging crops were higher in conventional till plots than no till plots (Hanavan et al. 2008, 2010, Hanavan and Bosque-Pérez 2017). In conventional till plots, 18 pea leaf weevil adults per square meter colonized, and 34 adults emerged from same plot, whereas in no till plots, 16 adults per square colonized, and 13 adults emerged from those plots (Hanavan et al. 2010). Therefore, this resulted higher foliar damage by pea leaf weevils on seedlings in conventional till plots than in no till plots (Hanavan et al. 2008). An explanation for pea leaf weevil population density differences in conventional versus no-till system is that plants in no till system have reduced nodulation than those in conventional tillage resulting in reduced caloric support for larval development, thus, impacting the population of new generation of pea leaf weevil adult emergence (Hanavan et al. 2010). Additional benefits of no-till systems are that beneficial predators, such as ground beetles, in no till plots are present in higher numbers than conventional till plots (Hanavan et al. 2010). Also, density of larval population and new generation pea leaf weevil was lower in no till plots than conventional till plots comparatively (Hanavan et al. 2010). These research efforts highlight the importance of good agronomic practices and the impact that they can have on pea leaf weevil populations and the damage that they cause. In England, when intercropping of faba with oats, less foliage herbivory and higher emigration rate of pea leaf weevil was observed (Baliddawa 1994).

Summary

Two research projects were carried out during this master’s degree project. The first project was comparison of adult and larval damage of pea leaf weevil in pulse crops and the second study was field efficacy of pea leaf weevil aggregation pheromone combined with contact insecticide as an attract-and-kill method in 2020. The details of the studies are reported in Chapter 2 and Chapter 3 of this thesis. The goals of the research were 1) to perform larval and adult damage assessment of different pea varieties (preference/tolerance of pea varieties). 2) to compare damage by pea leaf weevil to different host plants; pea, chickpea, faba bean and lentil, and 3) to determine field efficacy of aggregation pheromone.

REFERENCES CITED

Abbo, S., D. Shtienberg, J. Lichtenzveig, S. LevYadun, and A. Gopher. 2003. The chickpea, summer cropping, and a new model for pulse domestication in the ancient near east. The Quarterly Review of Biology. 78: 435–448.

Abou-Khater, L., F. Maalouf, A. Jighly, D. Rubiales, and S. Kumar. 2022. Adaptability and stability of faba bean (*Vicia faba* L.) accessions under diverse environments and herbicide treatments. Plant*s*. 11.

Aeschlimann, J. P. 1980. The *Sitona* (Col.: Curculionidae) species occurring on Medicago and their natural enemies in the Mediterranean region. Entomophaga. 25: 139-153.

Agelopoulos, N., M. A. Birkett, A. J. Hick, A. M. Hooper, J. A. Picket, E. M. Pow, L. E. Smart, D. W. M. Smiley, L. J. Wadhams, and C. M. Woodcock. 1999. Exploiting semiochemicals in insect control. Pesticide Science. 55: 225-235.

Ahmadi, A. A., and M. Alichi. 1991. The *Sitona* (Coleoptera, Curculionidae) fauna of Fars Province. [Proceedings of the Tenth Plant Protection Congress of Iran, 1-5 September 1991], University of Shahid Bahonar.

Ambrose, M. J. 1995. From near east center of origin, the prized pea migrates throughout world. Diversity. 11: 118-119.

Andersen, K. T. 1934. Experimentelle untersuchungen u¨ ber den einfluss der temperatur auf die eierzeugung von insekten. i. einfluss konstanter temperaturen auf die eierzeugung von *Sitona lineata* L. Biologisches zentralblatt. 54: 478–86.

Anonymous. 2008. Pea leaf weevil in southwest Saskatchewan [cited 12 February 2008]. Saskatchewan Agriculture and Food Available from: URL: http://www.saskpulse.com/media/pdfs/070625_ PeaLeafWeevil_in_Sask_-_SAF.pdf.

Antonelli, A. Pea leaf weevil: Its biology and control. 1970. Washington State University Cooperative Extension.

Arnett, R. H. Jr. 1960. The beetles of the United States (a manual for identification). Catholic University of America Press, Washington, DC.

Bahl, P. N., S. Lal, and B. M. Sharma. 1993. An overview of the production and problems in southeast Asia.1–10 pp. *In*: W Erksine and M C Saxena (eds.) Lentil in South Asia. Proceedings of the seminar on lentils in South Asia. ICARDA, Aleppo, Syria.

Baker, T. C. 2008. Use of pheromones in IPM. *In*: Radcliffe, E. B., W. D. Hutchison, and R. E. Canceladi (Eds.) Integrated Pest Management: Concepts, Tactics, Strategies and Case Studies. Cambridge University Press. 273-285 pp.

Baliddawa, C. W. 1984. Movement and feeding activity of adult pea leaf weevil, *Sitona lineatus* L. in an oat-broadbean diculture. Insect Science and its Application. 5: 33–39.

Baliddawa, C. W. 1988. The effect of crop microenvironment on the pea leaf weevil's behaviour: an explanation for weevil departure from diverse cropping systems. Insect Science and its Application. 9: 509-514.

Bardner, R., K. E. Fletcher, and D. C. Griffiths. 1983. Chemical control of the pea and bean weevil, *Sitona lineatus* L., and subsequent effects on the yield of field beans, *Vicia faba* L. J. Agr. Sci. 101: 71–80.

Barulina, E. I. 1930. The lentils of the USSR and other countries. Tr Po Prikl Bot Genet Sel [Bull Appl Genet & Select] Suppl 40: 1–319 [Russian]Cambridge.

Barzman, M., P. Barberi, A. N. E. Birch, P. Boonekamp, S. Dachbrodt-Saaydeh, B. Graf, B. Hommel, J. E. Jensen, J. Kiss, P. Kudsk, J. R. Lamichhane, A. Messean, A. C. Moonen, A. Ratnadass, P. Ricci, J. L. Sarah, and M. Sattin. 2015. Eight principles of integrated Pest management. Agronomy for Sustainable Development. 35: 1199-1215.

Beniwal, S. P. S., B. Bayaa, S. Weigand, K. H. Makkouk, and M. C. Saxena. 1993. Field guide to lentil diseases and insect pests. http:/www.icarda.org/Publications/Field_Guide/Lentil/Lentil.html.

Bethlenfalvay, G. J., S. S Abu-Shakra, and D. A. Phillips. 1978. Interdependence of nitrogen nutrition and photosynthesis in *Pisum sativum* L. Plant Physiol. 62: 131-133.

Biniaś, B., J. Gospodarek, and M. Rusin. 2017. Effect of water extract from mint on selected crop pests feeding and survival. Journal of Ecological Engineering. 18: 119–128.

Bjostad, L. B., B. E. Hibbard, and W. S. Cranshaw. 1993. Application of semiochemicals in integrated pest management programs. *In*: Duke, S. O., J. J. Menn, J. R. Plimmer. (Eds.). Pest Control with Enhanced Environmental Safety. American Chemical Society, USA. 199-218 pp.

Blaser-Diekmann, M. 1982. Survey on pests and diseases of faba beans (*Vicia faba*) in Egypt, Morocco and Tunisia. Fabis Newsletter, No. 4: 44-45.

Blatchley, W. S. and C. W. Leng. 1916. Rhynchophora or weevils of North Eastern America. New York Entomological Society. 24: 81-84.

Blight M. M., J. A. Pickett, M. C. Smith and L. J. Wadhams. 1984. An aggregation pheromone of *Sitona lineatus*: Identification and initial field studies. Naturwissenschaften. 71: 480.

Blight, M. M., and L. J. Wadhams. 1987. Male-produced aggregation pheromone in pea and bean weevil, *Sitona lineatus* (L.). Journal of Chemical Ecology. 13: 733-739.

Blight, M., G. W. Dawson, J. A. Pickett, and L. J. Wadhams. 1991. The identification and biological activity of the aggregation pheromone of *Sitona lineatus*. Aspects Applied Biology. 27: 137-142.

Bloem, S., R. F. Mizell, and C. W. O'Brien. 2002. Old traps for new weevils: new records for curculionids (Coleoptera: Curculionidae), brentids (Coleoptera: Brentidae) and anthribids (Coleoptera: Anthribidae) from Jefferson Co., Florida. Florida Entomologist. 85: 632–44. https://doi.org/10.1653/0015-4040(2002)085[0632:OTFNWN]2.0.CO;2.

Bogdan, J. 2018. Pea Leaf Weevil, Pulse Knowledge. Saskatchewan Pulse Growers. 1-5 pp.

Boroumand, H. 1975. Key to the groups and species of the genus *Sitona* (Col. - Curculionidae) in Iran. Journal of the Entomological Society of Iran. 2: 67-68.

Botha, J., D. Hardie, and F. Casella. 2004. The pea leaf weevil, *Sitona lineatus*: exotic threat to Western Australia. Government of Western Australia Department of Agriculture. Factsheet No. 11.

Bright, D. E. 1994. Revision of the Genus *Sitona* (Coleoptera: Curculionidae) of North America. Annals Entomological Society. Am. 87: 277-306.

Bullock, D. G. 1992. Crop rotation. Critical Review. Plant Science. 11: 309–326.

Buttery, B., and A. Gibson. 1990. The effect of nitrate on the time course of nitrogen fixation and growth in *Pisum sativum* and *Vicia faba*. Plant Soil. 127: 143–146.

Cantot, P., and J. Papineau. 1983. Discrimination des lupins a basse teneur en alcaloides par les adultes de *Sitona lineatus* L. (Col. Curculionidae); Discrimination of lupins with low alkaloid contents by adults of *Sitona lineatus* L. (Col. Curculionidae). Agronomie. 3: 937–940.

Cantot, P. 1986. Action larvaire de *Sitona lineatus* L. sure quelques facteurs de production du pois proteagineux (*Pisum sativum* L.). Agronomie. 9: 765-70.

Caracuta, V., M. Weinstein-Evron, D. Kaufman, R. Yeshurun, J. Silvent, and E. Boaretto. 2016. 14,000-year-old seeds indicate the Levantine origin of the lost progenitor of faba bean. Science. 6: 373-99.

Cárcamo, H. A., and S. Meers. 2007. The first insect pest of pulse crops in Alberta: The pea leaf weevil. Agronomy Update. 82–88 pp.

Cárcamo, H., and M. Vankosky. 2011. Managing the pea leaf weevil in field peas. Prairies Soil and Crops Journal. 4: 77–85. www.prairiesoilandcrops.ca.

Cárcamo, H., C. Herle, and V. Hervet. 2012. Greenhouse studies of thiamethoxam effects on pea leaf weevil, *Sitona lineatus*. Journal Insect Science. 12: 151.

Cárcamo, H. A., C. E. Herle, and N. Z. Lupwayi. 2015. *Sitona lineatus* (Coleoptera: Curculionidae) larval feeding on *Pisum sativum* L. affects soil and plant nitrogen. Journal of. Insect Science. 15: 74.

Cárcamo, H. A., M. A. Vankosky, A. Wijerathna, O. O. Olfert, S. B. Meers, and M. L. Evenden. 2018. Progress toward integrated pest management of pea leaf weevil: A Review. Annals of the Entomological Society of America. 111: 144-153. (https://doi.org/10.1093/aesa/say007).

Casey, T. L. 1888. On some new North American Rhynchophora, part I. Annals New. York. Academic Science. 4: 229- 296.

Champion, G. C. 1902-1906. Biologia Centrali Americana. Insecta. Coleoptera. Rhynchophora. Curculionidae. Curculioninae, vol. 4, part 4, pp. i-viii, 1-144 (1902), 145-312(1903), 313-440 (1904), 441-600(1905), 601-750(1906), illus.

Chang, G. C., C. E. Rutledge, R. C. Biggam, and S. D. Eigenbrode. 2004. Arthropod diversity in peas with normal or reduced waxy bloom. Journal of Insect Sciene. 4: 18.

Chen, W., H. C. Sharma, and F. J. Muehlbauer. 2011. Compendium of chickpea and lentil diseases and pests. American Phytopathological Society. 28-29 pp.

Clark, S. 2019. Pea (*Pisum sativum* L.) characteristics for use and successful planting. Plant Material Technical Note No. 19-01. USDA. Big Flat Plant Materials Center.

Coles, K., S. Meers, and H. A. Cárcamo. 2008. Pea leaf weevils on the move in Alberta and Saskatchewan. Agronomy Update. 110–4 pp.

Corre-Hellou, G., and Y. Crozat. 2005. N2 fixation and N supply in organic pea (*Pisum sativum* L.) cropping systems as affected by weeds and pea weevil (*Sitona lineatus* L.). European Journal Agronomy. 22: 449–458.

Cousin, R. 1997. Peas (*Pisum sativum* L.). Field Crops Res. 53: 111-130.

Cubero, J. I. 1974. On the evolution of *Vicia faba* L. Theor. Applied Genetics. 45: 47–51.

Cubero, J. I. 1981. Origin, taxonomy and domestication. *In*: Webb C, Hawtin G (Eds), Lentils 15–38 pp CAB, Slough, UK.

Danthanarayana, W. 1967. Host specificity of *Sitona* beetles. Nature. 213: 1153–4.

Dean, J. R., and R. W. Clark. 1980. Journal Plant Interaction Science. 60: 121-130.

Dhull S. B., M. K. Kidwai, R. Noor, P. Chawla, and P. K. Rose. 2021. A review of nutritional profile and processing of faba bean (*Vicia faba* L.). Legume Science. Wiley.

Downes, W. 1938. The occurrence of *Sitona lineatus* in British Columbia. Canadian Entomologist. 70: 22.

El-Dessouki, S. A. 1971. The effect of some *Sitona* spp. larvae on leguminous plants. Zeitschrift fu¨ r angewandte Entomologie. 67: 411–31.

El-Sayed, A. M., D. M. Sucking, C. H. Wearing and J. A. Byers. 2006. Potential of mass trapping for long-term pest management and eradication of invasive species. Journal of Economic Entomology. 99: 1550-1564.

El-Sayed, A. M., D. M. Sucking, J. A. Byers, E. B. Jang and C. H. Wearing. 2009. Potential of “lure and kill” in long-term pest management and eradication of invasive species. Journal of Economic Entomology. 102: 815-835.

Emden, M. van and Emden, F. van, 1939. Curculionidae: Brachyderinae III. In: Schenling, S. (ed.). Coleopterum Catalogous auspiciis et auxilio Dr W. Junk Publishers, The Hague, 164: 197–327 + 1–59 (index Brachyderinarum).

Endres, Gregory et al. 2016. “Field pea production.” North Dakota State Extension. www.ag.ndsu.edu/publications/crops/field-pea-production.

Ester, A., and G. Jeuring. 1992. Efficacy of some insecticides used in coating faba beans to control pea and bean weevil (*Sitona lineatus*) and the relation between yield and attack. FABIS Newsletter. 30: 32–41.

Etemadi, F., M. Hashemi, F. Mangan, and S. Weis. 2015. Faba beans growers guide in New England. http://ag.u mass.edu /sit es/ag.u mass.edu /files/research-re port s/faba _ bean _ guide _ 2.pdf.

Evenden, M. L. 2017. Semiochemical-based management of the pea leaf weevil (Coleoptera: Curculionidae). Annals of the Entomological of Society of America. 111: 154-160. Oxford University Press (OUP).

Fam, E. Z. 1983. Reducing losses due to insects in faba beans in Egypt. FABIS Newsletter, Faba Bean Information Service, ICARDA. 48-49.

FAOSTAT. 2019. http://www.fao.org/faostat/en/#data/QCL.

FAO. (Food and Agriculture Organization). 2020. Crop production and trade data. doi: http://www.fao.org/faostat/en/#data (accessed December 30, 2020).

FAO. 2008. Land and plant nutrition management service. Available at: www.fao.org/ag/agl/agll/spush.

FAOSTAT. 2020. http://www.fao.org/faostat/en/#data/QCL.

FAO. 2021. FAOSTATA statistical database. Retrieve d from http:/www.fao.org/faostat/.

FAOSTAT. 2022. Production of lentils in 2020. Crops/World Regions/Production Quantity from pick lists. United Nations, UN Food and Agriculture Organization, Statistics Division (FAOSTAT). Retrieved 20 March 2022.

Ferguson, A. W. 1994. Pests and plant injury on lupins in the south of England. Crop Protection. 13: 201–210.

Fisher, J. R. 1977. The population dynamics of the pea leaf weevil *Sitona lineatus* (L.) in northern Idaho and eastern Washington, Ph.D. Dissertation, University of Idaho, Moscow, Idaho, USA.

Fisher, J. R., and L. E. O'Keeffe. 1979 a. Host potential of some cultivated legumes for the pea leaf weevil, *Sitona lineatus* (L.) (Coleoptera: Curculionidae). Pan Pacific Entomologist. 55: 199–201.

Fisher, J. R., and L. E. O'Keeffe. 1979 b. Food plants of the pea leaf weevil *Sitona lineatus* (L.) (Coleoptera: Curculionidae) in northern Idaho and eastern Washington. Pan Pacific Entomologist. 55: 202–7.

Fisher, J. R., and L. E. O'Keeffe. 1979 c. Seasonal migration and flight of the pea leaf weevil, *Sitona lineatus* (Coleoptera: Curculionidae) in northern Idaho and eastern Washington. Entomology Experimental. Application. 26: 189–196.

Flowers, T. J., P. M. Gaur, and C. L. Laxmipathigowda. 2010. Salt sensitivity in chickpea. Plant Cell Environment. 33: 490–509.

George, K. S. 1962. Root nodule damage by larvae of *Sitona lineatus*, and its effect on yield of green peas. Plant Pathology. 11: 172–176.

Germar, E. F. 1817. (Note), *In* Miscellen und Correspondenz—Nachrichtenbl. Mag. Entomol. 2: 339-341.

Germar, E. F. 1824. Insectorum species novae aut minus cognitae descriptionibus illustratae. Coleoptera. 1.

Goldson, S. L., M. R. McNeill, J. R. Proffitt, and B. I. P. Barratt. 2005. Host specificity testing and suitability of a European biotype of the braconid parasitoid *Microctonus aethiopoides* as a biological control agent against *Sitona lepidus* (Coleoptera: Curculionidae) in New Zealand Biocontrol Science Technology. 15: 791-813.

Gossen, B. D., and P. R. Miller. 2004. Survival of *Ascochyta rabiei* in chickpea residue on the Canadian prairies. Canadian Journal of Plant Pathology, 26: 142-147. https://doi.org/10.1080/07060660409507125.

Greenwood, R. M., and N. O. Bathurst. 1978. Effect of rhizobial strain and host on the amino acid patterns in legume root nodules. N2. Journal Science. 21: 107-120.

Greib, V., and F. Klingauf. 1977. Untersuchungen zum Frafipflanzenspektrum von *Sitona lineatus* L. (Curculionidae: Coleoptera). Journal of Applied. Entomology. 82: 267–274.

Griffiths, D. C., R. Bardner, and J. Bater. 1986. Control *of Sitona lineatus* in autumn-sown faba beans. FABIS Newsletter. 14: 30-33.

Hamon, N., R. Bardner, L. Allen-Williams, and J. B. Lee. 1987. Flight periodicity and infestation size of *Sitona lineatus*. Annals of Applied. Biology. 111: 271–284. doi: 10.1111/j.1744-7348.1987.tb01453.x.

Hanavan, R. P., and N. A. Bosque-Pérez. 2012. Effects of tillage practices on pea leaf weevil (*Sitona lineatus* L., Coleoptera: Curculionidae) biology and crop damage: A farm-scale study in the US Pacific Northwest. Bulletin of Entomological Research. 102: 682-691. doi:10.1017/S0007485312000272.

Hanavan, R. P., N. A. Bosque-Pérez, D. J. Schotzko, S. O. Guy, and S. D. Eigenbrode. 2008. Early-season aerial adult colonization and ground activity of *S. lineatus* (Coleoptera: Curculionidae) in pea as influence by tillage system. Journal of Economic. Entomology. 101: 1606–1613.

Hanavan, R. P., N. A. Bosque-Pérez, D. J. Schotzko, and S. D. Eigenbrode. 2010. Influence of tillage on adult and immature *S. lineatus* (Coleoptera: Curculionidae) densities in pea. Journal of Economic. Entomology. 103: 691–697.

Hanavan, R. P., and N. A. Bosque-Pérez. 2017. Influence of no-tillage practices and later planting date on the, *Sitona lineatus,* in pea, *Pisum sativum*. Entomology Exp Application. 162: 77–85.

Hanelt, P., and D. Mettin. 1989. Biosystematics of the genus *Vicia* L. (Leguminosae). Annu. Rev. Ecol. Syst. 20: 199–223.

Hans, H. 1959. Beitrage zur Biologie von *Sitona lineatus*. Zeitschrift fu¨ r angewandte Entomologie Journal of Applied Entomology. 44: 343–86.

Harlan, J. R. 1969. Ethiopia: A centre of diversity. Econ. Bot. 23: 309-14.

Harlan, J. 1971. Agricultural origins: centers and noncenters. Science. 174: 468-474.

Hartley, S. 2007. Saskatchewan insect pest report. Minutes of the 2007 Western Committee on Crop Pests, Penticton, British Columbia, 18 Oct. 2007. http://www.westernforum.org/WCCP%20Minutes.html.

Harveson, R. M. 2021. Origin, domestication, history of pea production and usage. *In* Harveson, R. M., J. S. Pasche, L. Porter, W. Chen and M. Burrows (Eds.), Compendium of Pea Diseases and Pests. 1-2 pp.

Hatch, M. H. 1971. The beetles of the Pacific North-west, part V. Rhipiceroidea, Sternoxi, Phytophaga, Rhynchophora, and Lamellicornia. in University of Washington Publication in Biology. 16.

Havlickova, H. 1980. Causes of different feeding rates of pea leaf weevil, *Sitona lineatus* on three pea cultivars. Entomologia Experimentalis et Applicata. 27: 287–92.

Havlickova, H. 1982. Different response of alfalfa plants to artificial defoliation and to feeding by the pea leaf weevil (*Sitona lineatus L*.). Experientia. 38: 569-570.

Hawthorne, W. 1987. Beans, peas, vetches and other new crops. Occasional Publication, Australian Institute of Agricultural Science. 16-22

Heath, M. C., and P. D. Hebblethwaite. 1985. Solar radiation interception by leafless and leafed peas (*Pisum sativum*) under contrasting field conditions. Annals of Applied Biology. 107: 309-318.

Heichel, G. H., and C. P. Vance. 1983. Physiology and morphology of perennial legumes. *In*: Nitrogen Fixation. Vol3: Legumes. Ed. by W. J. Broughton. Oxford: Clarendon Press.

Hodgson, G. L., and G. E. Blackman. 1957. An analysis of the influence of plant density on the growth of *Vicia faba* (II). The significance of competition for light in relation to plant development at different densities. Journal of Experimental Biology. 8: 195-219.

Hoebeke, E. R., and A. G. Wheeler Jr. 1985. *Sitona lineatus* (L.), The pea leaf weevil: First records in eastern North America (Coleoptera: Curculionidae). Proceedings of the Entomological Society of Washington. 87: 216-220.

Hoffmann D., Q. Jiang, A. Men, M. Kinkema, and P. M. Gresshoff PM. 2007. Nodulation deficiency caused by fast neutron mutagenesis of the model legume *Lotus japonicus.* Journal of Plant Physiology. 164:460–469.

Hokkanen, H. M. T. 1991. Trap cropping in pest management. Annual Review of Entomology. 36: 119–138.

Horst I., T. Welham, S. Kelly, T. Kaneko, S. Sato, S. Tabata, M. Parniske and T. L. Wang. 2007. Tilling mutants of *Lotus japonicus* reveal that nitrogen assimilation and fixation can occur in the absence of nodule- enhanced sucrose synthase. Plant Physiology. 144: 806–820.

Hunter, M. D. 2001. Out of sight, out of mind: the impacts of root feeding insects in natural and managed systems. Agriculture for Entomology. 3: 3–9.

Iqbal, A., I. A. Khalil, N. Ateeq, M. S. Khan. 2006. Nutritional quality of important food legumes. Food Chemistry. 97: 331–335.

Jackson, D. J., and K. S. Macdougall. 1920. Bionomics of weevils of the genus *Sitones* injurious to leguminous crops in Britain. Annals of Applied Biology. 7: 269–298. (https://doi.org/10.1111/j.1744-7348.1920.tb05310.x).

Jaworska, M. 1992. U¨ ber den Befall einja¨ hriger Leguminosen durch den Erbsenrubler, *Sitona lineatus* L. (Col., Curculionidae). Anzeiger fu¨ r Scha¨ dlingskunde, Pflanzenschutz, Umweltschutz. 65: 70–2.

Jaworska, M. 1998. Laboratory preference of annual legumes by pea weevil *Sitona lineatus* L. (Col, Curculionidae) and their effect on susceptibility of weevils to entomogenous nematodes. Journal of Invertebrate Pathology. 71: 248–250.

Jensen, E. S., A. Eckholdt, and H. P. Ravn. 1989. The pea leaf weevil and N2-fixation in peas. Dankse Plantaevaernskonference Sygdomme og Skadedyr. 5: 229–237.

Jia, Z., Y. Liu, B. D. Gruber, K. Neumann, B. Kilian, A. Graner, and N.von Wirén. 2019. Genetic dissection of root system architectural traits in spring barley. Frontiers in Plant Science. 10: 1–14. (https://doi.org/10.3389/fpls.2019.00400).

Johnson, M. P., and L. E. O'Keeffe. 1981. Presence and possible assimilation of *Rhizobium leguminosarum* in the gut of pea leaf weevil, *Sitona lineatus*, larvae. Entomologia Experimentalis et Applicata. 29: 103–108.

Jukanti, A. K., P. M. Gaur, C. L. L. Gowda, and R. N. Chibbar. 2012. Nutritional quality and health benefits of chickpea (*Cicer arietinum* L.): A review. British Journal of Nutrition. 108: 11–26.

Juncus, L. 1998. Plant Guide. Figure 3: 5–8.

Karkanis, A., G. Ntatsi, C. K. Kontopoulou, A. Pristeri, D. Bilalis, and D. Savvas. 2016. Field pea in European cropping systems: adaptability, biological nitrogen fixation and cultivation practices. Not Bot Horti Agrobot Cluj-Napoca. 44: 325– 336.

Karuppuchamy, P., and S. Venugopal. 2016. Integrated pest management: Ecofriendly pest management for food security. 651–684 pp. https://doi.org/10.1016/B978-0-12-803265-7.00021-X.

King, J. M. 1981. Experiments for the control of pea and bean weevil (*Sitona lineatus*) in peas using granular and liquid insecticides.327-331 pp. *In* Proc. 1981 British Crop Protection Conf. Pests and diseases. 11th British Insecticide and Fungicide Conf., Brighton, England. 16-19 Nov. 1981. British Crop Protection Council, Croydon, England.

Kogan, M. 1998. Integrated pest management: Historical perspectives and contemporary developments. Annual Review of Entomology. 43: 243-270.

Kordan, B., and D. Sledz´. 1994. Food preferences of pea weevil (*Sitona lineatus* L.) and its survival on different pea (*Pisum sativum* L.) cultivars in laboratory conditions. Acta Academiae Agriculturae ac Technicae Olstenensis. 59: 107–13.

Krall, James M., D. Stephen, S. D. Miller, W. Scientist and Jack T. Cecil. 2006. Pea production in the high plains. Historical Materials from University of Nebraska- Lincoln Extension. 1: 1-12.

Lacordaire, J. T. 1863. Histoire naturelle des insectes. genera des ocl^opteres ou expose m6thodique et critique de tous les genres proposes jusqu'ici dans cet ordre d'insectes, vol. 6.

Landona, F., J. Levieux, J. Huignard, D. Rougon, and P. Taupin. 1995. Feeding activity of *Sitona lineatus L*. (Col., Curculionidae) on *Pisum sativum L*. (Leguminosae) during its imaginal life. Journal of Applied Entomology. 119: 515-522.

Landona F., S. Ferary, D. Pierre, J. Auger, J. C. Biemont, J. Levieux, et al. 1997. *Sitona lineatus* host plant odors and their components: effects on locomotor behavior and peripheral sensitivity variations. Journal of Chemical Ecology. 23: 2161–73.

Landolt, P. J., and T. W. Phillips. 1997. Host plant influences on sex pheromone behavior of phytophagous insects. Annual Revision. Entomology. 42: 371–391. doi:10.1146/annurev.ento.42.1.371.

LaRue, T. A. G., and W. G. W. Kurtz. 1973. Estimation of nitrogenase in legumes. Canadian Journal of Microbiology. 19: 304-305.

Law, J. H., and F. E. Reignier. 1971. Pheromones. Annual Review of Biochemistry. 40: 533-548.

LeConte, J. L., and G. H. Horn. 1876. The Rhynchophora of America north of Mexico. Proc. Am. Philos. Soc. 15, 96. 1883. Classification of the Coleoptera of North America. Smithson. Misc. Collect. 507.

Lee, C. 2011. Montana’s pulse industry: how it has developed, economic impact and potential for growth by. Montana Department of Agriculture. 1-98 pp.

Lee, J., and C. J. P. Upton. 1992. Relative efficiency of insecticide treatments in reducing yield loss from *Sitona* in faba beans. Test Agro-chemistry Cultivars 13: 6–7.

Leport, L., N. C. Turner, S. Davies, and K. Siddique. 2006. Variation in pod production and abortion among chickpea cultivars under terminal drought. European Journal of Agronomy 24: 236-246. https://doi.org/10.1016/j.eja.2005.08.005.

Lerin, J. 2004. Modeling embryonic development in *Sitona lineatus* (Coleoptera: Curculionidae) in fluctuating temperatures. Environmental Entomology. 33: 107–112.

Leroy, T., J. Pouzat, J. C. Biemont, and D. Pierre. 1999. Variation en fonction de le'tat physiologique de la sensibilite olfactive peripherique chez quatre coleopteres, *Callosobruchus maculatus* Fab., *Bruchidius atrolineatus* Pic., *Acanthoscelides obtectus* Say (Bruchidae) et *Sitona lineatus* L. (Curculionidae). Annales de la Socie´ te´ Entomologique de France. 35 (supplement): 159–64.

Linke, K. H., Saxena, M. C., Sauerborn J., Masri H, 1991. Effect of soil solarization on the yield of food legumes and on pest control. *In*: FAO Plant Production and Protection Paper. 139-154.

Linnaeus, C. 1758. Systema naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis, ed. 10, reformata. 1: 1-823. [+1 p. (Emendanda, Addenda), unnumbered.]. Salvii, Holmiae. [Cure. pp. 377-388.].

Lodos, N. 1971. Preliminary list of Curculionidae with notes on distribution and biology of species in Turkey: 1. *Sitona* Germar. Yearbook of the Faculty of Agriculture, University of Ege. 2: 1-35.

Lohaus, K., and S. Vidal. 2010. Abundance of *Sitona lineatus* L. (Col., Curculionidae) in peas (*Pisum sativum* L.): effects on yield parameters and nitrogen balance. Crop Protection. 29: 283–289.

Makasheva, R. K. 1979. Gorokh (Pea). *In* Kulturnaya Flora SSR; Korovina, O.N., Ed.; Kolos Publishing: Leningrad, Russia. 1–324 pp.

Maphosa, L., M. F. Richards, S. L. Norton, and G. N. Nguyen. 2020. Breeding for abiotic stress adaptation in Chickpea (*Cicer arietinum* L.): A comprehensive review: Crop Breeding, Genetics and Genomics. 2.

Margheim, J. F., D. D. Baltensperger, R. G. Wilson, D. J. Lyon, G. L. Hein, R. M. Harveson, P. A. Burgener, J. M. Krall, J. T. Cecil, and J. R. Rickertsen. 2004. EC04-183 Chickpea production in the high plains. University of Nebraksa- Lincoln. https://digitalcommons.unl.edu/ extensionhist/771.

Markkula, M., and P. Köppä. 1960. The composition of the *Sitona* (Col., Curculionidae) population on grassland legume and some other leguminous plants. Annales Entomologici Fennici. 26: 246–63.

Maxted, N., and N. Ambrose. 2000. Peas (*Pisum sativum* L.). Chapter 10. Plant genetic resources of legumes in the Mediterranean; N. Maxted, S. J. Bennett. Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands. Springer. 39: 181–190 pp.

Maxted, N., S. Kell, A. Toledo, E. Dulloo, V. Heywood, T. Hodgkin, D. Hunter, L. Guarino, A. Jarvis, and B. Ford-Lloyd. 2010. A global approach to crop wild relative conservation: Securing the gene pool for food and agriculture. Kew Bulletin. 65: 561–576.

McEwen, J., R. Bardner, G. G. Briggs, R. H. Bromilow, A. J. Cockbain, J. M. Day, K. E. Fletcher, B. J. Legg, R. J. Roughley, and G. A. Salt. 1981. The effects of irrigation, nitrogen fertilizer and the control of pests and pathogens on spring-sown field beans (*Vicia faba* L.) and residual effects on two following winter wheat crops. Journal of Agriculture Science. 96: 129–150.

Melamed-Madjar, V. 1966. The phenology of *Sitona* (Coleoptera: Curculionidae) in Israel. Israel Journal of Entomology. 1: 63-74.

Mínguez, M. I., and D. Rubiales. 2021. Faba bean. *In* Sadras,V. O. and D. F. Calderini (Eds.),Crop Physiology Case Histories for Major Crops. 452–481 pp. Academic Press. https://doi.org/10.1016/B978-0-12-819194-1.00015-3.

Mihailovic V., A. Mikic, B. Cupina, P. Eric. 2005. Field pea and vetches in Serbia and Montenegro. Grain Legumes. 44: 25-26.

Moreno, M., and J. I. Cubero. 1978. Variation in *Cicer arietinum* L. Euphytica 27: 465–485.

Mori, B. A., and M. L. Evenden. 2014. Mating disruption of *Coleophora deuratella* (Lepidoptera: Coleophoridae) using laminate flakes in red clover seed production fields. Pest Management Science. 71: 1149-1157.

Muehlbauer, F. J., J. I. Cubero, and R. J. Summerfield. 1985. Lentil (*Lens culinaris* Medic.). 266–311 pp *In*: R. J. Summerfield, and E. H. Roberts. (eds.), Grain Legume Crops. Collins, 8 Grafton Street, London, UK.

Muehlbauer, F. J., W. J. Kaiser, S. L. Clement, and R. J. Summerfield. 1995. Production and breeding of lentil. Advances in Agronomy. 54: 283–332.

Murray, P. J., and R. O. Clements. 1995. Distribution and abundance of three species of *Sitona* (Coleoptera: Curculionidae) in grassland England. Annals of Applied Biology. 127: 229–37.

Mutch, L. A., and P. W. Young. 2004. Diversity and specificity of *Rhizobium leguminosarum* biovar *viciae* on wild and cultivated legumes. Molecular Ecology. 13: 2435–44.

Natural History Museum. 1905. Specimen record from the collection in the Natural History Museum (London, UK)., London, UK: Natural History Museum (London).

Nielsen, B. S. 1990. Yield responses of *Vicia faba* in relation to infestation levels of *Sitona lineatus* L. (Col., Curculionidae). Journal of Applied Entomology. 110: 398–407.

Nikolova, I. M. 2016. Response of vetch varieties to *Sitona lineatus* L. in organic farming. Biology Agriculture Horticulture. 32: 63–71.

Nilsson, C. 1973. Fo¨ rekomsten ave Sitona-arter i vissa baljva¨ xtgro¨ dor (abstract). The Review of Applied Entomology Series A: Agricultural. 61: 11-49.

Nouri-Ghanbalani, G. 1978. Host plant resistance to the pea leaf weevil, *Sitona lineatus* L., in pea (*Pisum sativum* L.) and its inheritance. Dissert. Abs. Int. 545-B.

O'Brien, C. W., and G. J. Wibmer. 1982. Annotated checklist of the weevils (Curculionidae) of North America, Central America, and the West Indies (Coleoptera: Curculionidea). Memoirs of the American Entomolgical Society. 34.

Oelke, E. A., E. S. Oplinger, C. V. Hanson, D. W. Davis, D. H. Putnam, E. I. Fuller, and C. J. Rosen. 1991. Alternative field crops manual. University of Minnesota: Center for Alternative Plant and Animal Products and the Minnesota Extension Service, University of Wisconsin-Madison Extension Service.

Olfert, O., R. M. Weiss, H. A. Cárcamo, and S. Meers. 2012. The influence of abiotic factors on an invasive pest of pulse crops *Sitona lineatus* (L.) (Coleoptera: Curculionidae), in North America. Psyche. doi: 10.1155/2012/746342.

Olle, M., and P. Sooväli. 2020. The severity of field pea diseases depending on sowing rate and variety. Acta Agriculturae Scandinavica Section B Soil and Plant Science 70: 556-563. doi: 10.1080/09064710.2020.1803958.

Oplinger, E. S., L. L. S. Hardman, E. A. Oelke, A. R. Kaminski, E. E. Schulte, and J. D. Doll. 1990. Chickpeas (garbanzo bean). Alternative field crops manual. University of Wisconsin Coop. Ext., University of Minnesota Center for Alternative Plant and Animal Products and the Minnesota Extension Service.

Oschman, M. 1984: Untersuchungen zur ertragsbeeinflussung der ackerbohne (*Vicia faba* L.) durch den linierten blattrandkafer (*Sitona lineatus* L. Coleoptera, Curculionidae). Archiv fur Phytopathologie und Pflanzenschutz. 20: 371-381.

Otani, J. 2013. Pea Leaf Weevil: *Sitona lineatus* (L) Monitoring Protocol. Prairie Pest Monitoring Network. 1-5 pp. Retrieved from https://www.westernforum.org/Documents/IPMN Protocols/2011_PeaLeafWeevil protocol.pdf [accessed 26 May 2019].

Quinn, M. A., A. A. Hower. 1986. Effects of root nodules and taproots on survival and abundance of *Sitona hispidulus* (Coleoptera: Curculionidae) on *Medicago sativa*. Ecological Entomology. 11: 391-400.

Quinn, M. A., D. F. Bezdicek, L. E. Smart, and J. Martin. 1999. An aggregation pheromone system for monitoring *S. lineatus* (Coleoptera: Curculionidae) in the Pacific Northwest. Journal of Kansas Entomological Society. 72: 315–321.

Parihar, A. K. 2020. Genetic advancement in dry pea (*Pisum sativum* L.): Retrospect and prospect. *In*: S. S, Gosal, S. H, Wani. (eds) Accelerated Plant Breeding, Volume 3. Springer. Cham. https://doi.org/10.1007/978-3-030-47306-8_10.

Pate, J. S. 1958. Australian Journal of Biology. Science. 11: 366.

Pickett, J. A., C. M. Woodcock, C. A. O. Midega and Z. R. Khan. 2014. Push-pull farming systems. Current Opinion in Biotechnology. 26: 125-132.

Plaut, H. N. 1975. An unusual case of damage caused by *Sitona lineatus* L. and *Sitona crinitus* Hbst. to peanuts. Hassadeh. 55: 1567-1568.

Prescott, H. W., and M. H. Reeher. 1961. The pea leaf weevil, an introduced pest of legumes in the Pacific Northwest. U.S. Department of Agriculture Technological Bulletin. 1233-36 pp.

Prochaska, T. J., J. J. Knodel, and P. B. Beauzay. 2018. Integrated pest management of pea leaf weevil in North Dakota. North Dakota State University Extension Service. E1879.

Prochaska, T., J. Knodel, J. Janet and P. Beauzay. (n.d.). Pea leaf weevil - Farming Smarter, (1233), 12. Retrieved from http://www.farmingsmarter.com/growing-new-ideas/pea-leaf-weevil/.

Purushothaman, R., H. D. Upadhyaya, P. M. Gaur, C. L. L. Gowda, and L. Krishnamurthy. 2014. Kabuli and desi chickpeas differ in their requirement for reproductive duration. Field Crops Res 163: 24-31.

Rahate, K. A., M. Madhumita, and P. K. Prabhakar. 2020. Nutritional composition, anti-nutritional factors, pre-treatments-cum-processing impact and food formulation potential of faba bean (*Vicia faba* L.): A comprehensive review. LWT Food Science and Technology. 138: 110796.

Rasool, S., A. A. H. A. Latef, and P. Ahmad. 2015. Chickpea: Role and responses under abiotic and biotic stress. Legumes under Environmental Stress: Yield, Improvement and Adaptations 67–79 pp.

Redden, B., N. Maxted, B. Furman, and C. Coyne. 2007. Lens biodiversity. *In*: Yadav, S. S., D. L. McNeil, P. C. Stevenson (eds) Lentil. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6313-8_2.

Rivnay, E. 1962. Field crop pests. *In*: Field crop pests in the near East. Monographiae Biologicae, vol 10. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-1544-7_3.

Roy, A., K. Das, J. Kumar, and B. Rao. 2001. Dilaji: a new chickpea variety for Hills zone of Assam, India. International Chickpea and Pigeonpea Newsletter, 8: 6-7.

RStudio. 2021. A language and environment for statistical computing. Foundation Statistical Computing, Massachusetts, United States . https://www.R-project.org/.

Rutledge, C. E., A. P. Robinson, and S. D. Eigenbrode. 2003. Effects of a simple plant morphological mutation on the arthropod community and the impacts of predators on a principal insect herbivore. Oecologia. 135: 39–50.

Sandhu, J., and S. Singh. 2007. History and Origin. *In*: Yadav, S. S., D. L. McNeil, P. C Stevenson. (eds) Lentil. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6313-8_1.

Santra, D. K., and G. Saha. 2021. Botany of pea. *In* Harveson, R. M., J. S. Pasche, L. Porter, W. Chen and M. Burrows (Eds.), Compendium of pea diseases and pests. 3-4 pp.

Sarker, A., and W. Erskine. 2006. Recent progress in the ancient lentil. Journal of Agricultural Science. 144: 19–29.

Schoenherr, C. J., L. Gyllenhaal, and C. H. Boheman. 1840. Genera et species Curculionidum, cum synonymia hujus familiae. Roret, Parisiis. Vol. II.

Schotzko, D. J., and L. E. O'Keeffe. 1986. Reproductive system maturation and changes in flight muscles of female pea leaf weevils (Coleoptera: Curculionidae). Annals of the Entomological Society of America. 79: 109–111.

Scriber, J. M. 1984. Host plant suitability. *In*: Bell, W.J., R. T. Carde. (Eds.), Chemical Ecology of Insects. Chapman and Hall, London. 3–36 pp.

Seidenglanz, M. R. J., I. Smýkalová, J. Poslušná, and P. Kolařík. 2010. Differences between the effects of insecticidal seed and foliar treatments on pea leaf weevils (*Sitona lineatus* L.) in the field pea (*Pisum sativum* L.). Plant Protection. Science. 46: 19–27.

Sharma, A., R. K. Sandhi, and G. V. P. Reddy. 2019. A review of interactions between insect biological control agents and semiochemicals. Insects 10. Multidisciplinary Digital Publishing Institute.

Shorey, H. H. 1977. Manipulation of insect pests of agricultural crops. *In*: Shorey, H., and J. J. McKelvey. (Eds.), Chemical Control of Insect Behaviour: Theory and Application. Wiley, New York. 353–367 pp.

Singh, K. B., and B. Ocampo. 1997. Exploitation of wild *Cicer* species for yield improvement in chickpea. Theory Applied Genetics. 95: 418–423.

Smart, L. E., M. M. Blight, J. A. Pickett, and B. J. Pye. 1994. Development of field strategies incorporating semiochemicals for the control of the pea and bean weevil, *Sitona lineatus* L. Crop Protection. 13: 127–135.

Smýkal, P., G. Aubert, J. Burstin, C. J. Coyne, N. T. H. Ellis, and A. J. Flavell. 2012. Pea (*Pisum sativum* L.) in the Genomic Era. Agronomy. 2: 74–115.

Soroka., J. J., and H. A. Cárcamo. 2006. Pea insects, ecology and control. *In*: Pimentel D, editor. Encyclopedia of Pest Management. Taylor and Francis, London. 1–4 pp.

Spaink, H. P. 1994. The molecular basis of the host specificity of the *Rhizobium* bacteria. Antoine van Leeuwenhoek International Journal of General and Molecular Microbiology. 65: 81–98.

Sprent, J. I., and A. M. Bradford. 1977. Nitrogen fixation in field beans (*Vicia faba*) as affected by population density, shading and its relationship with soil moisture. Journal of agricultural. Science Cambridge. 88: 303-310.

Steene, F. vande., G. Vulsteke, M. de. Proft, and D. Callewaert. 1999. Seed coating to control the pea leaf weevil, *Sitona lineatus* (L.) in pea crops. Journal of Plant Diseases. Prot. 106: 633–637.

Sutton, W. D. 1983. Nodule development and senescence. *In*: Nitrogen Fixation. Vol. 3: Legumes, Ed. by W. J. Broughton. Oxford: Clarendon Press. 144-212 pp.

Szendrei, Z., and C. Rodriguez-Saona. 2010. A meta-analysis of insect pest behavioural manipulation with plant volatiles. Entomologia Experimentalis et Applicata. 134: 201-210.

Taupin, P. 1994. Protection insecticide – La précision génère la marge. Perspectives Agricoles. 187:3 pp.

Tewari, S., T. C. Leskey, A. L. Nielsen, J. C. Piñero, and C. R. Rodriguez-Saona. 2014. Use of pheromones in insect pest management, with special attention to weevil pheromones. *In* Integrated Pest Management: Current Concepts and Ecological Perspective. Elsevier. 141-168 pp.

Thompson, R. T. 1992. Observations on the morphology and classification of weevils (Coleoptera, Curculionoidea) with a key to the major groups. Journal of Natural History. 26: 835-891.

Tinzaara, W., M. Dicke, A. van Huis, and C. S. Gold. 2002. Use of info chemicals in pest management with special reference to banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). Insect Science Application. 22: 241-261.

van der Maesen, L. J. G. 1972. *Cicer* L., a monograph of the genus, with special reference to the chickpea (*Cicer arietinum* L.), its ecology and distribution. Mendelingen Landbouwhogeschool Wageningen, Wageningen, The Netherlands. 1 –341.

Vankosky, M., L. M. Dosdall, and H. A. Cárcamo. 2009. Distribution, biology and integrated management of the pea leaf weevil, *Sitona lineatus* L. (Coleoptera: Curculionidae), with an analysis of research needs. *In* CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources (Vol. 4). https://doi.org/10.1079/PAVSNNR20094007.

Vankosky, M. A., H. A Cárcamo, and L. M. Dosdall. 2010. Identification of potential natural enemies of the pea leaf weevil, *Sitona lineatus* L. in western Canada. Journal of Applied. Entomology. 135: 293–301. https://doi.org/10.1111/j.1439-0418.2010.01542.x.

Vankosky M. A. Integrated pest management of *Sitona lineatus* L. (Coleoptera : curculionidae) in crops of *Pisum sativum* L. (Fabales : Fabaceae) in western Canada. 2011. Library and Archives Canada = Bibliothèque et Archives Canada. 200 pp

Vankosky, M. A., H. A. Cárcamo, and L. M. Dosdall. 2011a. Response of *Pisum sativum* (Fabales: Fabaceae) to *Sitona lineatus* (Coleoptera: Curculionidae) infestation: effect of adult weevil density on damage, larval population and yield loss. Journal of Economic. Entomology. 104: 1550–1560.

Vankosky, M. A., H. A. Cárcamo, R. H. McKenzie, and L. M. Dosdall. 2011b. Integrated management of *Sitona lineatus* L. (Coleoptera: Curculionidae) with nitrogen fertilizer, Rhizobium inoculation and thiamethoxam insecticide. Agronomy. 103: 565–572.

Vankosky, M., H. Carcamo, M. Evenden, S. Hartley, S. Meers, A. Wijerathna, D. Sjølie, and O. Olfert. 2018. Pea leaf weevil update. Agriculture and Agri-Food Canada.9898Verkleij, F. N., P. A. M. van Amelsvoort, and P. H. Smits. 1992. Control of the pea weevil (*Sitona lineatus* L.) (Col., Curculionidae) by the entomopathogenic fungus *Metarhizium anisopliae* in field beans. Journal of Applied Entomology. 113: 183–193.

Velázquez De Castro, A. J., A. L. L. Friedman, and R. Borovec̆. 2010. *Sitonini* of Israel (Coleoptera: Curculionidae: Entiminae). Israel Journal of Entomology. 40: 71–108.

Wanner, K. 2016. Pea Leaf Weevil. Montana State University MontGuide. Pest Fact Sheets.

Westwood, J. O. 1840. Synopsis of the genera of British insects. *In* An introduction to the modern classification of insects, founded on the natural habits and cooperation organization of the different families, vol. 2. Longman, London.

White, C., and S. D. Eigenbrode. 2000. Effects of surface wax variation in *Pisum sativum* on herbivorous and entomophagous insects in the field. Environment Entomology. 29: 773–780.

Williams, L., L. E. O’Keeffe, and D. J. Schotzko. 1991. Chickpea, *Cicer arietinum*: a new host for the pea leaf weevil, *Sitona lineatus.* Field Crops Research. 27: 377–380. (https://doi.org/10.1016/0378-4290(91)90043-U).

Williams, L., D. J. Schotzko, and L. E. O'Keeffe. 1995. Pea leaf weevil herbivory on pea seedlings: effects on growth response and yield. Entomology Experimental Application. 76: 255-269.

Willsey, T., J. Patey, C. Vucurevich, S. Chatterton, and H. Carcamo. 2021. Evaluation of foliar and seed treatments for integrated management of root rot and pea leaf weevil in field pea and faba bean. Crop Protection. 143. https://doi.org/10.1016/j.cropro.2021.105538.

Witzgall, P., P. Kirsch and A. Cork. 2010. Sex pheromones and their impact on pest management. Journal of Chemical Ecology. 36: 80-100.

Wojciechowicz-Zytko, E., and M. Młynarczyk. 2002. The preference of different broad bean cultivars by *Sitona lineatus* L. (Coleoptera: Curculionidae). Journal of Plant Protection Research. 42: 81–9.

Wolfson, J. L. 1987. Impact of Rhizobium nodules on *Sitona hispidulus*, the clover root curculio. Entomology Experimental Application. 43: 237-243.

Xiao, J. X., Y. A. Zhu, W. L. Bai, Z. Y. Liu, T. A. N. G. Li, and Y. Zheng. 2021. Yield performance and optimal nitrogen and phosphorus application rates in wheat and faba bean intercropping. Journal of Integrative Agriculture. 20: 3012–3025. https://doi.org/10.1016/S2095-3119(20)63489-X.

Yadav, S. S., A. H. Rizvi, M. Manohar, A. K. Verma, R. Shrestha, C. Chengci, G. Bejiga, W. Chen, M. Yadav, and P. N. Bahl. 2007. Lentil growers and production systems around the world. *In*: Yadav, S.S., D. L. McNeil, P. C. Stevenson. (eds) Lentil. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6313-8_23.

Yates, F. 1954. The analysis of experiments containing different crop rotations. Biometrics. 10: 324–346.

Zhou, R., B. Hyldgaard, X. Yu, E. Rosenqvist, R. M. Ugarte, S. Yu, Z. Wu, C. O. Ottosen, and T. Zhao. 2018. Phenotyping of faba beans (*Vicia faba* L.) under cold and heat stresses using chlorophyll fluorescence. Euphytica. 214: 68 pp.

Zohary, D. 1972. The wild progenitor and the place of origin of the cultivated lentil. Economic Botany. 26: 326–332.

CHAPTER TWO

PEA LEAF WEEVIL, *SITONA LINEATUS* L. (COLEOPTERA: CURCULIONIDAE), ADULT FEEDING PREFERENCE AND LARVAL DEVELOPMENT ON PULSE CROP PLANTS IN MONTANA

Contribution of Authors and Co-Authors

Manuscript in Chapter 2

Author: Pragya Kiju

Contributions: Investigation, Data curation, Software, Visualization, Writing – original draft

Co-Author: Kevin Wanner

Contributions: Conceptualization, Resources, Supervision, Validation, Writing – review & editing

Co-Author: Michel Ivie

Contributions: Investigation, Writing – review & editing

Co-Author: Kevin McPhee

Contributions: Resource, Writing – review & editing

Co-Author: G.V.P. Reddy

Contributions: Conceptualization, Funding acquisition, Project administration

Manuscript Information

Pragya Kiju, Kevin Wanner, Michael Ivie, Kevin McPhee, and G.V.P Reddy

Journal of Pest Management

STATUS OF MANUSCRIPT:

_x Prepared for submission to a peer-reviewed journal
__ Officially submitted to a peer-reviewed journal
___Accepted by a peer-reviewed journal
___Published in a peer-reviewed journal

[Journal of Pest Management]

[06/22/2022]

ABSTRACT

BACKGROUND**:** Montana accounts for ca. 40 % of US dry pea production and the pea leaf weevil (PLW), (*Sitona lineatus* (L.)), is the most common insect pest in this region. After crop emergence adult PLW feed on the foliage to mature and mate, and the underground larval stage feed and develop on the nitrogen fixing root nodules. Producers commonly apply prophylactic insecticide treatments to the seed at planting as well as one or two post-emergent insecticide sprays to control PLW damage. Towards developing alternative management strategies based on Integrated Pest Management (IPM), this field study evaluated pulse crops grown in Montana for adult feeding preference and larval development. Ten different field pea varieties, along with two faba bean, lentil and chickpea varieties, were evaluated during the 2020 and 2021 field seasons at the Montana State University Arthur H. Post Agronomy Farm.

RESULTS**:** Significant PLW pest pressure was observed within the research plots during both experimental years. Field pea and faba bean were preferred by the foliage feeding adult stage, with all but one variety averaging 39.2 to 86.3 average notches per plant. The pea variety ‘Lifter’ was significantly preferred over all other comparisons, averaging 135.5 and 95.0 notches per plant in 2020 and 2021 respectively. Adult PLW feeding on lentil and chickpea was minimal, averaging 3.3 to 8.2 and 0.5 to 1.6 notches per plant, respectively. Numbers of larvae were highest on the roots of pea varieties, a known reproductive host, and almost nil on lentil and chickpea roots. Faba bean is also known as reproductive host, but unexpectedly, larval populations were also low on the two faba bean varieties.

CONCLUSIONS**:** Results from this study do not provide evidence for alternative IPM strategies for field peas based on host plant tolerance or resistance within the range of varieties tested. However, differences in preference and larval development between different pulse crops and varieties, and their developmental stage, suggest that trap crops may be a successful strategy for PLW management.

Keywords: Pea leaf weevil, pulse crop, variety, pheromone, trap crop

Introduction

Pea leaf weevil (PLW), *Sitona lineatus* L. (Coleoptera: Curculionidae), is an economic pest of pea, *Pisum sativum* L. (Fabales: Fabaceae) and faba bean *Vicia faba* L. (Fabales: Fabaceae) crops.[1] The PLW is an invasive pest to North America (NA) introduced from its native range in Europe and North Africa.[1–6] It was first recorded on the west coast of NA in 1936 under codling moth bands near Victoria, British Columbia Canada and subsequently infested cannery pea crops grown in the Fraser River Valley of southern British Columbia.[7] By 1940 the PLW was infesting peas in the United States (US), just south of British Columbia, on the San Juan Islands of Washington State.[7] In 1984 PLW was recorded for the first time on the eastern coast of NA, in the state of Virginia.[4] After introduction, PLW quickly spread along the eastern and western coastal states and is now distributed from Washington to northern California in the west, and from Virgina to Texas in the east.[4,6,8–10]

Montana ranked first nationally in acreage planted and production of pulse crops in 2020, accounting for ca. 45% of total dry pea production.[11] During the last decade Montana has increased cultivation of pulse crops as growers diversify from primarily producing small grains, corresponding to a ca. 40% decrease in wheat production in 2016/2017.[11] The acreage of dry edible pea production in Montana increased from 495,000 acres in 2020 to 570,000 acres in 2021.[12] In addition to dry peas, 530,000 acres were planted to lentil and 175,000 acres to chickpea, in 2021[11,12] In general, faba bean is not produced in Montana.[13]

To the north of Montana, the Canadian provinces of Alberta and Saskatchewan represent a major pulse production area, and the PLW has infested the collective region, spreading from the west to the east. The PLW was reported in 1995 near Swift Current Saskatchewan infesting field pea for the first time[14] and in southern Alberta in 1997.[15] Pest scouting and mapping recorded field infestations near Lethbridge, Alberta, in 2000 and southwestern Saskatchewan in 2007 and its range in this region continued to expand, north to Red Deer and Edmonton Alberta by 2014 and 2017 respectively, and across southern Saskatchewan by 2017.[16] First reports of PLW in Montana are not available, but it was well established in Gallatin County by 2008 and subsequently continued to move eastward.[17] In 2016 it was first confirmed infesting field pea crops in southwest, north-central and northwestern North Dakota.[6,15–17] Dry pea production in this region is significant: 168,411 metric tons in Montana and 181,976 in North Dakota, and 1,799,100 metric tons in Alberta and 2,477,700 in Saskatchewan.[12,18] Therefore, expansion of PLW range into this major field pea production area of North America is concerning.

The PLW is univoltine producing a single generation each year.[19] The adults overwinter in debris near field margins or within legume fields.[20] Early in the spring the emerging adults are oligophagous and migrate to and feed on a variety of plants in the Fabaceae family, chewing characteristic half-moon shaped notches from the leaf edges of plants.[2,17,19–24] While the adults can consume about 40 mm^2 of pea leaves in a single day[25], defoliation is generally not considered economic as the host plants can compensate and recover.[17,26] However, when pest pressure is severe, young seedlings may not recover from damage to the terminal growth resulting in stand thinning during crop establishment.[19] While the adults are oligophagous,[1–4] pea and faba bean plants are considered the only reproductive hosts that larvae can successfully develop on.[2,5–7]

Adult males produce an aggregation pheromone (4- methyl 3,5 heptanedione) that attracts both males and females for mating on or near the host plant.[27,28] After mating females lay eggs singly on the soil surface and larvae develop below ground.[29,30] After hatching the neonate larvae move through the soil searching for the nitrogen-fixing root nodules where they feed and develop.[24,31] The milky white colored larvae with dark brown head capsules curl into a distinctive “c” shape.[17] The larval stage can cause yield loss and economic damage by destroying the root nodules that contain the N-fixing *Rhizobium leguminosarum* Frank (Rhizobiales: Rhizobiaceae) bacteria, which may also result in reduced grain protein content and less residual soil nitrogen levels.[1,24,31–38] Secondary damage can result from root rot pathogens that can infect insect damaged tissue.[39,40] In the absence of management intervention yield loss has been estimated to be as much as 2,114 kg per acre.[15]

Producers have relied on insecticides to manage PLW, applications of insecticide to the seed prior to planting, and one or two foliar sprays targeting the adults in the spring season.[41,42] Both approaches have limitations; seed treatments must be applied prophylactically before pest pressure can be surveyed, and foliar sprays may not reduce adult female populations before egg laying (and subsequent larval damage) occurs.[41–44] The benefit of insecticidal treatments to yield have not been thoroughly studied until recently.[17] Additionally, the reliance on insecticide-based pest management may increase the risk of pea leaf weevil populations developing resistance, in addition to negative impacts of pesticides on the environment and nontarget organisms. Pea leaf weevils resistant to pyrethroid insecticides have recently been reported in the United Kingdom.[45] The status of PLW as a primary pest of field pea in the major pulse producing region of NA necessitates the develop of alternative management strategies based on Integrated Pest Management (IPM), such as breeding for tolerance or resistance. Towards this goal we evaluated the feeding preference of adult PLW, and larval development, on ten different varieties of field pea in comparison to faba bean, lentil and chickpea hosts in a two-year field trial.

Materials and Methods

Field Site

The field plot study was conducted on the Montana State University Arthur H. Post Agronomy Farm (geographic coordinates, 45.85° N and -111.15° W; elevation 1,461 m) (Fig. S1.) near Bozeman, Montana during 2020 and 2021. The 103 hectare (ha) farm is a College of Agriculture and Montana Agricultural Experiment Station site dedicated to cropping systems research that also has a history of pea leaf weevil infestation from endemic populations. Temperature and rainfall data were recorded by a weather monitoring station maintained on the research farm. Ten field pea, two faba bean, two chickpea and two lentil varieties were planted in a randomized complete block design, n = 4 replicated blocks. Each block was divided into 16 plots measuring 3.1 by 1.4 m (4.4 m^2) in dimension and each plot was separated by a 0.8 m buffer area with no crop. The outer edges of the field plot were surrounded by two rows of field pea to buffer edge effects. A Wintersteiger small plot drill was used to plant 6 rows with a 22.9 cm row spacing. Planting densities were 86, 151, 43 and 43 plants per square meter for field pea, lentil, chickpea and faba bean respectively. The seeding rate was corrected for seed germination using the formula: seeding rate (kg/ha) = (thousand seed weight (g/1000 seeds)) * (target plant population (plant/m^2)) / ((germination %) * (emergence %)).

The field site was maintained as no-till site and the seed was planted into the prior year's crop stubble.

Plots were planted on 29 April 2020 and the 30 April 2021 into AJ oat stubble from the previous season's crop. Prior to planting, seeds were treated with the fungicide Vibrance Maxx (Syngenta Crop Protection, Greensboro, North Carolina) at a rate of 100.3 ml per 100 kg seed on 27 April 2020 and 25 April 2021. *Rhizobium* inoculant (12.8 gram) PRIMO GX2 (Verdesian, Cary, North Carolina) was added to each seed packet prior to planting (Table S1). The site was maintained without irrigation (dryland production) or fertilizer both years. Actual nitrogen and phosphorus levels available in the soil was 18 kg per one hectare and 28 parts per million (ppm), respectively.

Weeds were controlled using herbicides in both years. As a pre-plant tank mix, the field was sprayed with a 94 liter per hectare tank mix of Prowl H_2O at the rate of 1.7 kg per one hectare, Sharpen at the rate of 0.07 kg per one hectare, Round-up RT_3 at the rate of 2.2 kg per one hectare and Hel-Fire at the rate of 0.5 per one hectare in 2020 and 2021. Similarly, Assure II was applied post-emergence at the rate of 0.6 kg per one hectare to remove volunteer cereals during mid-June in 2020. The field was sprayed on 25 March 2021 with a 187.08 liter per hectare tank mix of Glystar plus at the rate of 2.2 kg per one hectare and 1.0 % NIS (Non-ionic surfactant). The field was sprayed again on 12 April 2021 with a 93.54 liter per hectare tank mix of Prowl H_2O at the rate of 1.7 kg per one hectare, Sharpen at the rate of 0.07 kg per hectare, Round-up RT_3 at the rate of 2.3 kg per hectare, Hel-Fire at the rate of 0.5 kg per one hectare. The final treatment was applied on 7 June 2021 and consisted of 187 liter tank mix of Assure 0.7 kg per one hectare and 0.25 % of NIS.

Pea Leaf Weevil Adult Feeding Preference

Adult PLW feeding results in characteristic half-moon shaped notches removed from leaf margins. The number of feeding notches were recorded as a measure of preference for the different pulse crop varieties. Vegetative leaf and leaf-like structures and their terminology vary between pulse crops and varieties. Nine of ten field pea varieties were semi-leafless where tendrils were modified leaflets, and the stipules were smaller. One field pea variety, Lifter, had true leaves with stipules. All faba bean varieties had compound leaves and conspicuous stipules with toothed margins. Lentil and chickpea varieties all had compound pinnate leaves. Adult feeding was recorded on the leaves, leaflets and stipules, including the terminal clam leaves that had not yet fully developed, but not the tendrils.

Adult feeding notches were recorded approximately 5 - 6 weeks after planting, on 2 - 4 June 2020 and 8 - 11 June 2021) (Table 2.6. S1.1). Ten individual plants were randomly selected and removed using a hand trowel, from the 2nd and 5th rows of each plot, and stored at 4 °C in a walk-in cooler until notching was assessed in the laboratory. Additionally, the growth stage of each plant was recorded by counting the number of leaves and the number of nodes.

On 31 May 2020 and 3 June 2021 overall adult PLW feeding was assessed visually using six numerical categories (Table 2.7. S1.2). Ten plants were selected randomly from each plot and assigned to one of six categories: 0 (notches not observed), 1 (1-5 notches observed on plant), 2 (> 5 notches observed per plant but not on the majority of leaves), 3 (several notches observed on portions of most leaves), 4 (notches completely surround most leaves), and 5 (feeding results in defoliation in addition to notches).

Adult activity was monitored using pitfall traps baited with the aggregation pheromone. Moth unitraps baited with 4- methyl 3,5 heptanedione septum lures (ChemTica International, Heredia, Costa Rica) were buried with the trap entrance at soil level. Traps were deployed between 12 May to 20 June 2020 and 26 May to 20 July 2021 and the insects collected in the interval of 8 to 10 days.

Larval Population Assessment

Larval development on the different pulse crop varieties was estimated at two sampling dates each year, 23 June and 10 July 2020 and 25 June and 10 July 2021) (Table 2.6.S1.1). Five plants were selected from the 2nd and 5th rows of each plot and removed with a shovel to include the intact roots and a consistent amount of surrounding soil, placed in a paper bag and stored at 4 °C in a walk-in cooler in the laboratory. To collect larvae and pupae each plant with roots and soil was soaked in a bucket of tap water in the laboratory. Any weevils that were floating on the surface were collected and recorded. The soil with the water was passed through a 0.37 cm diameter sieve to collect larvae and/or pupae that were not within root nodules. The remaining roots were gently washed and then stored at 4 °C until examination. The total number of root nodules was counted, and each nodule dissected under a stereomicroscope to collect any additional larvae remaining within the nodules. Collected larvae and pupae were stored in 70% (v/v) ethyl alcohol at 4 °C.

Yield

Grain yield was recorded in 2020; but in 2021 deer and goose feeding activity within the plots prevented yield data collection. Plants within a 2-meter square area within the 3rd and 4th rows were cut using a sickle. Grains were harvested using a thresher on 8 August 2020 (Table 2.8 S1.3) and the seeds were dried at 121 °C and weighed.

Statistical Analysis

The statistical analysis was performed using R version 4.1.1 (R core team, 2021). Data were fitted to a linear model to test for normality, equal variance, and independence variance. Here for the statistical analysis, as there are two main independent variables the number of notches/ plant and the number of larvae/ plant. Also, plant growth measurements (number of nodes/plant, number of leaves/plant), number of nodules/plant and visual rating were used as independent variable /response variable. While variety, species, blocks were quantified against each of independent variable separately; they were used as fixed effects (treatments). The level for the factor 'species' were 'pea', 'faba', 'lentil', 'chickpea'. The level for the factor variety were 'AC Agassiz', 'Aragorn', 'SW Arcadia', 'CDC Treasure', 'Greenwood', 'Delta', 'DS Admiral', 'Hampton', 'Lifter', 'Majoret', 'Faba bean', 'Faba bean ss', 'Sierra', 'CDC Orion', 'CDC Richela' and 'Pennell'. Shapiro-Wilk test was performed test to normality. Field data were analyzed on a yearly basis. Variety/plant species were considered fixed treatment effects and replicate (blocks) was considered random. ANOVA was conducted to test significance of the main effects. Within GLM analysis of variance (ANOVA) was conducted to test for significance of treatment factors followed by a post hoc ranked Tukey HSD test using the 'multcomp' package (Hothorn et al. 2008) in R version 4.1.1.

Visual leaf damage data was fitted to a generalized linear model using ANOVA. Assumptions of normality and constant variance were met. Mean separation using a post hoc ranked Tukey HSD test was conducted using the 'multcomp' package (Hothorn et al. 2008) in R version 4.1.1.Pearson correlation was performed to analyze presence of any correlation between number of notches/plant and number of leaves/plant and between number of nodules/plant and number of larvae/plant.

Results

During the two-year trial, on-site total monthly precipitation and average daily temperature at the Arthur H. Post Agronomy Farm reflected the drought conditions affecting areas of the western US. Cumulative rainfall from 1 April to 31 August 2020 was 165.5 mm, and 200.4 mm for 2021, while long-term cumulative April to August rainfall averaged over the last 63 years (1958-2021) was 403.86 mm (Table 1). During the growing season, total monthly precipitation was much lower in May 2020, June 2021 and July 2020 and 2021, compared to the long-term average (Table 1). Comparatively, May 2020 received less rainfall (19.8 mm) than May 2021 (78.9 mm) while June received more rainfall in 2020 compared to 2021 (92.7 mm and 20.3 mm, respectively) (Table 2.1) and July was relatively drier for both years (16.8 and 21.1 mm, respectively) (Table 2.1). The average daily temperature for the year was 8.5 °C in 2020 and 8.6 °C in 2021, higher than the long-term average of 6.4 °C. During June and July 2021 average daily temperatures were higher compared to the long-term average. Average daily temperatures in June and July 2021 were notably warmer (18.6 and 22.5 °C, respectively) compared to June and July 2020 (15.3 and 18.3 °C, respectively). The highest temperatures were recorded on 19 August 2020 (34.4 °C) and 15 August 2021 (37.2 °C) and the last damaging spring frost (a low below -0.6 °C) was recorded on 11 May in 2020 and 6 June in 2021. The first damaging fall frost was recorded on 8 September in 2020 and 21 September in 2021, resulting in a frost-free period of 120 days in 2020 and 107 days in 2021, compared to the long-term average of 106 days.

Adult PLW feeding on the different pulse crops and varieties was assessed during the first week of June in 2020 and 2021, when most pea varieties were at the five to six node stage (Tables 2.2 and 2.3). Adult weevils were observed within the experimental plots shortly after crop emergence, feeding and mating on or near emerging seedlings. The number of notches per pea plant was not correlated with the number of leaves per plant.in 2020 ($r = 0.17$, $p = 0.17$, Pearson correlation) (Figure. 2.2A.) and in 2021 ($r = 0.3$. $p = 0.06$, person correlation) (Fig. 2.2B) (Appendix A1).

Pitfall traps baited with aggregation pheromone and deployed near the experiment plot detected adult male and female activity between 10 May to 19 May 2020, when traps were deployed and first emptied, respectively (Figure 2.1.A). During 2020 average trap catches were highest between 3 June and 11 June. In 2021 pheromone traps catches were first deployed on 26 May and emptied on 2 June, during which an average of 5.2 ± 1.6 adults were captured per trap, increasing to an average of 17.2 ± 4.3 adults between 2 June and 14 June 2021 (Figure 2.1.B). Average trap catches declined during early July 2021 but then increased to their highest levels on the subsequent and last sampling date of 20 July (24.2 ± 6.3). Trap catches between the 11 and 20 July 2021 likely reflect the next generation of adults emerging from pupae that developed during June. Pupae were recovered from soil samples taken on 10 July 2020 (Table 2.4) and pupae and newly emerged adults from soil sampled on 20 July 2021 (Table 2.5).

Adult feeding was consistent throughout the experimental plots and was relatively higher in 2020 compared to 2021. Feeding preference was assessed by counting the number of notches per plant, the number of notches specifically on the terminal clam leaf, and by visually rating the amount of feeding damage. With the exception of Lifter, the number of notches per pea plant ranged from 76.2 ± 4.5 to 86.3 ± 3.3 in 2020 (Table 2.2) and 56.2 ± 2.5 to 70.8 ± 7.3 in 2021 (Table 2.3). However, the range of notches per pea clam leaf was lower in 2020 (1.8 ± 0.5 to 5.8 ± 0.5) compared to 2021 (3.8 ± 0.5 to 7.1 ± 0.7). Visual rating of overall feeding on the 10 pea varieties was similar between experimental years (ranges, 3.5 ± 0.2 to 3.9 ± 0.1 and 3.6 ± 0.1 to 4.0 ± 0, 2020 and 2021 respectively) (Tables 2.2 and 2.3) (Appendix A3 and A4). These values correspond to "most leaves having several notches" to "notches circling most leaves" (Table 2.6.S1.1). Since clam leaves are recent terminal growth, clam leaf notching to pea varieties recorded on 2 June 2020 and 8 June 2021 indicates active adult feeding on these dates, consistent with adult male and female captures in the pheromone baited traps (Figure. 2.1A and 1B).

Nine of the 10 field pea varieties were semi-leafless, and the number of notches/plant was not statistically different between these varieties in 2020 or 2021 ($p = 0.05$, Tukey HSD Test) (Tables 2.2 and 2.3). However, in both years, the pea variety Lifter had significantly more notches per plant compared to the nine semi-leafless pea varieties (Lifter is a true-leaf pea variety). Statistically significant differences in the number of notches per clam leaf or the feeding damage score was not observed for any of the 10 pea varieties in 2020 or 2021.

Adult pea leaf weevil feeding on faba bean was not significantly different from the semi-leafless pea varieties whereas feeding on the lentil and chickpea varieties was significantly less (Tables 2.2 and 2.3). The average number of notches per faba bean plant ranged from 39.2 ± 2.2 to 69.8 ± 4.1 during the two-year study. In 2020 only one faba bean variety (PI222216) was available, and to maintain an experimental site with 64 plots, the same variety was planted twice. This duplicated entry yielded consistent values for all variables recorded (leaves/plant, nodes/plant, notches/plant, notches/clam leaf and feeding damage score) (Table 2.2). In 2021 a second variety of faba bean (faba bean ss) was added to the experimental design (both were varieties bred for forage consumption). While the difference was not statistically different, this variety sustained less adult feeding, 39.2 ± 2.2 compared to 72.7 ± 0.8 notches/plant.

The two lentil varieties sustained very light adult feeding while almost no feeding was observed on the two chickpea varieties. Compared to pea and faba bean, adult feeding notches on lentil plants was 90% less, ranging from 3.3 ± 0.5 to 8.2 ± 1.3 notches/plant during the two-year trial period (Tables 2.2 and 2.3). A range of only 0.5 ± 0.4 to 1.6 ± 0.4 notches per chickpea plant was observed. By the 2 June 2020 and 8 June 2021, feeding on lentil and chickpea plants had ceased, since there was no notching to the clam leaves on these dates, but clam leaf feeding on faba bean and pea varieties continued. During the 2020 growing season, but not 2021, adult PLWs appeared to prefer feeding on the faba bean clam leaves as notching was 4 to 10 times higher on the 2 June compared to the pea variety clam leaves ($p= 0.05$, Tukey HSD test) (Tables 2.2 and 2.3).

Similar to adult feeding, the range of larval populations at the first sampling date was higher in 2020 compared to 2021 (Tables 2.4 and 2.5). The average number of larvae per pea plant ranged from 4.0 ± 1.5 to 12.4 ± 4.2 on 23 June 2020 and 1.6 ± 1.0 to 4.8 ± 1.1 on 25 June 2021 (Appendix B2). Three to four weeks later (10 July 2020 and 20 July 2021) the number of larvae per pea plant decreased, ranging from 0 to 1.5 ± 0.5 and 0 to 1.2 ± 0.6, respectively. Consistent with decreasing numbers of larvae, pupae and newly eclosed adults were recovered from the soil surrounding pea plants on the second evaluation date (Tables 2.4 and 2.5). Variety effects on larvae/plant, nodules/plant, pupae/plant and adults/plant were not significant at the second sampling date for either experimental year ($P > 0.05$). Nodules/plant on the first sampling date in 2021 also was not a significant factor, and nodules per plant in 2020 was significantly different only between Greenwood (25.9 ± 3.8) and the two lentil varieties (‘Pennell’, 8.4 ± 3.4; and ‘CDC Richela’, 9.8 ± 3.3) (Tables 2.4 and 2.5).

During the first sampling date in 2020 faba bean plants had about 80% fewer larvae compared to the pea varieties, 1.6 ± 0.5 and 1.5 ± 0.9, respectively (Table 4) (Appendix B1). The number of larvae per faba bean plant did not decline on the second sampling date in 2020 (2.0 ± 1.5 and 1.3 ± 1.6) and fewer pupae were recovered. During 2021 essentially no larvae were recovered from the two faba bean varieties (Table 2.5). Similarly, essentially no larvae, pupae or newly eclosed adults were recovered from lentil and chickpea plants in 2020 or 2021.

The number of nodules per plant was counted at the same time larvae were dissected from root samples stored at 4 °C. Storing nodules under these conditions does not impede their accurate assessment.[5] During the first larval damage assessment the average number of nodules per plant (field pea varieties) ranged from 12.8 ± 5.1 to 25.9 ± 3.8 in 2020 and 9.3 ± 3.2 to 14.2 ± 0.3 in 2021 (Tables 2.4 and 2.5) (Appendix B1 and B2). The highest numbers in 2020 were recorded from Greenwood (25.9 ± 3.8) and Delta (24.3 ± 2.4) while SW Arcadia had the fewest in 2020 that is 12.8 ± 5.1. The highest numbers of nodules in 2021 was recorded from CDC Treasure (14.2 ± 0.3) and AC Agassiz (14.1 ± 1.7) while SW Arcadia (9.3 ± 3.2) had the fewest in 2021 (Appendix B3).

During the second larval damage assessment the average number of nodules per plant (field pea varieties) ranged from 11.0 ± 1.3 to 16.5 ± 2.1 in 2020 and 5.4 ± 2.1 to 11.7 ± 2.6 in 2021 (Table 4 and 5) (Appendix B2, Appendix B4). The highest numbers of nodules in 2020 were recorded from Delta (16.3 ± 1.9) and Lifter (16.5 ± 2.1) while SW Arcadia had the fewest in 2020 (11.0 ± 1.3). The highest numbers of nodules in 2021 was recorded from Majoret (11.7 ± 2.6) and Hampton (11.5 ± 1.2) while Delta (5.4 ± 2.1) had the fewest in 2021.

Discussion

Pea leaf weevil populations at the experimental site were high in 2020 and 2021, providing sufficient pest pressure to evaluate the different pulse crops and field pea varieties.[42] Larval populations in 2020 reached an average of 12.4 ± 4.2 per pea plant, approximating the estimated carrying capacity of pulse crop root systems where the nitrogen fixing nodules are a limiting resource.[37] This dryland production site supported these high larval populations despite the low average rainfall in the 2020 growing season, half that compared to long-term average. Dry vs. wet growing seasons are not believed to favor PLW populations.[5] During the following 2021 season PLW populations were noticeably lower, adult feeding on pea foliage was ca. 23-30% less and ca. 60% fewer larvae were collected. While the 2021 growing season received more precipitation compared to 2020, June 2021 received less than ¼ of the June 2020 rainfall; adequate soil moisture during late May to early July may be an important factor for larval development and survival.[5] In addition, lower temperatures during May 2021 (last frost was June 6th) compared to May 2020, followed by higher average daily temperatures during June and July 2021, may have reduced the duration of adult activity and pest pressure compared to 2020.

Therefore, air temperature is important as it influences severity of PLW.[46] During both years adult pheromone trap catches were highest during the first two weeks of June.

Breeding programs that produce crop varieties able to resist pest damage through non-preference or negative effects on insect development have been one cornerstone of IPM programs.[47] A few laboratory and field studies have suggested host preference based on adult PLW feeding varies between different cultivars. Studies of pea and broad bean cultivars in Poland provided evidence that some were preferred over others by the adults.[48,49] Preference of adult feeding on different varieties of non-reproductive hosts (white clover, *Trifolium repens* and lupin, *Lupinus mutabilis*) has also been demonstrated.[50,51] This study evaluated adult feeding and larval numbers on 10 field pea varieties common to Montana and the region (9 semi-leafless and one true leaf variety). Large numbers of adult feeding notches were recorded on pea plants during both experimental years and the results were consistent between the 9 semi-leafless varieties (averages ranging from 73.3 – 86.3 notches per plant in 2020 and 56.2 – 70.8 in 2021) with no significant differences. Lifter, a pea variety with normal leaflets, had statistically significantly greater numbers of notches during both years, averaging 135.5 and 95.0 notches per plant in 2020 and 2021, respectively (Tukey HSD test, $p = 0.05$). However, the stipules of Lifter are larger compared to the semi-leafless varieties, providing additional area for adult feeding, a factor that cannot be eliminated in this study. The lack of any significant difference in notching to the developing clam leaves between the 9 semi-leafless varieties and Lifter suggests that preference was not the cause of the higher observed number of notches per plant. These results agree with Tulisalo and Markkula (1970)[52], where no differences in adult feeding were observed between 84 different pea varieties and lines tested in Finland.

Food resources, specifically the seasonal availability of N-fixing root nodules and their total number per plant, correlate to the numbers of PLW larvae that can develop successfully on a root system.[37,53–55]. Differences between pea varieties in the number of larvae supported could also indicate additional genetic factors that might limit larval development. Significant differences in the number of root nodules per pea plant variety were not detected in either year. While not statistically different, SW Arcadia recorded the fewest nodules at the first assessment date in both years, but the numbers of larvae recovered from this variety were not the fewest observed, suggesting root nodules between different varieties was not a limiting factor. The number of larvae recovered from each variety was variable, ranging from an average of 4.0 - 12.4 per pea plant in 2020 and 1.6 -4.8 in 2021, and no significant differences were detected. Collectively these results suggest no evidence for resistance to PLW adults or larvae among the pea varieties tested. Future efforts to identify traits that provide resistance to PLW, that incorporate greater genetic diversity such as wild progenitor germplasm or biotechnological approaches, may be more fruitful.

During the late summer and early fall season when the next emerged generation is preparing to overwinter adult PLW feed more broadly on a variety of legume species.[19,30,56,57] After spring emergence and mating, however, adults prefer to feed specifically on reproductive hosts that stimulate female egg production.[2,20,22,23,58,59] Pea and bean plants are the two known primary reproductive hosts of the PLW[1–3,20,60] and this study included two faba bean (small seed high tannin varieties), chickpea and lentil varieties. Consistent with prior studies, adult PLW feeding on the non-reproductive chickpea and lentil hosts was significantly lower compared to peas (Tukey HSD test, $p = 0.05$). At least 97.2 – 98.8% fewer notches were recorded on lentil plants compared to peas, consistent with reports that PLW adults only feed on lentils under no-choice conditions.[30] No pupae and only a couple of larvae were recovered from the 20 lentil plots planted over two years. After harvesting a pea crop, adult PLWs have been reported to migrate into chickpea fields where they feed and lay eggs, raising concerns that chickpea could become a reproductive host.[29] Notching of the chickpea varieties tested in this study was as much as 9 times greater compared to lentil but remained at least 94% lower compared to peas. Almost no larvae were recovered from the 20 chickpea plots but a few pupae were recovered in 2021. With the exception of the lentil variety Pennell no notching was observed on the lentil and chickpea clam leaves, suggesting that the limited feeding that was observed occurred at earlier crop stages.

Faba bean is reported to be equal or better compared to pea as a reproductive host for PLW.[59] Notching of ‘Snowbird - a medium seed size zero tannin variety of faba bean - was approximately double of that recorded for the pea variety CDC Meadow when planted side-by-side in a recent insecticide trial (untreated controls, 50.8 vs 26.2 average notches, respectively).[42] In our study, small seed faba varieties with high seed tannin content were used (accession numbers PI222216 and XXXYYY from the Plant Introduction Station in Pullman, Washington and propagated by Dr. Perry Miller at Montana State University). In our comparison notching to the faba bean varieties was not significantly different from the pea varieties. Interestingly, and contrary to Willsey et al. (2021)[42], the number of larvae recovered from the faba beans plots was quite low, less than half of lowest value from the pea varieties in 2020 and an average of 0 and 0.3 in 2021 (compared to the lowest value of 1.6 from the pea varieties). Due to plot variation, statistically significant differences resulted only between the highest pea variety values (Majoret in 2020 and AC Agassiz in 2021) and the faba bean varieties, $p = 0.05$, Tukey HSD test. Different development times between pea and faba bean and the availability of suitable root nodules for newly hatched larvae may be one factor affecting the number of larvae collected. Faba bean tended to have fewer nodes at the first assessment date compared to peas, particularly in 2021 when early spring temperatures were cool (7 of 10 pea varieties has significantly more nodes compared to faba bean in 2021, $p = 0.05$, Tukey HSD test). Adult PLW have been reported to shift hosts during the reproductive period apparently in response to nutritional quest in the foliage that may reflect quality of the root system/nodules for developing larvae.[61] Here it is interesting to note that in 2020 (but not 2021) adults clearly preferred feeding on the faba bean clam shell leaves (an indicator of recent feeding) compared to peas. Preference of PLW for its reproductive hosts may be influenced by interactions between variety and growing conditions that affect host suitability for larval development.

Further studies on host plant preference and PLW development may provide a basis to develop pest management approaches based on trap crops and push-pull strategies. Planting the boarder of spring wheat fields with varieties that attract ovipositing females has been developed in Montana as a strategy to reduce damage caused by the wheat stem sawfly within the field.[62,63] In the case of the PLW, field boarders planted with early emerging spring or winter varieties, or a mixture of reproductive host plant varieties that mature at different rates, may attract and concentrate ovipositing females. This strategy could be used in conjunction with insecticide treatments to the boarder plants and application of the aggregation pheromone. In this study PLW adults fed on the faba bean varieties but commensurate numbers of larvae were not collected from the plots. Determining whether females oviposit in the direct vicinity after feeding on a reproductive host, and subsequent survival of newly hatched larvae on the root nodules of small seed high tannin varieties, may help guide future trap crop studies.

Acknowledgements

Support for this research was provided by a NIFA Montana grant through award Grant19SCG04712, Department of Agriculture/ MT Specialty Crop Block program. The authors would like to Ruth O'Neill and Mary Ellen Holmes for helping and providing valuable comments.

Conflict of Interest

The authors declare no conflict of interests.

REFERENCES CITED

1 Baliddawa C, Movement and feeding activity of adult pea leaf weevil, *Sitona lineatus* L. in an oat-broadbean diculture. *Insect Sci Application* **5**:33–39 (1984).

2 Landona F, Levieux J, Huignard J, Rougon D, and Taupin P, Feeding activity of *Sitona lineatus* L. (Col., Curculionidae) on *Pisum sativum* L. (Leguminosae) during its imaginal life. *Journal of Applied Entomology* **119**:515–522 (1995).

3 Cárcamo HA, Vankosky MA, Wijerathna A, Olfert OO, Meers SB, and Evenden ML, Progress toward integrated pest management of pea leaf weevil: A Review. *Annals of the Entomological Society of America* **111**:144–153 (2018).

4 Hoebeke ER and Wheeler AG, *Sitona lineatus* (L.) .The pea leaf weevil: first records in eastern North America (Coleoptera : Curculinoidae). *Proc Entmol Soc Wash* **87**:216–220 (1985).

5 Olfert O, Weiss RM, Cárcamo HA, and Meers S, The influence of abiotic factors on an invasive pest of pulse crops, *Sitona lineatus* (L.) (Coleoptera: Curculionidae), in North America. *Psyche (London)*, Hindawi Limited (2012).

6 Prochaska TJ, Knodel JJ, and Beauzay PB, Integrated pest management of pea leaf weevil in North Dakota, 2018. https://www.ag.ndsu.edu/publications/crops/integrated-pest-management-of-pea-leaf-weevil-in-north-dakota [accessed 30 May 2019].

7 Prescott HW and Reehher MM, THE PEA LEAF WEEVIL, an introduced pest of legumes in the Pacific Northwest. *USDA* 1233-36 (1961).

8 Aeschlimann J, The *Sitona* [Col.: Curculionidae] species occurring on Medicago and their natural enemies in the Mediterranean region. *Entomophaga* **25**:139–153 (1980).

9 El-Dessouki SA, The effect of some *Sitona* spp. larvae on leguminous plants. *Z Angew Entomol* **67**:411–431 (1971).

10 Cárcamo H and Meers S, The first insect pest of pulse crops in Alberta: the pea leaf weevil. *Agronomy Update* 82–88 (2007).

11 US Department of Agriculture National Agricultural Statistics Service, (2021).

12 US Department of Agriculture National Agricultural Statistics Service, (2022).

13 Tallman S, Small-seeded fava bean as cash crop and within cover crop mixture, *United States Department of Agriculture*, 2017. https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/mtpmcsr13232.pdf [accessed 12 December 2021].

14 Pepper JL, Diversity and community assemblages of -dwelling beetles and spiders on fragmented grasslands of southern Saskatchewan grasslands of southern Saskatchewan, *Proquest Dissertations and Theses* **MQ45339** (1999).

15 Cárcamo H and Vankosky M, Managing the pea leaf weevil in field peas. *Prairies Soil and Crops Journal* **4**:77–85 (2011).

16 Historical Pea Leaf Weevil Forecast Maps, *Alberta Agriculture and Forestry*, 2017.

17 Wanner K, Pea Leaf Weevil, *MontGuide*, 2016. https://agresearch.montana.edu/wtarc/producerinfo/entomology-insect-ecology/PeaLeafWeevil/MontGuide.pdf [accessed 8 July 2019].

18 Statistics Canada & Agriculture and agri-food Canada, Area, yield, production of canadian principal field crops report. *Reports and Statistics Data for Canadian Principal Field Crops*: 2019–2020 (2021).

19 Jackson DJ, Bionomics of weevils of the genus *Sitones* injurious to leguminous crops in Britain. *Annals of Applied Biology* **7**:269–298 (1920).

20 Schotzko DJ and O’Keeffe LE, Reproductive system maturation and changes in flight muscles of female pea leaf weevils (Coleoptera: Curculionidae). *Ann Entomol Soc Am* **79**:109–111 (1986).

21 Oelke EA, Oplinger ES, Hanson CV, Davis DW, Putnam DH, Fuller EI, and Rosen CJ. Dry field pea, *Alternative Field Crops Manual*, 1991. https://hort.purdue.edu/newcrop/afcm/cowpea.html [accessed 2 October 2021].

22 Fisher JR and O’keeffe LE, Seasonal migration and flight of the pea leaf weevil, *Sitona lineatus* (Coleoptera: Curculionidae) in Northern Idaho and Eastern Washington. *Ent exp & appl* **26**:189–196 (1979).

23 Hamon N, Bardner R, Allen-William L, and Lee J, Flight periodicity and infestation size

of *Sitona lineatus*. *Annals of Applied Biology* **111**:271–284 (1987).

24 Otani J, Pea Leaf Weevil : *Sitona lineatus* Linnaeus Monitoring Protocol, *Prairies Pest Monitoring Network*, 2013. https://www.westernforum.org/Documents/IPMN Protocols/2011_PeaLeafWeevil protocol.pdf [accessed 26 May 2019].

25 Biniaś B, Gospodarek J, and Rusin M, Effect of water extract from mint on selected crop pests feeding and survival. *Journal of Ecological Engineering* **18**:119–128 (2017).

26 Williams L, Schotzko DJ, and O'Keeffe LE, Pea leaf weevil herbivory on pea seedlings: effects on growth response and yield. *Entomologia Experimentalis et Applicata* **76**:255–269 (1995).

27 Blight MM and Wadhams LJ, Male produced aggregation pheromone in pea and bean weevil, *Sitona lineatus* (L.). *Journal of Chemical Ecology* **13**:733–739 (1987).

28 Smart LE, Blight MM, Pickett JA, and Pye BJ, Development of field strategies incorporating semiochemicals for the control of the pea and. *Crop Protection* **13**:127–135 (1994).

29 Williams III L and Schotzko D, Chickpea, *Cicer arietinum:* a new host for the pea leaf weevil, *Sitona lineatus*. *Field Crops Research* **27**:377–380 (1991).

30 Schotzko DJ and O'Keeffe LE, Effects of food plants and duration of hibernal quiescence on reproductive capacity of pea leaf weevil (Coleoptera: Curculionidae). *J Econ Entomol* **81**:490–496 (1988).

31 Johnson M and O'Keeffe L, Presence and possible assimilation of *Rhizobium leguminosarum* in the gut of pea leaf weevil, *Sitona lineatus,* larvae. *Entomologia Experimentalis et Applicata* **29**:103–108 (1981).

32 George KS, Root nodule damage by larvae of *Sitona lineat*us and its effect on yield of green peas. *Plant Pathology* **11**:172–176 (1962).

33 Hamon N, Allen-Williams L, Lee J, and Bardner R, Larval instar determination of the pea and bean weevil *Sitona lineatus* L. (Coleoptera: Curculionidae). *Entomologist's Monthly Magazine* **120**:167–171 (1984).

34 Jensen E, Eckholdt A, and Ravn H, Dankse plantaevaernskonference sygdomme og skadedyrs / The pea leaf weevil and N2-fixation in peas of 6th Danish Plant Protection

Conference: Pests and Diseases, Statens Planteavlsforsoeg, Lyngby (Denmark).- Lyngby, **5:** 229–237 (1989).

35 Cárcamo HA, Herle CE, Lupwayi NZ, and Weintraub P, *Sitona lineatus* (Coleoptera: Curculionidae) Larval feeding on *Pisum sativum* L. affects soil and plant nitrogen. *Journal of Insect Science* **15**:74–78, Library of the University of Arizona (2015).

36 Endres G, Forster S, Kandel H, Pasche J, Wunsch M, Knodel J, *et al.*, Field pea production. *North Dakota State University*, 2016. www.ag.ndsu.edu [accessed 20 June 2021].

37 Nielsen BS, Yield responses of *Vicia faba* in relation to infestation levels of *Sitona lineat*us L. (Col., Curculionidae). *J Appl Ent* **110**:398–407 (1990).

38 Corre-Hellou G and Crozat Y, N2 fixation and N supply in organic pea (*Pisum sativum* L.) cropping systems as affected by weeds and pea weevil (*Sitona lineatus* L.). *European Journal of Agronomy* **22**:449–458, Elsevier (2005).

39 Gospodarek J, Boligłowa E, and Gleń K, Comparison of the non-chemical and chemical method for broad bean protection against *Sitona* spp. / Porównanie niechemicznego i chemicznego sposobu ochrony bobu przed oprzędzikami (*Sitona* spp.). *Progress in plant protection/ Postepy w ochronie roślin* **52**:26–30 (2012).

40 Borowiecki J and Księżak J, Stan badań nad oprzędzikiem pręgowanym (*Sitona lineatus* L .) — szkodnikiem grochu. *Zakład Uprawy Roślin Pastewnych* **8**:100–110 (2001).

41 Seidenglanz M, Rotrekl J, Smýkalová IVA, Poslušná J, and Kolařík P, Differences between the effects of insecticidal seed and foliar treatments on pea leaf weevils (*Sitona lineatus* L.) in the field pea (*Pisum sativum* L.). *Plant Protection Science* **46**:25–33, Czech Academy of Agricultural Sciences (2010).

42 Willsey T, Patey J, Vucurevich C, Chatterton S, and Carcamo H, Evaluation of foliar and seed treatments for integrated management of root rot and pea leaf weevil in field pea and faba bean. *Crop Protection* **143**, Elsevier Ltd (2021).

43 Steene F van de, Vulsteke G, Proft M de, and Callewaert D, Seed coating to control the pea leaf weevil , *Sitona lineatus* (L.) in pea crops / Saatgutpillierung zur Bekämpfung des Gestreiften Blattrandkäfers Sitona lineatus (L.) in Erbsenfeldern. *Journal of Plant Diseases and Protection* **106**:633–637 (1999).

44 Vankosky M, Dosdall L, and Cárcamo H, Distribution, biology and integrated management of the pea leaf weevil, *Sitona lineatus* L. (Coleoptera: Curculionidae), with an analysis of research needs. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* **4** (2009).

45 Briggs H, Insecticide resistance in pea and bean weevil detected in UK. *Farmer Guardian*, 2015. https://www.fginsight.com/news/news/insecticide-resistance-in-pea-and-bean-weevil-detected-in-uk-3819 [accessed 6 May 2021].

46 Almogdad M and Semaškien R, Abundance, Harmfulness, and control of pea leaf weevil in broad beans (*Vicia faba* Linn.). *Agriculture* **12**:394 (2022).

47 Pedigo LP and Rice ME, Entomology and Pest Management, 6th Edition, Upper Saddle River, N.J. : Pearson Prentice Hall, ©2009 (2009).

48 Kordan B and Sledź D, Food preferences of pea weevil (*Sitona lineata* L.) and its survival on different pea (*Pisum sativum* L.) cultivars in laboratory conditions. *Acta Academiae Agriculturae ac Technicae Olstenensis* **59**:107–113 (1994).

49 Wojciechowicz-Zytko E, Młynarczyk M, The preference of different broad bean cultivars by *Sitona lineatus* L. (Coleoptera: Curculionidae). *Journal of Plant Protection Research* **42**:81–89 (2002).

50 Cantot P and Papineau J, Discrimination of lupins with low alkaloid contents by adults of *Sitona lineatus* L. (Col. Curculionidae). *Agronomie* **3**:937–940 (1983).

51 Murray P, Evaluation of a range of varieties of white clover for resistance to feeding by weevils of the genus *Sitona*. *Plant Varieties and Seeds* **9**:9–14 (1996).

52 Tulisalo U and Markkula M, Resistance of pea to the pea weevil, *Sitona lineatus* (L.) (Col., Curculionidae). *Annales Agriculturae Fenniae* **3**:139–141 (1970).

53 El-Dessouki SA and Stein W, Intraspecific competition between larvae of *Sitona* spp . (Col ., Curculionidae). *Oceologia* **6**:106–108 (1970).

54 Quinn MA and Hower AA, Effects of root nodules and taproots on survival and abundance of *Sitona hispidulus* (Coleoptera: Curculionidae) on *Medicago sativa*. *Ecological Entomology* **11**:391–400 (1986).

55 Wolfson JL, Impact of rhizobium nodules on *Sitona hispidulus*, the clover root curculio.

Entomologia Experimentalis et Applicata **43**:237–243 (1987).

56 Murray P and Clements R, Studies on the feeding of *Sitona lineatus* L. (Coleoptera: Curculionidae) on white clover (*Trifolium repens* L.) seedlings. *Annals of Applied Biology* **121**:233–238 (1992).

57 Vankosky MA, Cárcamo HA, and Dosdall LM, Identification of potential natural enemies of the pea leaf weevil, *Sitona lineatus* L. in western Canada. *Journal of Applied Entomology* **135**:293–301 (2010).

58 Hans H, Beitrage zur Biologie von *Sitona lineatus*. Zeitschrift für angewandte. *Entomologie* **44**:343–386 (1959).

59 Jaworska M, The laboratory preference of annual legumes by pea weevil *Sitona lineatus* L. (Col., Curculionidae) and their effect on susceptibility of weevils to entomogenous nematodes. *Journal of Invertebrate Pathology* **71**:248–250 (1998).

60 Bogdan J, Pea leaf weevil pulse knowledge. *Saskatchewan Pulse Growers* 1-5 (2018).

61 Magdalena Jaworska V, Über den befall einjähriger leguminosen durch den erbsenrüßler, *Sitona lineatus* L. (Col., Curculionidae). *Anz Schadlingskde, Pflanzenschutz, Umweltschutz* **65**:70–72, Verlag Paul Parey (1992).

62 Buteler M, Weaver DK, Bruckner PL, Carlson GR, Berg JE, and Lamb PF, Using agronomic traits and semiochemical production in winter wheat cultivars to identify suitable trap crops for the wheat stem sawfly. *Canadian Entomologist* **142**:222–233 (2010).

63 Beres BL, Dosdall LM, Weaver DK, Cárcamo HA, and Spaner DM, Biology and integrated management of wheat stem sawfly and the need for continuing research. *Canadian Entomologist* **143**:105–125 (2011).

Table 2.1. Total monthly precipitation (mm) and average daily temperature (°C) during January to August 2020 and 2021 at the Montana State University Arthur H. Post Agronomy Farm compared to the long-term average for the period 1958 to 2021.

Month	Total monthly precipitation (mm)			Average daily temperature (°C)		
	2020	2021	1958-2021	2020	2021	1958-2021
Jan	7.9	18.5	13.2	-0.6	-2.4	-5.0
Feb	21.3	22.6	13.5	-2.9	-8.2	-2.9
Mar	31.5	14.5	25.9	0.9	2.9	1.1
Apr	22.1	27.9	42.4	5.6	5.9	5.8
May	19.8	78.9	66.0	11.5	10.1	10.7
Jun	92.7	20.3	67.8	15.3	18.6	15.0
Jul	16.8	21.1	32.2	18.3	22.5	18.9
Aug	14.2	52.1	31.2	20.3	18.4	18.4

Table 2.2. Plant growth and adult pea leaf weevil damage in 2020. Number of leaves/plant, nodes/plant, adult feeding notches/plant, and notches/clam leaf were determined in the laboratory after subsampling 10 plants per plot on 2 June 2020 (10 field pea and two faba bean, lentil and chickpea varieties). Plant feeding damage scores were visually determined within-field on 31 May using a 0-5 scale (Supplementary Table 1). Values for each plot are an average of 10 plants/plot, n = 4 plots/variety ($\bar{x}$ ± SE).

Variety	Leaves/plant	Nodes/plant	Notches/plant	Notches/clam	Damage score
AC Agassiz	11.0 ± 0.5a	5.7 ± 0.3bcdef	86.3 ± 3.3b	2.9 ± 0.9bcd	3.6 ± 0.3c
Aragorn	8.6 ± 0.3bcde	4.2 ± 0.1ef	77.4 ± 2.4b	5.8 ± 0.5b	3.7 ± 0.2c
CDC Treasure	10.2 ± 0.5abc	5.6 ± 0.3cdef	77.0 ± 3.7b	2.2 ± 0.8bcd	3.6 ± 0.3c
Delta	11.2 ± 0.8a	5.1 ± 0.4cdef	82.8 ± 6.4b	1.8 ± 0.5bcd	3.6 ± 0.1c
DS Admiral	10.9 ± 0.4ab	5.5 ± 0cdef	81.9 ± 6.1b	2.0 ± 0.4bcd	3.5 ± 0.2c
Greenwood	11.4 ± 0.4a	6.0 ± 0.3bcde	83.5 ± 6.5b	2.4 ± 0.8bcd	3.8 ± 0.2bc
Hampton	9.5 ± 0.5abcd	4.7 ± 0.2def	83.5 ± 8.1b	5.0 ± 0.9bc	3.7 ± 0bc
Lifter	10.6 ± 0.3ab	6.9 ± 0.2abc	142.4 ± 10.5a	1.3 ± 0.5cd	3.9 ± 0.1abc
Majoret	10.6 ± 0.7ab	5.4 ± 0.3cdef	73.3 ± 4.7b	2.9 ± 0.4bcd	3.7 ± 0.1bc
SW Arcadia	10.3 ± 0.2abc	4.9 ± 0.2def	75.7 ± 3.3b	3.6 ± 0.5bcd	3.9 ± 0.1abc
Faba bean 1	8.0 ± 0.3cde	4.0 ± 0ef	69.8 ± 4.1b	17.5 ± 2.6a	4.5 ± 0.1a
Faba bean 2	7.5 ± 0.5de	4.2 ± 0.1f	66.0 ± 5.6b	20.0 ± 0a	4.5 ± 0.1ab
Pennell [1]	7.0 ± 0.4e	6.1 ± 0.7bcd	4.3 ± 0.7c	0d	0.5 ± 0.1d
CDC Richela [1]	6.8 ± 0.3e	5.4 ± 0.4cdef	8.2 ± 1.3c	0d	0.6 ± 0.1d
Sierra [2]	8.6 ± 0.4bcde	7.6 ± 0.9ab	0.9 ± 0.4c	0d	0.1± 0d
CDC Orion [2]	9.7 ± 0.2abcd	8.6 ± 0.6a	0.6 ± 0.2c	0d	0d

[1] Lentil

[2] Chickpea

Table 2.3. Plant growth and adult pea leaf weevil damage in 2021. Number of leaves/plant, nodes/plant, Adult feeding notches/plant, and notches/clam leaf were determined in the laboratory after subsampling 10 plants per plot on 8 June 2021 (10 field pea and two faba bean, lentil and chickpea varieties). Plant feeding damage scores were visually determined within-field on 2 June using a 0-5 scale (Supplementary Table 1). Values for each plot are an average of 10 plants/plot, n = 4 plots/variety ($\bar{x}$ ± SE).

Variety	Leaves/plant	Nodes/plant	Notches/plant	Notches/clam	Damage score
AC Agassiz	12.8 ± 0.2a	6.4 ± 0.1cd	66.4 ± 5.5b	4.2 ± 1.0ab	3.7 ± 0.2c
Aragorn	12.7 ± 0.4a	6.1 ± 0.3cd	65.5 ± 5.8b	5.9 ± 1.5ab	3.8 ± 0.1c
CDC Treasure	11.9 ± 1.6abc	5.8 ± 0.7cde	57.0 ± 9.0b	6.6 ± 3.1a	4.0± 0bc
Delta	12.1 ± 0.9abc	5.8 ± 0.7cde	64.3 ± 10.0b	5.3 ± 1.2ab	3.9 ± 0.1bc
DS Admiral	13.5 ± 0.2a	6.5 ± 0.1bcd	63.9 ± 7.4b	4.2 ± 0.8ab	3.7 ± 0.2c
Greenwood	13.7 ± 0.4a	6.8 ± 0.1bcd	64.3 ± 4.1b	5.3 ± 1.0ab	3.7 ± 0.1c
Hampton	11.8 ± 0.4abc	6.0 ± 0.2cd	57.3 ± 4.1b	7.3 ± 1.3a	3.8 ± 0.1c
Lifter	12.2 ± 0.5ab	5.7 ± 0.3de	95.0 ± 8.6a	5.5 ± 2.0ab	3.6 ± 0.1c
Majoret	14.2 ± 0.4a	7.1 ± 0.2bcd	70.8 ± 7.3ab	3.8 ± 0.5ab	3.9 ± 0.1bc
SW Arcadia	12.2 ± 0.3ab	6.1 ± 0.2cd	56.2 ± 2.5b	7.1 ± 0.7a	3.9 ± 0.1bc
Faba bean	7.7 ± 0.6d	3.6 ± 0.2f	39.2 ± 2.2b	5.9 ± 1.3ab	4.6 ± 0.1a
Faba bean ss	8.5 ± 0.8cd	4.1 ± 0.1ef	72.7 ± 0.8ab	5.4 ± 0.7ab	4.3 ± 0.1ab
Pennell [1]	9.3 ± 0.7bcd	8.0 ± 0b	6.5 ± 2.3c	0.2 ± 0.2b	0.1 ± 0.1d
CDC Richela [1]	8.2 ± 0.2d	7.3 ± 0.1bc	3.3 ± 0.5c	0b	0d
Sierra [2]	11.3 ± 0.1abc	10.3 ± 0.1a	1.6 ± 0.4c	0b	0d
CDC Orion [2]	12.0 ± 0.1abc	11.2 ± 0.3a	0.5 ± 0.4c	0b	0d

[1] Lentil

[2] Chickpea

Table 2.4. Pea leaf weevil development and root nodulation, 2020. Larvae/plant and nodules/plant were recorded on 23 June 2020 and larvae/plant, nodules/ plant, pupae/plant and newly emerged adults/plant were recorded on 10 July 2020, from 5 subsampled plants/plot (10 field pea and two faba bean, lentil and chickpea varieties). Values for each plot are an average of 5 plants/plot, n = 4 plots/variety ($\overline{x}$ ± SE).

Variety	23 June		10 July		
	Larvae/plant	Nodules/plant	Larvae/plant[a]	Nodules/plant[b]	Pupae/plant[c]
AC Agassiz	4.0 ± 1.5abc	20.9 ± 3.1ab	1.2 ± 1.1	13.7 ± 0.8	0.6 ± 0.4
Aragorn	6.5 ± 2.0abc	19.5 ± 4.3ab	0.4 ± 0.2	15.8 ± 1.7	1.7 ± 0.6
CDC Treasure	4.4 ± 1.1abc	17.0 ± 2.9ab	0.8 ± 0.5	13.0. ± 0.8	2.3 ± 0.8
Delta	11.5 ± 2.4ab	24.3 ± 1.3ab	0.2 ± 0.1	16.3 ± 1.9	4.8 ± 2.4
DS Admiral	10.8 ± 2.9ab	18.2 ± 1.4ab	0	12.9 ± 1.9	0
Greenwood	10.2 ± 3.2ab	25.9 ± 3.8a	0.6 ± 0.6	15.4 ± 1.2	1.8 ± 1.8
Hampton	8.1 ± 1.9abc	20.5 ± 8.5ab	0.4 ± 0.2	14.3 ± 2.0	0.8 ± 0.8
Lifter	10.4 ± 1.8ab	20.2 ± 1.4ab	0.3 ± 0.3	16.5 ± 2.1	3.5 ± 2.0
Majoret	12.4 ± 4.2a	24.0 ± 1.8ab	0.2 ± 0.1	11.4 ± 1.7	2.8 ± 1.3
SW Arcadia	9.1 ± 2.4abc	12.8 ± 5.1ab	1.5 ± 0.5	11.0 ± 1.3	1.3 ± 0.7
Faba bean 1	1.6 ± 0.5bc	13.4 ± 1.1ab	2.0 ± 1.5	13.7 ± 1.6	0.4 ± 0.4
Faba bean 2	1.5 ± 0.9bc	10.2 ± 2.2ab	1.3 ± 0.6	19.8 ± 5.9	0.1 ± 0.1
Pennell [1]	0c	8.3 ± 3.4b	0	12.6 ± 0.8	0
CDC Richela [1]	0.1 ± 0.1c	9.8 ± 3.3b	0	9.5 ± 0.4	0
Sierra [2]	0.2 ± 0.1c	12.0 ± 2.2ab	0.3 ± 0.3	16.1 ± 3.0	0
CDC Orion [2]	0c	12.5 ± 2.0ab	0	17.3 ± 1.3	0

[1] Lentil

[2] Chickpea

[a, b, c] Means in columns followed by the same letter are not significantly different according to Tukey's HSD test (P ≤ 0.05).

Table 2.5. Pea leaf weevil development and root nodulation, 2021. Larvae/plant and nodules/plant were recorded on 25 June 2021 and larvae/plant, nodules/ plant, pupae/plant and newly emerged adults/plant were recorded on 20 July 2021, from 5 subsampled plants/plot (10 field pea and two faba bean, lentil and chickpea varieties). Values for each plot are an average of 5 plants/plot, n = 4 plots/variety ($\overline{x}$ ± SE).

Variety	25 June		20 July			
	Larvae/plant	Nodules/plant	Larvae/plant	Nodules/plant	Pupae/plant	Adults/plant
AC Agassiz	4.8 ± 1.1a	14.1 ± 1.7	0.3 ± 0.2ab	8.3 ± 2.8	0.3 ± 0.3	0
Aragorn	2.7 ± 1.1ab	12.6 ± 0.8	0.3 ± 0.2ab	10.6 ± 1.6	0.1 ± 0.1	0
CDC Treasure	3.5 ± 0.6ab	14.2 ± 0.3	0.1 ± 0.1b	7.4 ± 2.9	0.1 ± 0.1	0
Delta	3.8 ± 0.9ab	13.6 ± 0.1	0b	5.4 ± 3.2	0.5 ± 0.5	0.1 ± 0.1
DS Admiral	2.2 ± 1.0ab	12.7 ± 0.6	0.1 ± 0b	9.9 ± 3.7	0.1 ± 0.1	0.1 ± 0.1
Greenwood	2.8 ± 1.4ab	13.6 ± 0.9	0.1 ± 0.1b	11.3 ± 1.6	0.6 ± 0.4	0
Hampton	1.6 ± 1.0ab	11.7 ± 4.6	1.2 ± 0.6a	11.5 ± 1.8	0.3 ± 0.3	0
Lifter	3.2 ± 0.8ab	13.7 ± 0.9	0.2 ± 0.1b	10.6 ± 1.0	0.3 ± 0.3	0.2 ± 0.1
Majoret	2.5 ± 0.7ab	13.6 ± 0.6	0b	11.7 ± 3.9	0.3 ± 0.2	0.3 ± 0.3
SW Arcadia	4.3 ± 1.6ab	9.3 ± 3.2	0.1 ± 0.1b	10.7 ± 0.7	0.3 ± 0.3	0
Faba bean	0b	9.4 ± 3.3	0b	9.8 ± 4.5	0	0
Faba bean ss	0.3 ± 0.1b	8.5 ± 3.1	0b	4.4 ± 2.6	0	0
Pennell [1]	0b	6.9 ± 2.6	0b	8.0 ± 1.7	0	0
CDC Richela [1]	0b	9.1 ± 1.0	0b	9.9 ± 1.8	0	0
Sierra [2]	0b	9.3 ± 0.6	0b	8.9 ± 0.6	0.1 ± 0.1	0
CDC Orion [2]	0b	6.1 ± 0.4	0b	8.3 ± 3.0	0	0

[1] Lentil

[2] Chickpea

[a, b, c] Means in columns followed by the same letter are not significantly different according to Tukey's HSD test (P ≤ 0.05).

Table 2.6. Supplementary Table 1.1. Planting and field sampling dates in 2020 and 2021 at the Montana State University Arthur H. Post Agronomy Farm.

Task	2020	2021
Planting	27 April	29 April
Install pheromone traps	12 May	26 May
Empty traps 1	19 May	2 June
Empty traps 2	27 May	14 June
Empty traps 3	3 June	24 June
Empty traps 4	11 June	11 July
Empty traps 5	20 June	20 July
Adult damage assessment	2 June	8 June
Rating scale	31 May	3 June
1st larval damage	23 June	25 June
2nd larval damage	10 July	20 July
Yield	8 August	

Table 2.7. Supplementary Table 1.2. Definition of six categories (0-5) used to visually rate overall plant feeding by adult pea leaf weevil.

Feeding Damage	Definition
0	0 notches/plant
1	< 3 notches/plant
2	> 5 notches/plant
3	Most leaves have several notches
4	Notches circles most leaves
5	Defoliated plant

Table 2.8. Supplementary Table 1.3. Grain yield (g) in 2020 from a 2 m^2 area subsampled from the 3rd and 4th row of each plot, n = 4 plots/variety ($\bar{x}$ ± SE).

Variety	Grain yield (g/2 m^2)
AC Agassiz	393.3 ± 26.1a
Aragorn	270.8 ± 25.5abc
CDC Treasure	381.1 ± 40.0a
Delta	338.6 ± 15.4a
DS Admiral	331.9 ± 48.2a
Greenwood	396.4 ± 31.1a
Hampton	352.7 ± 36.6a
Lifter	278.7 ± 19.5ab
Majoret	328.2 ± 29.0a
SW Arcadia	299.1 ± 35.9ab
Faba bean 1	92.2 ± 6.0c
Faba bean 2	125.8 ± 12.7bc
Pennell [1]	329.3 ± 35.5a
CDC Richela [1]	353.8 ± 44.6a
Sierra [2]	316.0 ± 52.5a
CDC Orion [2]	355.4 ± 57.7a

[1] Lentil

[2] Chickpea

Figure 2.1. Adult pea leaf weevil pheromone trap catches in **A)** 2020 **B)** 2021. Values represent the number of adults accumulated between sampling dates, reported on the day were emptied, n = 4 traps in 2020 and 5 traps in 2021 (x̅ ± SE).

A. B.

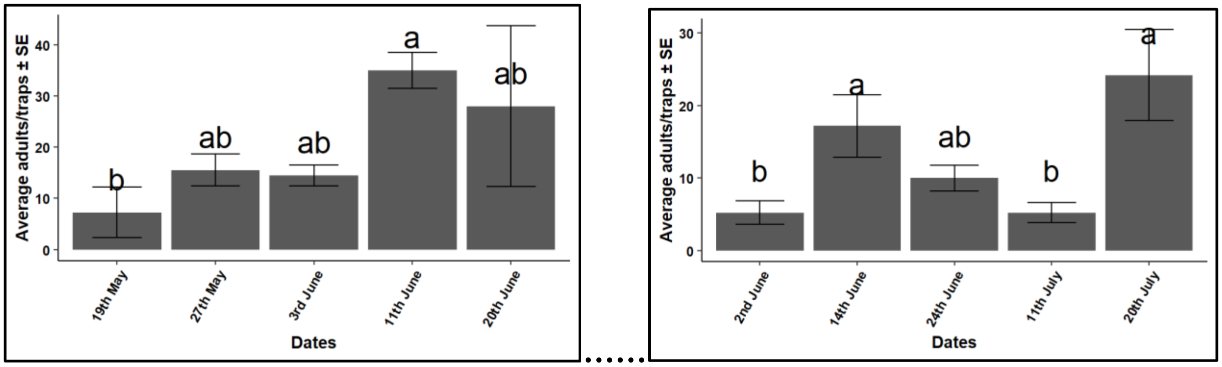


Figure 2.2. Correlation coefficient of average notches/plant with average leaves/plant in field pea varieties in **A)** 2020 **B)** 2021 during adult damage assessment.

A. B.

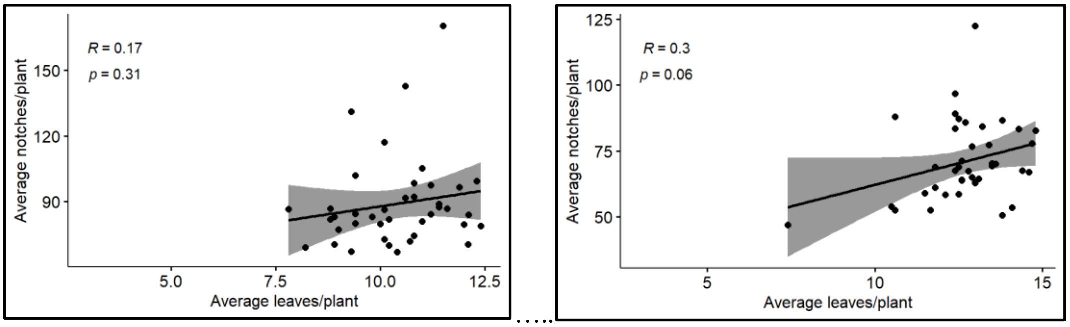
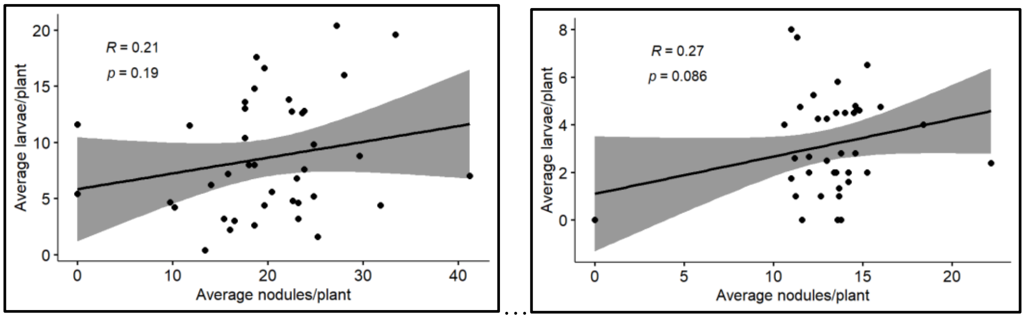
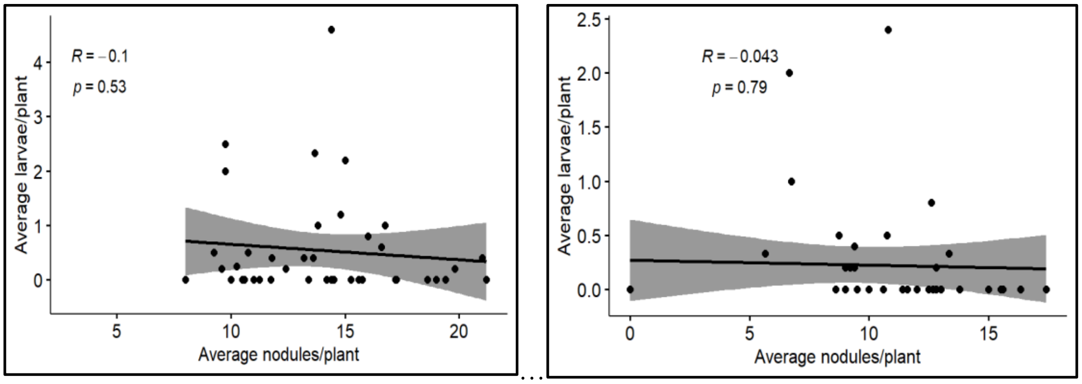


Figure 2.3. Correlation coefficient of average larvae/plant with average nodules/plant in field pea varieties in **A)** 2020 **B)** 2021 during first larval damage assessment.


A.

B.

Figure 2.4. Correlation coefficient of average larvae/plant with average nodules/plant in field pea varieties in **A)** 2020 **B)** 2021 during second larval damage assessment. r represents the correlation coefficient.


A.

B.

Figure 2.5. Supplementary Figure 1. Geographic location of field plots at the Montana State University Arthur H. Post Agronomy Farm.

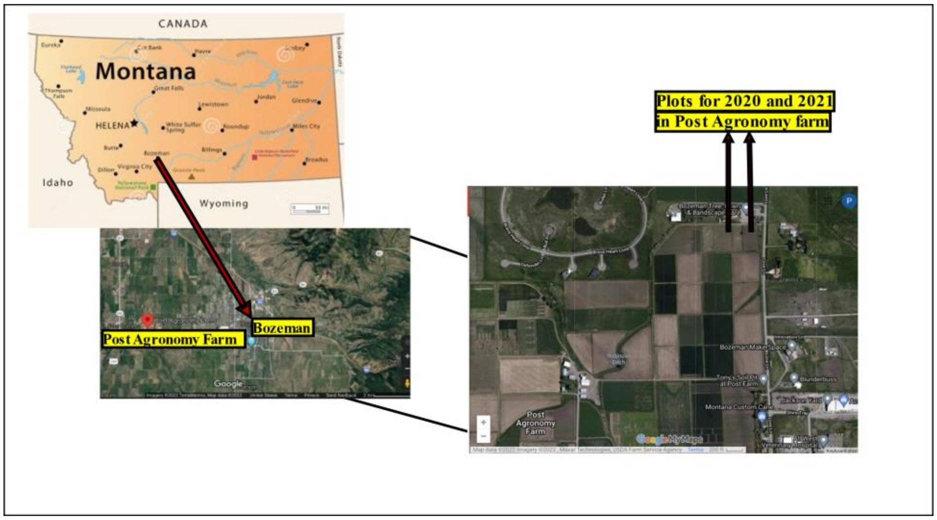


Figure 2.6. Supplementary Figure 2.**A)** Adult Pea leaf weevil and **B)** Adult Pea leaf weevil mating on pea.

A.

B

Figure 2.7. Supplementary Figure 3. Pea leaf weevil larvae **A)** under electron microscope and **B)** inside root nodules under electron microscope.

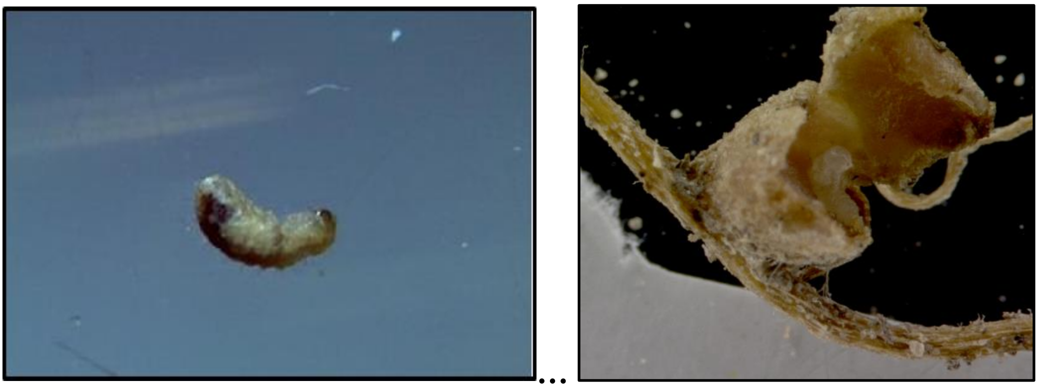


Figure 2.8. Supplementary Figure 4. **A)** Notches made by adult pea leaf weevil on pea plant and **B)** Vegetative structure of pea plant.

A.

B.

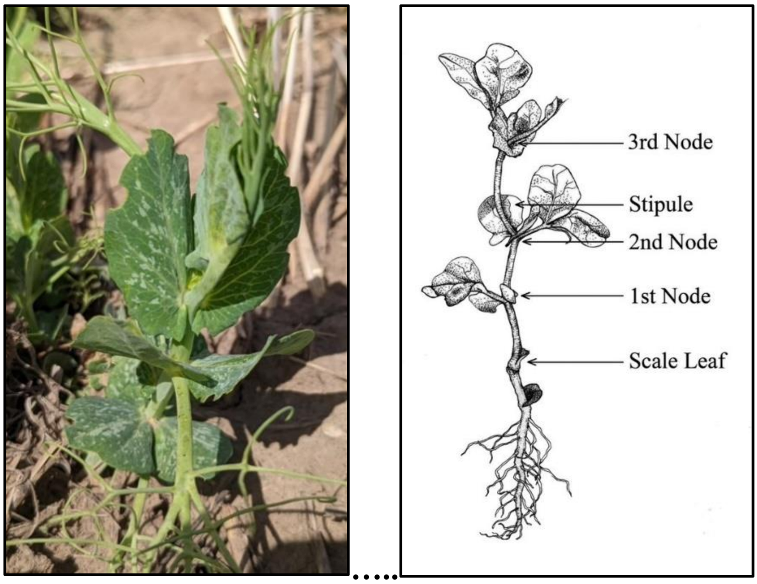


Figure 2.9. Supplementary Figure 5.A) Notches made by adult pea leaf weevil on faba bean and **B)** Pea leaf weevil mating on faba bean.

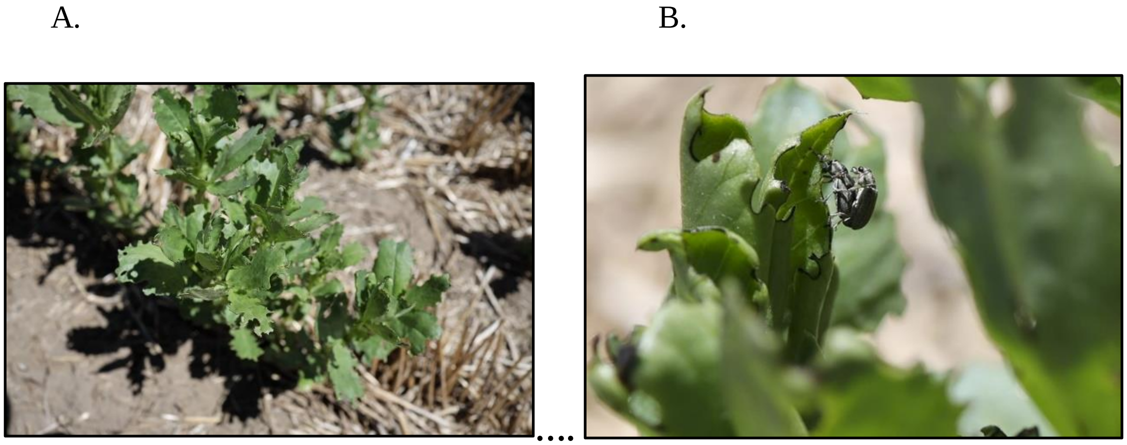


Figure 2.10. Supplementary Figure 6. Growth stage of lentil, faba bean, pea and chickpea when visual damage assessment for rating scale and adult damage assessment of pea leaf weevil was conducted.

CHAPTER THREE

FIELD EFFICACY OF PEA LEAF WEEVIL AGGREGATION PHEROMONE COMBINED WITH CONTACT INSECTICIDE AS AN ATTRACT-AND-KILL METHOD, 2020

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

Author: Pragya Kiju

Contributions: Investigation, Data curation, Software, Visualization, Writing – original draft

Co-Author: Kevin Wanner

Contributions: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing

Co-Author: G.V.P Reddy

Contributions: Resources, Supervision

Manuscript Information

Pragya Kiju, Kevin Wanner, G.V.P Reddy

Arthropod Management Test

STATUS OF MANUSCRIPT:

___ Prepared for submission to a peer-reviewed journal
____ Officially submitted to a peer-reviewed journal
____ Accepted by a peer-reviewed journal
____x _ Published in a peer-reviewed journal

[Arthropod Management Test]
[3/22/2022]

A field experiment was conducted to assess the efficacy of an aggregation pheromone combined with a contact insecticide as an attract-and-kill method to reduce adult pea leaf weevil (PEA LEAF WEEVIL) populations. The attractant, PEA LEAF WEEVIL aggregation pheromone (4–methyal-3,5-heptanedione) was provided by ChemTica International (Heredia Province, Santo Domingo, Costa Rica), as plastic pellet (Appendix C2 B), and rubber septa formulations (Appendix C2 A). DeltaGard G Insecticide Granules (0.1% deltamethrin) were used as a contact insecticide. The objective of this field experiment was to assess and demonstrate the potential of an attract-and-kill strategy as a new PEA LEAF WEEVIL management tactic to reduce pest pressure using adult aggregation pheromone.

The field site was located at the Montana State University Arthur Post Agronomy Farm, Bozeman, Montana, where field peas have been grown with a consistent history of PEA LEAF WEEVIL infestation. As a low-cost approach, pheromone baits and granular insecticide were placed in the bottom of small circular pits dug into the soil measuring 5 cm deep and 6 cm in diameter. Six treatments were placed in the bottom of these simple pit fall traps: 1) one pheromone pellet plus insecticide; 2) three pheromone pellets plus insecticide; 3) five pheromone pellets plus insecticide; 4) one pheromone rubber septum plus insecticide; 5) one pheromone rubber septum and no insecticide; and 6) insecticide only. Treatments with insecticide received 0.3 gram of DeltaGard G Insecticide Granules. Treatments were replicated four times in a Complete Randomized Block Design (CRBD) during the 2020 field season. An experimental block consisted of six pitfall traps spaced 10 m apart along a linear transect, with four parallel transects separated by 10 m representing the four replicated blocks. The first treatments were placed in the field on May 11th, 2020 and evaluated every 8-10 days from May 18th to June 19th,

2020. During each evaluation PEA LEAF WEEVIL adults were collected from the pitfall traps and stored in the lab in 95% ethanol, counted, and identified (Appendix C1). The male:female ratio was approximately even. PEA LEAF WEEVIL counts were entered and analyzed in R studio cloud version 4.0.3 (R Studio team, 2020). The response variable, the total number of adult PEA LEAF WEEVIL collected, was transformed on a log scale (Total+1) to normalize the distribution for general linear modelling using ANOVA, followed by a post-hoc Tukey HSD test.

Treatment and assessment date were statistically significant factors in this experiment, $p < 0.001$ (Table 1). Experimental block was not a significant factor. Treatment 5, pheromone rubber septum only, trapped the fewest PEA LEAF WEEVIL while Treatment 4, pheromone rubber septum plus granular insecticide trapped the highest number of PEA LEAF WEEVIL (Table 2), significant at $p = 0.05$, Tukey HSD test. Treatment 5 results can be explained by attraction of PEA LEAF WEEVIL to the pheromone rubber septum, and subsequent dispersal away in the absence of a contact insecticide. However, Treatment 4 resulted in higher mortality and higher numbers of adult PEA LEAF WEEVIL recovered from the pitfall traps. PEA LEAF WEEVIL counts in Treatment 6, insecticide only, reflect incidental trap catches from adults crawling on the ground. After the first incidental catch, Treatment 6 pitfall traps may have become attractive if the trapped PEA LEAF WEEVIL emitted pheromone naturally. The number of PEA LEAF WEEVIL adults trapped using the pheromone pellets was more variable. Only Treatment 2, three pheromone pellets plus insecticide, was significantly different from Treatment 5, pheromone rubber septum alone ($p = 0.05$, Tukey HSD test) and it was not significantly different from Treatment 6, insecticide only. In general, PEA LEAF WEEVIL trap catches were the highest on the first assessment date and declined in number each successive collection date

(Table 2). Field observations of PEA LEAF WEEVIL feeding damage and mating adults indicated that activity extended well into June. The successive decline in PEA LEAF WEEVIL adult counts can be explained by degradation of the pitfall traps that were not replenished with pheromone and insecticide. Declining pheromone levels, degradation of the simple soil pits by weather erosion and declining insecticidal activity could all explain sequentially lower trap catches during the experimental period. Better performance of pitfall traps baited with larger pheromone rubber septum suggests higher pheromone release rates may enhance PEA LEAF WEEVIL attract-and-kill strategies. Results from this preliminary study have demonstrated the potential of PEA LEAF WEEVIL aggregation pheromone as an attract-and-kill method under field conditions. Future research is needed to determine optimal field application methods to dispense the pheromone attractant and insecticide treatments for suppression of adult populations below economically damaging levels. Combining attract-and-kill and push-pull strategies to concentrate adult PEA LEAF WEEVIL populations migrating into emerging field pea crops may be an effective approach.

This research was supported by a MT Specialty Crop Block Program through award Grant 19SCG04712, United States Department of Agriculture (NIFA).

Table 3.1. Analysis of variance (ANOVA) showing the effects of block and date on treatment in 2020 at Montana State University Arthur H. Post Agronomy Farm.

ANOVA factor	Sum of squares	Degrees Freedom	F- value	p-value
Treatment	24.891	5	13.76	6.8e-10
Date	17.710	4	12.23	6.1e-8
Block	1.685	3	1.55	0.21

Table 3.2. Average number of adult pea leaf weevil collected in six different treatments (n -4) through attract and kill method in 2020 at Montana State University Arthur H. Post Agronomy Farm.

Treatment number	Materials	Total PEA LEAF WEEVIL Counts	Average PEA LEAF WEEVIL Counts (n=4)	Weekly PEA LEAF WEEVIL counts (Average, n=4)				
				18th May	26th May	2nd Jun	10th Jun	19th Jun
1	1 Pheromone pellet + insecticide	7	1.4bc	0.5	0.75	0	0	0.5
2	3 Pheromone pellets + insecticide	54	10.6b	6	3.75	3.5	0	0
3	5 Pheromone pellets + insecticide	24	4.8bc	4.67	1	0.75	0	0.25
4	Pheromone septum + insecticide	157	31.4a	22.5	12.5	4.75	1	0
5	Pheromone septum only	1	0.2c	0	0.25	0	0	0
6	Insecticide only	20	4bc	1.5	1.5	0	1.5	0.5

CHAPTER FOUR

SUMMARY

Growers in Canada, Montana and North Dakota have expanded the range of pea production in recent years. This has increased the area for legume production and suitable climatic conditions may have allowed increased pea leaf weevil populations to develop. Pea leaf weevil damage across the pulse crops has been rising across Montana. Adult pea leaf weevil damage is not considered as economic as larval pea leaf weevil damage. Pea leaf weevil larvae reduce photosynthetic capacity of the defoliated leaves impact root nodulation, yellowing of leaves, nitrogen deficiency and reproductive organ development thus leading to decrease in yield. Larval growth and density are affected by host species, variety, soil condition, plant growth stage, root nodule availability, carrying capacity of the host. Abiotic factors like temperature, precipitation influences the adult and larval feeding behavior.

In this study, among four pulse crops, adult pea leaf weevil concentrated its feeding in pea and faba bean. To some extent adult feeding was seen in chickpea followed by lentil. While among 10 varieties of pea, Lifter had the highest number of notches. This might be due to Lifter being true leaf variety and having more surface area for adult feeding as it has bigger stipules. Similarly in case of larval feeding, this study shows pea leaf weevil preferring peas in the early growth stage (1st larval damage assessment, 4-6 node stage) which shifted to faba bean at the later growth (2nd larval damage assessment, flowering stage) as when pupae were found in field pea, only larvae were found in faba beans during second larval damage assessment (flowering stage). This shows that faba beans can support pea leaf weevil development for a longer period. Larval damage among field pea varieties was not seen statistically significant.

Integrated pest management of pea leaf weevil has been focused on larval damage of pea leaf weevil since it causes economic damage. Foliar application, input of nitrogen, cultural and biological control are some of the tools that has been tested against managing pea leaf weevil population. Semiochemical management is also another method for effective management of pea leaf weevil where aggregation pheromone (4–methyal-3,5-heptanedione) is deployed. Pea leaf weevil are sensitive to host plant odor (*cis*-3-hexen-1-yl) which is produced by peas in higher quantity compared to other leguminous crops. Incorporating aggregation pheromone, host plant volatiles in attract and kill, and push-pull strategies may be an effective approach to concentrate adult pea leaf weevil populations migrating into emerging field pea crops.

Further research efforts are needed to understand the effect of temperature on relationship between damage and population density of pea leaf weevil. Distribution maps of pea leaf weevil would have been effective to forecast weevil population density if these relationships were known which would have guided insecticide application for effective management of pea leaf weevil. Research focusing on development of a quantitative model that helps to estimate adult weevil population in spring will be effective. Since, pea leaf weevil larvae are concealed inside root nodules in soil, chemical control of pea leaf weevil populations is difficult and expensive. Combining trap crops (faba bean) with a pheromone increases effectiveness as it attracts more pea leaf weevil to the trap crops. There should be more investigation on the effect of tillage on pea leaf weevil population. Further research efforts are needed to understand the impact of soil nitrogen on plant yield and pea leaf weevil populations since little research has been done in this area. The pheromone monitoring system could be used to detect adult pea leaf weevil invasions in areas where they are expected. This study focuses on adult and larval damage assessment which is labor intensive and time inefficient. Therefore, alternative ways for effective damage assessment should be explored and more research is needed.

REFERENCES CITED

Abbo, S., D. Shtienberg, J. Lichtenzveig, S. LevYadun, and A. Gopher. 2003. The chickpea, summer cropping, and a new model for pulse domestication in the ancient near east. The Quarterly Review of Biology. 78: 435–448.

Abou-Khater, L., F. Maalouf, A. Jighly, D. Rubiales, and S. Kumar. 2022. Adaptability and stability of faba bean (*Vicia faba* L.) accessions under diverse environments and herbicide treatments. Plant*s*. 11.

Aeschlimann, J. P. 1980. The *Sitona* (Col.: Curculionidae) species occurring on Medicago and their natural enemies in the Mediterranean region. Entomophaga. 25: 139-153.

Agelopoulos, N., M. A. Birkett, A. J. Hick, A. M. Hooper, J. A. Picket, E. M. Pow, L. E. Smart, D. W. M. Smiley, L. J. Wadhams, and C. M. Woodcock. 1999. Exploiting semiochemicals in insect control. Pesticide Science. 55: 225-235.

Ahmadi, A. A., and M. Alichi. 1991. The *Sitona* (Coleoptera, Curculionidae) fauna of Fars Province. [Proceedings of the Tenth Plant Protection Congress of Iran, 1-5 September 1991], University of Shahid Bahonar.

Almogdad, M., and R. Semaškien. 2022. Abundance, Harmfulness, and Control of Pea Leaf Weevil in Broad Beans (*Vicia faba* Linn.). Agriculture. 12: 394.

Ambrose, M. J. 1995. From near east center of origin the prized pea migrates throughout world. Diversity. 11: 118-119.

Andersen, K. T. 1934. Experimentelle untersuchungen u¨ ber den einfluss der temperatur auf die eierzeugung von insekten. i. einfluss konstanter temperaturen auf die eierzeugung von *Sitona lineata* L. Biologisches zentralblatt. 54: 478–86.

Anonymous. 2008. Pea leaf weevil in southwest Saskatchewan [cited 12 February 2008]. Saskatchewan Agriculture and Food Available from: URL: http://www.saskpulse.com/media/pdfs/070625_ PeaLeafWeevil_in_Sask_-_SAF.pdf.

Antonelli, A. Pea leaf weevil: Its biology and control. 1970. Washington State University Cooperative Extension.

Arnett, R. H. Jr. 1960. The beetles of the United States (a manual for identification). Catholic University of America Press, Washington, DC.

Bahl, P. N., S. Lal, and B. M. Sharma. 1993. An overview of the production and problems in southeast Asia.1–10 pp. *In*: W Erksine and M C Saxena (eds.) Lentil in South Asia. Proceedings of the seminar on lentils in South Asia. ICARDA, Aleppo, Syria.

Baker, T. C. 2008. Use of pheromones in IPM. *In*: Radcliffe, E. B., W. D. Hutchison, and R. E. Canceladi (Eds.) Integrated Pest Management: Concepts, Tactics, Strategies and Case Studies. Cambridge University Press. 273-285 pp.

Baliddawa, C. W. 1984. Movement and feeding activity of adult pea leaf weevil, *Sitona lineatus* L. in an oat-broadbean diculture. Insect Science and its Application. 5: 33–39.

Baliddawa, C. W. 1988. The effect of crop microenvironment on the pea leaf weevil's behaviour: an explanation for weevil departure from diverse cropping systems. Insect Science and its Application. 9: 509-514.

Bardner, R., K. E. Fletcher, and D. C. Griffiths. 1983. Chemical control of the pea and bean weevil, *Sitona lineatus* L., and subsequent effects on the yield of field beans, *Vicia faba* L. J. Agr. Sci. 101: 71–80.

Barulina, E. I. 1930. The lentils of the USSR and other countries. Tr Po Prikl Bot Genet Sel [Bull Appl Genet & Select] Suppl 40: 1–319 [Russian]Cambridge.

Barzman, M., P. Barberi, A. N. E. Birch, P. Boonekamp, S. Dachbrodt-Saaydeh, B. Graf, B. Hommel, J. E. Jensen, J. Kiss, P. Kudsk, J. R. Lamichhane, A. Messean, A. C. Moonen, A. Ratnadass, P. Ricci, J. L. Sarah, and M. Sattin. 2015. Eight principles of integrated Pest management. Agronomy for Sustainable Development. 35: 1199-1215.

Beniwal, S. P. S., B. Bayaa, S. Weigand, K. H. Makkouk, and M. C. Saxena. 1993. Field guide to lentil diseases and insect pests. http:/www.icarda.org/Publications/Field_Guide/Lentil/Lentil.html.

Beres, B. L., L. M. Dosdall, D. K. Weaver, H. A. Cárcamo, and D. M. Spaner. 2011. Biology and integrated management of wheat stem sawfly and the need for continuing research. Canadian Entomologist**.** 143: 105–125.

Bethlenfalvay, G. J., S. S Abu-Shakra, and D. A. Phillips. 1978. Interdependence of nitrogen nutrition and photosynthesis in *Pisum sativum* L. Plant Physiol. 62: 131-133.

Biniaś, B., J. Gospodarek, and M. Rusin. 2017. Effect of water extract from mint on selected crop pests feeding and survival. Journal of Ecological Engineering. 18: 119–128.

Bjostad, L. B., B. E. Hibbard, and W. S. Cranshaw. 1993. Application of semiochemicals in integrated pest management programs. *In*: Duke, S. O., J. J. Menn, J. R. Plimmer. (Eds.). Pest Control with Enhanced Environmental Safety. American Chemical Society, USA. 199-218 pp.

Blaser-Diekmann, M. 1982. Survey on pests and diseases of faba beans (*Vicia faba*) in Egypt, Morocco and Tunisia. Fabis Newsletter, No. 4: 44-45.

Blatchley, W. S. and C. W. Leng. 1916. Rhynchophora or weevils of North Eastern America. New York Entomological Society. 24: 81-84.

Blight M. M., J. A. Pickett, M. C. Smith and L. J. Wadhams. 1984. An aggregation pheromone of *Sitona lineatus*: Identification and initial field studies. Naturwissenschaften. 71: 480.

Blight, M. M., and L. J. Wadhams. 1987. Male-produced aggregation pheromone in pea and bean weevil, *Sitona lineatus* (L.). Journal of Chemical Ecology. 13: 733-739.

Blight, M., G. W. Dawson, J. A. Pickett, and L. J. Wadhams. 1991. The identification and biological activity of the aggregation pheromone of *Sitona lineatus*. Aspects Applied Biology. 27: 137-142.

Bloem, S., R. F. Mizell, and C. W. O'Brien. 2002. Old traps for new weevils: new records for curculionids (Coleoptera: Curculionidae), brentids (Coleoptera: Brentidae) and anthribids (Coleoptera: Anthribidae) from Jefferson Co., Florida. Florida Entomologist. 85: 632–44. https://doi.org/10.1653/0015-4040(2002)085[0632:OTFNWN]2.0.CO;2.

Bogdan, J. 2018. Pea Leaf Weevil, Pulse Knowledge. Saskatchewan Pulse Growers. 1-5 pp.

Boroumand, H. 1975. Key to the groups and species of the genus *Sitona* (Col. - Curculionidae) in Iran. Journal of the Entomological Society of Iran. 2: 67-68.

Borowiecki, J., and J. Księżak. 2001. Stan badań nad oprzędzikiem pręgowanym (*Sitona lineatus* L .) — szkodnikiem grochu.. Zakład Uprawy Roślin Pastewnych. 8: 100–110.

Botha, J., D. Hardie, and F. Casella. 2004. The pea leaf weevil, *Sitona lineatus*: exotic threat to Western Australia. Government of Western Australia Department of Agriculture. Factsheet No. 11.

Briggs, H. 2015. Insecticide resistance in pea and bean weevil detected in UK. Farmer Guardian. https://www.fginsight.com/news/news/insecticide-resistance-in-pea-and-bean-weevil-detected-in-uk-3819 [accessed 6 May 2021].

Bright, D. E. 1994. Revision of the Genus *Sitona* (Coleoptera: Curculionidae) of North America. Annals Entomological Society. Am. 87: 277-306.

Bullock, D. G. 1992. Crop rotation. Critical Review. Plant Science. 11: 309–326.

Buteler, M., D. K. Weaver, P. L. Bruckner, G. R. Carlson, J. E. Berg, and P. F. Lamb. 2010. Using agronomic traits and semiochemical production in winter wheat cultivars to identify suitable trap crops for the wheat stem sawfly. Canadian Entomologist. 142: 222–233.

Buttery, B., and A. Gibson. 1990. The effect of nitrate on the time course of nitrogen fixation and growth in *Pisum sativum* and *Vicia faba*. Plant Soil. 127: 143–146.

Cantot, P., and J. Papineau. 1983. Discrimination des lupins a basse teneur en alcaloides par les adultes de *Sitona lineatus* L. (Col. Curculionidae); Discrimination of lupins with low alkaloid contents by adults of *Sitona lineatus* L. (Col. Curculionidae). Agronomie. 3: 937–940.

Cantot, P. 1986. Action larvaire de *Sitona lineatus* L. sure quelques facteurs de production du pois proteagineux (*Pisum sativum* L.). Agronomie. 9: 765-70.

Caracuta, V., M. Weinstein-Evron, D. Kaufman, R. Yeshurun, J. Silvent, and E. Boaretto. 2016. 14,000-year-old seeds indicate the Levantine origin of the lost progenitor of faba bean. Science. 6: 373-99.

Cárcamo, H. A., and S. Meers. 2007. The first insect pest of pulse crops in Alberta: The pea leaf weevil. Agronomy Update. 82–88 pp.

Cárcamo, H., and M. Vankosky. 2011. Managing the pea leaf weevil in field peas. Prairies Soil and Crops Journal. 4: 77–85. www.prairiesoilandcrops.ca.

Cárcamo, H., C. Herle, and V. Hervet. 2012. Greenhouse studies of thiamethoxam effects on pea leaf weevil, *Sitona lineatus*. Journal Insect Science. 12: 151.

Cárcamo, H. A., C. E. Herle, and N. Z. Lupwayi. 2015. *Sitona lineatus* (Coleoptera: Curculionidae) larval feeding on *Pisum sativum* L. affects soil and plant nitrogen. Journal of. Insect Science. 15: 74-78.

Cárcamo, H. A., M. A. Vankosky, A. Wijerathna, O. O. Olfert, S. B. Meers, and M. L. Evenden. 2018. Progress toward integrated pest management of pea leaf weevil: A Review. Annals of the Entomological Society of America. 111: 144-153. (https://doi.org/10.1093/aesa/say007).

Casey, T. L. 1888. On some new North American Rhynchophora, part I. Annals New. York. Academic Science. 4: 229- 296.

Champion, G. C. 1902-1906. Biologia Centrali Americana. Insecta. Coleoptera. Rhynchophora. Curculionidae. Curculioninae, vol. 4, part 4, pp. i-viii, 1-144 (1902), 145-312(1903), 313-440 (1904), 441-600(1905), 601-750(1906), illus.

Chang, G. C., C. E. Rutledge, R. C. Biggam, and S. D. Eigenbrode. 2004. Arthropod diversity in peas with normal or reduced waxy bloom. Journal of Insect Sciene. 4: 18.

Chen, W., H. C. Sharma, and F. J. Muehlbauer. 2011. Compendium of chickpea and lentil diseases and pests. American Phytopathological Society. 28-29 pp.

Clark, S. 2019. Pea (*Pisum sativum* L.) characteristics for use and successful planting. Plant Material Technical Note No. 19-01. USDA. Big Flat Plant Materials Center.

Coles, K., S. Meers, and H. A. Cárcamo. 2008. Pea leaf weevils on the move in Alberta and Saskatchewan. Agronomy Update. 110–4 pp.

Corre-Hellou, G., and Y. Crozat. 2005. N2 fixation and N supply in organic pea (*Pisum sativum* L.) cropping systems as affected by weeds and pea weevil (*Sitona lineatus* L.). European Journal Agronomy. 22: 449–458.

Cousin, R. 1997. Peas (*Pisum sativum* L.). Field Crops Res. 53: 111-130.

Cubero, J. I. 1974. On the evolution of *Vicia faba* L. Theor. Applied Genetics. 45: 47–51.

Cubero, J. I. 1981. Origin, taxonomy and domestication. *In*: Webb C, Hawtin G (Eds), Lentils 15–38 pp CAB, Slough, UK.

Danthanarayana, W. 1967. Host specificity of *Sitona* beetles. Nature. 213: 1153–4.

Dean, J. R., and R. W. Clark. 1980. Journal Plant Interaction Science. 60: 121-130.

Dhull S. B., M. K. Kidwai, R. Noor, P. Chawla, and P. K. Rose. 2021. A review of nutritional profile and processing of faba bean (*Vicia faba* L.). Legume Science. Wiley.

Downes, W. 1938. The occurrence of *Sitona lineatus* in British Columbia. Canadian Entomologist. 70: 22.

El-Dessouki, S. A. and W. Stein. 1970. Intraspecific competition between larvae of *Sitona* spp . (Col ., Curculionidae). Oceologia. 6: 106–108.

El-Dessouki, S. A. 1971. The effect of some *Sitona* spp. larvae on leguminous plants. Zeitschrift fu¨r angewandte Entomologie. 67: 411–31.

El-Sayed, A. M., D. M. Sucking, C. H. Wearing and J. A. Byers. 2006. Potential of mass trapping for long-term pest management and eradication of invasive species. Journal of Economic Entomology. 99: 1550-1564.

El-Sayed, A. M., D. M. Sucking, J. A. Byers, E. B. Jang and C. H. Wearing. 2009. Potential of “lure and kill” in long-term pest management and eradication of invasive species. Journal of Economic Entomology. 102: 815-835.

Emden, M. van and Emden, F. van, 1939. Curculionidae: Brachyderinae III. In: Schenling, S. (ed.). Coleopterum Catalogous auspiciis et auxilio Dr W. Junk Publishers, The Hague, 164: 197–327 + 1–59 (index Brachyderinarum).

Endres, Gregory et al. 2016. Field pea production. North Dakota State Universtity Extension. www.ag.ndsu.edu/publications/crops/field-pea-production.

Ester, A., and G. Jeuring. 1992. Efficacy of some insecticides used in coating faba beans to control pea and bean weevil (*Sitona lineatus*) and the relation between yield and attack. FABIS Newsletter. 30: 32–41.

Etemadi, F., M. Hashemi, F. Mangan, and S. Weis. 2015. Faba beans growers guide in New England. http://ag.u mass.edu /sit es/ag.u mass.edu /files/research-re port s/faba bean guide _ 2.pdf.

Evenden, M. L. 2017. Semiochemical-based management of the pea leaf weevil (Coleoptera: Curculionidae). Annals of the Entomological of Society of America. 111: 154-160. Oxford University Press (OUP).

Fam, E. Z. 1983. Reducing losses due to insects in faba beans in Egypt. FABIS Newsletter, Faba Bean Information Service, ICARDA. 48-49.

FAOSTAT. 2019. http://www.fao.org/faostat/en/#data/QCL.

FAO. (Food and Agriculture Organization). 2020. Crop production and trade data. doi: http://www.fao.org/faostat/en/#data (accessed December 30, 2020).

FAO. 2008. Land and plant nutrition management service. Available at: www.fao.org/ag/agl/agll/spush.

FAOSTAT. 2020. http://www.fao.org/faostat/en/#data/QCL.

FAO. 2021. FAOSTATA statistical database. Retrieve d from http:/www.fao.org/faostat/.

FAOSTAT. 2022. Production of lentils in 2020. Crops/World Regions/Production Quantity from pick lists. United Nations, UN Food and Agriculture Organization, Statistics Division (FAOSTAT). Retrieved 20 March 2022.

Ferguson, A. W. 1994. Pests and plant injury on lupins in the south of England. Crop Protection. 13: 201–210.

Fisher, J. R. 1977. The population dynamics of the pea leaf weevil *Sitona lineatus* (L.) in northern Idaho and eastern Washington, Ph.D. Dissertation, University of Idaho, Moscow, Idaho, USA.

Fisher, J. R., and L. E. O'Keeffe. 1979 a. Host potential of some cultivated legumes for the pea leaf weevil, *Sitona lineatus* (L.) (Coleoptera: Curculionidae). Pan Pacific Entomologist. 55: 199–201.

Fisher, J. R., and L. E. O'Keeffe. 1979 b. Food plants of the pea leaf weevil *Sitona lineatus* (L.) (Coleoptera: Curculionidae) in northern Idaho and eastern Washington. Pan Pacific Entomologist. 55: 202–7.

Fisher, J. R., and L. E. O'Keeffe. 1979 c. Seasonal migration and flight of the pea leaf weevil, *Sitona lineatus* (Coleoptera: Curculionidae) in northern Idaho and eastern Washington. Entomology Experimental. Application. 26: 189–196.

Flowers, T. J., P. M. Gaur, and C. L. Laxmipathigowda. 2010. Salt sensitivity in chickpea. Plant Cell Environment. 33: 490–509.

George, K. S. 1962. Root nodule damage by larvae of *Sitona lineatus*, and its effect on yield of green peas. Plant Pathology. 11: 172–176.

Germar, E. F. 1817. (Note), *In* Miscellen und Correspondenz—Nachrichtenbl. Mag. Entomol. 2: 339-341.

Germar, E. F. 1824. Insectorum species novae aut minus cognitae descriptionibus illustratae. Coleoptera. 1.

Goldson, S. L., M. R. McNeill, J. R. Proffitt, and B. I. P. Barratt. 2005. Host specificity testing and suitability of a European biotype of the braconid parasitoid *Microctonus aethiopoides* as a biological control agent against *Sitona lepidus* (Coleoptera: Curculionidae) in New Zealand Biocontrol Science Technology. 15: 791-813.

Gospodarek, J., E. Boligłowa, and K. Gleń. 2012. Comparison of the non-chemical and chemical method for broad bean protection against *Sitona* spp. / Porównanie niechemicznego i chemicznego sposobu ochrony bobu przed oprzędzikami (*Sitona* spp.). Progress in plant protection/ Postepy w ochronie roślin. 52: 26–30.

Gossen, B. D., and P. R. Miller. 2004. Survival of *Ascochyta rabiei* in chickpea residue on the Canadian prairies. Canadian Journal of Plant Pathology, 26: 142-147. https://doi.org/10.1080/07060660409507125.

Greenwood, R. M., and N. O. Bathurst. 1978. Effect of rhizobial strain and host on the amino acid patterns in legume root nodules. N2. Journal Science. 21: 107-120.

Greib, V., and F. Klingauf. 1977. Untersuchungen zum Frafipflanzenspektrum von *Sitona lineatus* L. (Curculionidae: Coleoptera). Journal of Applied. Entomology. 82: 267–274.

Griffiths, D. C., R. Bardner, and J. Bater. 1986. Control *of Sitona lineatus* in autumn-sown faba beans. FABIS Newsletter. 14: 30-33.

Hamon, N., L. Allen-Williams, J. B. Lee, and R. Bardner. 1984. Larval instar determination of the pea and bean weevil *Sitona lineatus* L. (Coleoptera: Curculionidae). Entomologist's Monthly Magazine. 120: 167–171.

Hamon, N., R. Bardner, L. Allen-Williams, and J. B. Lee. 1987. Flight periodicity and infestation size of *Sitona lineatus*. Annals of Applied. Biology. 111: 271–284. doi: 10.1111/j.1744-7348.1987.tb01453.x.

Hanavan, R. P., and N. A. Bosque-Pérez. 2012. Effects of tillage practices on pea leaf weevil (*Sitona lineatus* L., Coleoptera: Curculionidae) biology and crop damage: A farm-scale study in the US Pacific Northwest. Bulletin of Entomological Research. 102: 682-691. doi:10.1017/S0007485312000272.

Hanavan, R. P., N. A. Bosque-Pérez, D. J. Schotzko, S. O. Guy, and S. D. Eigenbrode. 2008. Early-season aerial adult colonization and ground activity of *S. lineatus* (Coleoptera: Curculionidae) in pea as influence by tillage system. Journal of Economic. Entomology. 101: 1606–1613.

Hanavan, R. P., N. A. Bosque-Pérez, D. J. Schotzko, and S. D. Eigenbrode. 2010. Influence of tillage on adult and immature *S. lineatus* (Coleoptera: Curculionidae) densities in pea. Journal of Economic. Entomology. 103: 691–697.

Hanavan, R. P., and N. A. Bosque-Pérez. 2017. Influence of no-tillage practices and later planting date on the, *Sitona lineatus*, in pea, *Pisum sativum*. Entomology Exp Application. 162: 77–85.

Hanelt, P., and D. Mettin. 1989. Biosystematics of the genus *Vicia* L. (Leguminosae). Annu. Rev. Ecol. Syst. 20: 199–223.

Hans, H. 1959. Beitrage zur Biologie von *Sitona lineatus*. Zeitschrift fu¨ r angewandte Entomologie Journal of Applied Entomology. 44: 343–86.

Harlan, J. R. 1969. Ethiopia: A centre of diversity. Econ. Bot. 23: 309-14.

Harlan, J. 1971. Agricultural origins: centers and noncenters. Science. 174: 468-474.

Hartley, S. 2007. Saskatchewan insect pest report. Minutes of the 2007 Western Committee on Crop Pests, Penticton, British Columbia, 18 Oct. 2007. http://www.westernforum.org/WCCP%20Minutes.html.

Harveson, R. M. 2021. Origin, domestication, history of pea production and usage. *In* Harveson, R. M., J. S. Pasche, L. Porter, W. Chen and M. Burrows (Eds.), Compendium of Pea Diseases and Pests. 1-2 pp.

Hatch, M. H. 1971. The beetles of the Pacific North-west, part V. Rhipiceroidea, Sternoxi, Phytophaga, Rhynchophora, and Lamellicornia. in University of Washington Publication in Biology. 16.

Havlickova, H. 1980. Causes of different feeding rates of pea leaf weevil, *Sitona lineatus* on three pea cultivars. Entomologia Experimentalis et Applicata. 27: 287–92.

Havlickova, H. 1982. Different response of alfalfa plants to artificial defoliation and to feeding by the pea leaf weevil (*Sitona lineatus L*.). Experientia. 38: 569-570.

Hawthorne, W. 1987. Beans, peas, vetches and other new crops. Occasional Publication, Australian Institute of Agricultural Science. 16-22

Heath, M. C., and P. D. Hebblethwaite. 1985. Solar radiation interception by leafless and leafed peas (*Pisum sativum*) under contrasting field conditions. Annals of Applied Biology. 107: 309-318.

Heichel, G. H., and C. P. Vance. 1983. Physiology and morphology of perennial legumes. *In*: Nitrogen Fixation. Vol3: Legumes. Ed. by W. J. Broughton. Oxford: Clarendon Press.

Historical Pea Leaf Weevil Forecast Maps. 2017. Alberta Agriculture and Forestry.

Hodgson, G. L., and G. E. Blackman. 1957. An analysis of the influence of plant density on the growth of *Vicia faba* (II). The significance of competition for light in relation to plant development at different densities. Journal of Experimental Biology. 8: 195-219.

Hoebeke, E. R., and A. G. Wheeler Jr. 1985. *Sitona lineatus* (L.), The pea leaf weevil: First records in eastern North America (Coleoptera: Curculionidae). Proceedings of the Entomological Society of Washington. 87: 216-220.

Hoffmann D., Q. Jiang, A. Men, M. Kinkema, and P. M. Gresshoff PM. 2007. Nodulation deficiency caused by fast neutron mutagenesis of the model legume *Lotus japonicus.* Journal of Plant Physiology. 164:460–469.

Hokkanen, H. M. T. 1991. Trap cropping in pest management. Annual Review of Entomology. 36: 119–138.

Horst I., T. Welham, S. Kelly, T. Kaneko, S. Sato, S. Tabata, M. Parniske and T. L. Wang. 2007. Tilling mutants of *Lotus japonicus* reveal that nitrogen assimilation and fixation can occur in the absence of nodule- enhanced sucrose synthase. Plant Physiology. 144: 806–820.

Hunter, M. D. 2001. Out of sight, out of mind: the impacts of root feeding insects in natural and managed systems. Agriculture for Entomology. 3: 3–9.

Iqbal, A., I. A. Khalil, N. Ateeq, M. S. Khan. 2006. Nutritional quality of important food legumes. Food Chemistry. 97: 331–335.

Jackson, D. J., and K. S. Macdougall. 1920. Bionomics of weevils of the genus *Sitones* injurious to leguminous crops in Britain. Annals of Applied Biology. 7: 269–298. (https://doi.org/10.1111/j.1744-7348.1920.tb05310.x).

Jaworska, M. 1992. U¨ ber den Befall einja¨ hriger Leguminosen durch den Erbsenrubler, *Sitona lineatus* L. (Col., Curculionidae). Anzeiger fu¨ r Scha¨ dlingskunde, Pflanzenschutz, Umweltschutz. 65: 70–2.

Jaworska, M. 1998. The laboratory preference of annual legumes by pea weevil *Sitona lineatus* L. (Col, Curculionidae) and their effect on susceptibility of weevils to entomogenous nematodes. Journal of Invertebrate Pathology. 71: 248–250.

Jensen, E. S., A. Eckholdt, and H. P. Ravn. 1989. The pea leaf weevil and N2-fixation in peas. Dankse Plantaevaernskonference Sygdomme og Skadedyr. 5: 229–237.

Jia, Z., Y. Liu, B. D. Gruber, K. Neumann, B. Kilian, A. Graner, and N.von Wirén. 2019. Genetic dissection of root system architectural traits in spring barley. Frontiers in Plant Science. 10: 1–14. (https://doi.org/10.3389/fpls.2019.00400).

Johnson, M. P., and L. E. O'Keeffe. 1981. Presence and possible assimilation of *Rhizobium leguminosarum* in the gut of pea leaf weevil, *Sitona lineatus,* larvae. Entomologia Experimentalis et Applicata. 29: 103–108.

Jukanti, A. K., P. M. Gaur, C. L. L. Gowda, and R. N. Chibbar. 2012. Nutritional quality and health benefits of chickpea (*Cicer arietinum* L.): A review. British Journal of Nutrition. 108: 11–26.

Juncus, L. 1998. Plant Guide. Figure 3: 5–8.

Karkanis, A., G. Ntatsi, C. K. Kontopoulou, A. Pristeri, D. Bilalis, and D. Savvas. 2016. Field pea in European cropping systems: adaptability, biological nitrogen fixation and cultivation practices. Not Bot Horti Agrobot Cluj-Napoca. 44: 325– 336.

Karuppuchamy, P., and S. Venugopal. 2016. Integrated pest management: Ecofriendly pest management for food security. 651–684 pp. https://doi.org/10.1016/B978-0-12-803265-7.00021-X.

King, J. M. 1981. Experiments for the control of pea and bean weevil (*Sitona lineatus*) in peas using granular and liquid insecticides.327-331 pp. *In* Proc. 1981 British Crop Protection Conf. Pests and diseases. 11th British Insecticide and Fungicide Conf., Brighton, England. 16-19 Nov. 1981. British Crop Protection Council, Croydon, England.

Kogan, M. 1998. Integrated pest management: Historical perspectives and contemporary developments. Annual Review of Entomology. 43: 243-270.

Kordan, B., and D. Sledz´. 1994. Food preferences of pea weevil (*Sitona lineatus* L.) and its survival on different pea (*Pisum sativum* L.) cultivars in laboratory conditions. Acta Academiae Agriculturae ac Technicae Olstenensis. 59: 107–113.

Krall, James M., D. Stephen, S. D. Miller, W. Scientist and Jack T. Cecil. 2006. Pea production in the high plains. Historical Materials from University of Nebraska- Lincoln Extension. 1: 1-12.

Lacordaire, J. T. 1863. Histoire naturelle des insectes. genera des ocl^opteres ou expose m6thodique et critique de tous les genres proposes jusqu'ici dans cet ordre d'insectes, vol. 6.

Landona, F., J. Levieux, J. Huignard, D. Rougon, and P. Taupin. 1995. Feeding activity of *Sitona lineatus L*. (Col., Curculionidae) on *Pisum sativum L.* (Leguminosae) during its imaginal life. Journal of Applied Entomology. 119: 515-522.

Landona, F., S. Ferary, D. Pierre, J. Auger, J. C. Biemont, J. Levieux, et al. 1997. *Sitona lineatus* host plant odors and their components: effects on locomotor behavior and peripheral sensitivity variations. Journal of Chemical Ecology. 23: 2161–73.

Landolt, P. J., and T. W. Phillips. 1997. Host plant influences on sex pheromone behavior of phytophagous insects. Annual Revision. Entomology. 42: 371–391. doi:10.1146/annurev.ento.42.1.371.

LaRue, T. A. G., and W. G. W. Kurtz. 1973. Estimation of nitrogenase in legumes. Canadian Journal of Microbiology. 19: 304-305.

Law, J. H., and F. E. Reignier. 1971. Pheromones. Annual Review of Biochemistry. 40: 533-548.

LeConte, J. L., and G. H. Horn. 1876. The Rhynchophora of America north of Mexico. Proc. Am. Philos. Soc. 15, 96. 1883. Classification of the Coleoptera of North America. Smithson. Misc. Collect. 507.

Lee, C. 2011. Montana's pulse industry: how it has developed, economic impact and potential for growth by. Montana Department of Agriculture. 1-98 pp.

Lee, J., and C. J. P. Upton. 1992. Relative efficiency of insecticide treatments in reducing yield loss from *Sitona* in faba beans. Test Agro-chemistry Cultivars 13: 6–7.

Leport, L., N. C. Turner, S. Davies, and K. Siddique. 2006. Variation in pod production and abortion among chickpea cultivars under terminal drought. European Journal of Agronomy 24: 236-246. https://doi.org/10.1016/j.eja.2005.08.005.

Lerin, J. 2004. Modeling embryonic development in *Sitona lineatus* (Coleoptera: Curculionidae) in fluctuating temperatures. Environmental Entomology. 33: 107–112.

Leroy, T., J. Pouzat, J. C. Biemont, and D. Pierre. 1999. Variation en fonction de le’tat physiologique de la sensibilite olfactive peripherique chez quatre coleopteres, *Callosobruchus maculatus* Fab., *Bruchidius atrolineatus* Pic., *Acanthoscelides obtectus* Say (Bruchidae) et *Sitona lineatus* L. (Curculionidae). Annales de la Socie´ te´ Entomologique de France. 35 (supplement): 159–64.

Linke, K. H., Saxena, M. C., Sauerborn J., Masri H, 1991. Effect of soil solarization on the yield of food legumes and on pest control. *In*: FAO Plant Production and Protection Paper. 139-154.

Linnaeus, C. 1758. Systema naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis, ed. 10, reformata. 1: 1-823. [+1 p. (Emendanda, Addenda), unnumbered.]. Salvii, Holmiae. [Cure. pp. 377-388.].

Lodos, N. 1971. Preliminary list of Curculionidae with notes on distribution and biology of species in Turkey: 1. *Sitona* Germar. Yearbook of the Faculty of Agriculture, University of Ege. 2: 1-35.

Lohaus, K., and S. Vidal. 2010. Abundance of *Sitona lineatus* L. (Col., Curculionidae) in peas (*Pisum sativum* L.): effects on yield parameters and nitrogen balance. Crop Protection. 29: 283–289.

Magdalena J. V. 1992. Über den Befall einjähriger Leguminosen durch den Erbsenrüßler, *Sitona lineatus* L. (Col., Curculionidae). Anz Schadlingskde, Pflanzenschutz, Umweltschutz. 65: 70–72, Verlag Paul Parey.

Makasheva, R. K. 1979. Gorokh (Pea). *In* Kulturnaya Flora SSR; Korovina, O.N., Ed.; Kolos Publishing: Leningrad, Russia. 1–324 pp.

Maphosa, L., M. F. Richards, S. L. Norton, and G. N. Nguyen. 2020. Breeding for abiotic stress adaptation in Chickpea (*Cicer arietinum* L.): A comprehensive review: Crop Breeding, Genetics and Genomics. 2.

Margheim, J. F., D. D. Baltensperger, R. G. Wilson, D. J. Lyon, G. L. Hein, R. M. Harveson, P. A. Burgener, J. M. Krall, J. T. Cecil, and J. R. Rickertsen. 2004. EC04-183 Chickpea production in the high plains. University of Nebraksa- Lincoln. https://digitalcommons.unl.edu/ extensionhist/771.

Markkula, M., and P. Köppä. 1960. The composition of the *Sitona* (Col., Curculionidae) population on grassland legume and some other leguminous plants. Annales Entomologici Fennici. 26: 246–63.

Maxted, N., and N. Ambrose. 2000. Peas (*Pisum sativum* L.). Chapter 10. Plant genetic resources of legumes in the Mediterranean; N. Maxted, S. J. Bennett. Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands. Springer. 39: 181–190 pp.

Maxted, N., S. Kell, A. Toledo, E. Dulloo, V. Heywood, T. Hodgkin, D. Hunter, L. Guarino, A. Jarvis, and B. Ford-Lloyd. 2010. A global approach to crop wild relative conservation: Securing the gene pool for food and agriculture. Kew Bulletin. 65: 561–576.

McEwen, J., R. Bardner, G. G. Briggs, R. H. Bromilow, A. J. Cockbain, J. M. Day, K. E. Fletcher, B. J. Legg, R. J. Roughley, and G. A. Salt. 1981. The effects of irrigation, nitrogen fertilizer and the control of pests and pathogens on spring-sown field beans (*Vicia faba* L.) and residual effects on two following winter wheat crops. Journal of Agriculture Science. 96: 129–150.

Melamed-Madjar, V. 1966. The phenology of *Sitona* (Coleoptera: Curculionidae) in Israel. Israel Journal of Entomology. 1: 63-74.

Mínguez, M. I., and D. Rubiales. 2021. Faba bean. *In* Sadras,V. O. and D. F. Calderini (Eds.),Crop Physiology Case Histories for Major Crops. 452–481 pp. Academic Press. https://doi.org/10.1016/B978-0-12-819194-1.00015-3.

Mihailovic V., A. Mikic, B. Cupina, P. Eric. 2005. Field pea and vetches in Serbia and Montenegro. Grain Legumes. 44: 25-26.

Moreno, M., and J. I. Cubero. 1978. Variation in *Cicer arietinum* L. Euphytica 27: 465–485.

Mori, B. A., and M. L. Evenden. 2014. Mating disruption of *Coleophora deuratella* (Lepidoptera: Coleophoridae) using laminate flakes in red clover seed production fields. Pest Management Science. 71: 1149-1157.

Muehlbauer, F. J., J. I. Cubero, and R. J. Summerfield. 1985. Lentil (*Lens culinaris* Medic.). 266–311 pp *In*: R. J. Summerfield, and E. H. Roberts. (eds.), Grain Legume Crops. Collins, 8 Grafton Street, London, UK.

Muehlbauer, F. J., W. J. Kaiser, S. L. Clement, and R. J. Summerfield. 1995. Production and breeding of lentil. Advances in Agronomy. 54: 283–332.

Murray, P. and R. Clements. 1992. Studies on the feeding of *Sitona lineatus* L. (Coleoptera: Curculionidae) on white clover (*Trifolium repens* L.) seedlings. Annals of Applied Biology. 121: 233–238.

Murray, P. J., and R. O. Clements. 1995. Distribution and abundance of three species of *Sitona* (Coleoptera: Curculionidae) in grassland England. Annals of Applied Biology. 127: 229–37.

Murray, P. 1996. Evaluation of a range of varieties of white clover for resistance to feeding by weevils of the genus *Sitona*. Plant Varieties and Seeds**.** 9: 9–14.

Mutch, L. A., and P. W. Young. 2004. Diversity and specificity of *Rhizobium leguminosarum* biovar *viciae* on wild and cultivated legumes. Molecular Ecology. 13: 2435–44.

Natural History Museum. 1905. Specimen record from the collection in the Natural History Museum (London, UK)., London, UK: Natural History Museum (London).

Nielsen, B. S. 1990. Yield responses of *Vicia faba* in relation to infestation levels of *Sitona lineatus* L. (Col., Curculionidae). Journal of Applied Entomology. 110: 398–407.

Nikolova, I. M. 2016. Response of vetch varieties to *Sitona lineatus* L. in organic farming. Biology Agriculture Horticulture. 32: 63–71.

Nilsson, C. 1973. Fo¨ rekomsten ave Sitona-arter i vissa baljva¨ xtgro¨ dor (abstract). The Review of Applied Entomology Series A: Agricultural. 61: 11-49.

Nouri-Ghanbalani, G. 1978. Host plant resistance to the pea leaf weevil, *Sitona lineatus* L., in pea (*Pisum sativum* L.) and its inheritance. Dissert. Abs. Int. 545-B.

O'Brien, C. W., and G. J. Wibmer. 1982. Annotated checklist of the weevils (Curculionidae) of North America, Central America, and the West Indies (Coleoptera: Curculionidea). Memoirs of the American Entomolgical Society. 34.

Oelke, E. A., E. S. Oplinger, C. V. Hanson, D. W. Davis, D. H. Putnam, E. I. Fuller, and C. J. Rosen. 1991. Alternative field crops manual. University of Minnesota: Center for Alternative Plant and Animal Products and the Minnesota Extension Service, University of Wisconsin-Madison Extension Service.

Olfert, O., R. M. Weiss, H. A. Cárcamo, and S. Meers. 2012. The influence of abiotic factors on an invasive pest of pulse crops *Sitona lineatus* (L.) (Coleoptera: Curculionidae), in North America. Psyche. doi: 10.1155/2012/746342.

Olle, M., and P. Sooväli. 2020. The severity of field pea diseases depending on sowing rate and variety. Acta Agriculturae Scandinavica Section B Soil and Plant Science 70: 556-563. doi: 10.1080/09064710.2020.1803958.

Oplinger, E. S., L. L. S. Hardman, E. A. Oelke, A. R. Kaminski, E. E. Schulte, and J. D. Doll. 1990. Chickpeas (garbanzo bean). Alternative field crops manual. University of Wisconsin Coop. Ext., University of Minnesota Center for Alternative Plant and Animal Products and the Minnesota Extension Service.

Oschman, M. 1984: Untersuchungen zur ertragsbeeinflussung der ackerbohne (*Vicia faba* L.) durch den linierten blattrandkafer (*Sitona lineatus* L. Coleoptera, Curculionidae). Archiv fur Phytopathologie und Pflanzenschutz. 20: 371-381.

Otani, J. 2013. Pea Leaf Weevil: *Sitona lineatus* (L) Monitoring protocol. Prairie pest Monitoring network. 1-5 pp. Retrieved from https://www.westernforum.org/Documents/IPMN Protocols/2011_PeaLeafWeevil protocol.pdf [accessed 26 May 2019].

Quinn, M. A., A. A. Hower. 1986. Effects of root nodules and taproots on survival and abundance of *Sitona hispidulus* (Coleoptera: Curculionidae) on *Medicago sativa*. Ecological Entomology. 11: 391-400.

Quinn, M. A., D. F. Bezdicek, L. E. Smart, and J. Martin. 1999. An aggregation pheromone system for monitoring *S. lineatus* (Coleoptera: Curculionidae) in the Pacific Northwest. Journal of Kansas Entomological Society. 72: 315–321.

Parihar, A. K. 2020. Genetic advancement in dry pea (*Pisum sativum* L.): Retrospect and prospect. *In*: S. S, Gosal, S. H, Wani. (eds) Accelerated Plant Breeding, Volume 3. Springer. Cham. https://doi.org/10.1007/978-3-030-47306-8_10.

Pate, J. S. 1958. Australian Journal of Biology. Science. 11: 366.

Pedigo, L. P., and M. E. Rice. 2009. Entomology and Pest Management, 6th Edition, Upper Saddle River, N. J. : Pearson Prentice Hall.

Pepper, J. L. 1999. Diversity and community assemblages of -dwelling beetles and spiders on fragmented grasslands of southern Saskatchewan grasslands of southern Saskatchewan. Proquest Dissertations and Theses. MQ45339.

Pickett, J. A., C. M. Woodcock, C. A. O. Midega and Z. R. Khan. 2014. Push-pull farming systems. Current Opinion in Biotechnology. 26: 125-132.

Plaut, H. N. 1975. An unusual case of damage caused by *Sitona lineatus* L. and *Sitona crinitus* Hbst. to peanuts. Hassadeh. 55: 1567-1568.

Prescott, H. W., and M. H. Reeher. 1961. The pea leaf weevil, an introduced pest of legumes in the Pacific Northwest. U.S. Department of Agriculture Technological Bulletin. 1233-36 pp.

Prochaska, T. J., J. J. Knodel, and P. B. Beauzay. 2018. Integrated pest management of pea leaf weevil in North Dakota. North Dakota State University Extension Service. E1879. Retrieved from https://www.ag.ndsu.edu/publications/crops/integrated-pest-management-of-pea-leaf-weevil-in-north-dakota [accessed 30 May 2019].

Prochaska, T., J. Knodel, J. Janet and P. Beauzay. (n.d.). Pea leaf weevil - Farming Smarter, (1233), 12. Retrieved from http://www.farmingsmarter.com/growing-new-ideas/pea-leaf-weevil/.

Purushothaman, R., H. D. Upadhyaya, P. M. Gaur, C. L. L. Gowda, and L. Krishnamurthy. 2014. Kabuli and desi chickpeas differ in their requirement for reproductive duration. Field Crops Res 163: 24-31.

Quinn, M. A., and A. A. Hower. 1986. Effects of root nodules and taproots on survival and abundance of *Sitona hispidulus* (Coleoptera: Curculionidae) on *Medicago sativa*. Ecological Entomology. 11: 391–400.

Rahate, K. A., M. Madhumita, and P. K. Prabhakar. 2020. Nutritional composition, anti-nutritional factors, pre-treatments-cum-processing impact and food formulation potential of faba bean (*Vicia faba* L.): A comprehensive review. LWT Food Science and Technology. 138: 110796.

Rasool, S., A. A. H. A. Latef, and P. Ahmad. 2015. Chickpea: Role and responses under abiotic and biotic stress. Legumes under Environmental Stress: Yield, Improvement and Adaptations 67–79 pp.

Redden, B., N. Maxted, B. Furman, and C. Coyne. 2007. Lens biodiversity. *In*: Yadav, S. S., D. L. McNeil, P. C. Stevenson (eds) Lentil. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6313-8_2.

Rivnay, E. 1962. Field crop pests. *In*: Field crop pests in the near East. Monographiae Biologicae, vol 10. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-1544-7_3.

RStudio. 2021. A language and environment for statistical computing. Foundation Statistical Computing, Massachusetts, United States . https://www.R-project.org/.

Roy, A., K. Das, J. Kumar, and B. Rao. 2001. Dilaji: a new chickpea variety for Hills zone of Assam, India. International Chickpea and Pigeonpea Newsletter, 8: 6-7.

Rutledge, C. E., A. P. Robinson, and S. D. Eigenbrode. 2003. Effects of a simple plant morphological mutation on the arthropod community and the impacts of predators on a principal insect herbivore. Oecologia. 135: 39–50.

Sandhu, J., and S. Singh. 2007. History and Origin. *In*: Yadav, S. S., D. L. McNeil, P. C Stevenson. (eds) Lentil. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6313-8_1.

Santra, D. K., and G. Saha. 2021. Botany of pea. *In* Harveson, R. M., J. S. Pasche, L. Porter, W. Chen and M. Burrows (Eds.), Compendium of pea diseases and pests. 3-4 pp.

Sarker, A., and W. Erskine. 2006. Recent progress in the ancient lentil. Journal of Agricultural Science. 144: 19–29.

Schoenherr, C. J., L. Gyllenhaal, and C. H. Boheman. 1840. Genera et species Curculionidum, cum synonymia hujus familiae. Roret, Parisiis. Vol. II.

Schotzko, D. J., and L. E. O’Keeffe. 1986. Reproductive system maturation and changes in flight muscles of female pea leaf weevils (Coleoptera: Curculionidae). Annals of the Entomological Society of America. 79: 109–111.

Schotzko D. J., and L. E. O'Keeffe. 1988. Effects of food plants and duration of hibernal quiescence on reproductive capacity of pea leaf weevil (Coleoptera: Curculionidae). Journal of Economic Entomology. 81:490–496.

Scriber, J. M. 1984. Host plant suitability. *In*: Bell, W.J., R. T. Carde. (Eds.), Chemical Ecology of Insects. Chapman and Hall, London. 3–36 pp.

Seidenglanz, M., J. Rotrekl, I. V. A. Smýkalová, J. Poslušná, and P. Kolařík. 2010. Differences between the effects of insecticidal seed and foliar treatments on pea leaf weevils (*Sitona lineatus* L.) in the field pea (*Pisum sativum* L.). Plant Protection. Science. 46: 19–27.

Sharma, A., R. K. Sandhi, and G. V. P. Reddy. 2019. A review of interactions between insect biological control agents and semiochemicals. Insects 10. Multidisciplinary Digital Publishing Institute.

Shorey, H. H. 1977. Manipulation of insect pests of agricultural crops. *In*: Shorey, H., and J. J. McKelvey. (Eds.), Chemical Control of Insect Behaviour: Theory and Application. Wiley, New York. 353–367 pp.

Singh, K. B., and B. Ocampo. 1997. Exploitation of wild *Cicer* species for yield improvement in chickpea. Theory Applied Genetics. 95: 418–423.

Smart, L. E., M. M. Blight, J. A. Pickett, and B. J. Pye. 1994. Development of field strategies incorporating semiochemicals for the control of the pea and bean weevil, *Sitona lineatus* L. Crop Protection. 13: 127–135.

Smýkal, P., G. Aubert, J. Burstin, C. J. Coyne, N. T. H. Ellis, and A. J. Flavell. 2012. Pea (*Pisum sativum* L.) in the Genomic Era. Agronomy. 2: 74–115.

Soroka., J. J., and H. A. Cárcamo. 2006. Pea insects, ecology and control. *In*: Pimentel D, editor. Encyclopedia of Pest Management. Taylor and Francis, London. 1–4 pp.

Spaink, H. P. 1994. The molecular basis of the host specificity of the *Rhizobium* bacteria. Antoine van Leeuwenhoek International Journal of General and Molecular Microbiology. 65: 81–98.

Sprent, J. I., and A. M. Bradford. 1977. Nitrogen fixation in field beans (*Vicia faba*) as affected by population density, shading and its relationship with soil moisture. Journal of agricultural. Science Cambridge. 88: 303-310.

Statistics Canada and Agriculture and Agri-Food Canada. 2021. Area, Yield, Production of Canadian Principal Field Crops Report. Reports and Statistics Data for Canadian Principal Field Crops: 2019–2020.

Steene, F. vande., G. Vulsteke, M. de. Proft, and D. Callewaert. 1999. Seed coating to control the pea leaf weevil, *Sitona lineatus* (L.) in pea crops. Journal of Plant Diseases. Protection. 106: 633–637.

Sutton, W. D. 1983. Nodule development and senescence. *In*: Nitrogen Fixation. Vol. 3: Legumes, Ed. by W. J. Broughton. Oxford: Clarendon Press. 144-212 pp.

Szendrei, Z., and C. Rodriguez-Saona. 2010. A meta-analysis of insect pest behavioural manipulation with plant volatiles. Entomologia Experimentalis et Applicata. 134: 201-210.

Tallman, S. 2017. Small-seeded fava bean as cash crop and within cover crop mixture. United States Department of Agriculture. Retrieved from: https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/mtpmcsr13232.pdf [accessed 12 December 2021].

Taupin, P. 1994. Protection insecticide – La précision génère la marge. Perspectives Agricoles. 187:3 pp.

Tewari, S., T. C. Leskey, A. L. Nielsen, J. C. Piñero, and C. R. Rodriguez-Saona. 2014. Use of pheromones in insect pest management, with special attention to weevil pheromones. *In* Integrated Pest Management: Current Concepts and Ecological Perspective. Elsevier. 141-168 pp.

Thompson, R. T. 1992. Observations on the morphology and classification of weevils (Coleoptera, Curculionoidea) with a key to the major groups. Journal of Natural History. 26: 835-891.

Tinzaara, W., M. Dicke, A. van Huis, and C. S. Gold. 2002. Use of info chemicals in pest management with special reference to banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). Insect Science Application. 22: 241-261.

Tulisalo, U., and M. Markkula. 1970. Resistance of pea to the pea weevil, *Sitona lineatus* (L.) (Col., Curculionidae). Annales Agriculturae Fenniae. 3: 139–141.

US Department of Agriculture National Agricultural Statistics Service, (2021).

US Department of Agriculture National Agricultural Statistics Service, (2022).

van der Maesen, L. J. G. 1972. *Cicer* L., a monograph of the genus, with special reference to the chickpea (*Cicer arietinum* L.), its ecology and distribution. Mendelingen Landbouwhogeschool Wageningen, Wageningen, The Netherlands. 1–341.

Vankosky, M., L. M. Dosdall, and H. A. Cárcamo. 2009. Distribution, biology and integrated management of the pea leaf weevil, *Sitona lineatus* L. (Coleoptera: Curculionidae), with an analysis of research needs. *In* CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources (Vol. 4). https://doi.org/10.1079/PAVSNNR20094007.

Vankosky, M. A., H. A Cárcamo, and L. M. Dosdall. 2010. Identification of potential natural enemies of the pea leaf weevil, *Sitona lineatus* L. in western Canada. Journal of Applied. Entomology. 135: 293–301. https://doi.org/10.1111/j.1439-0418.2010.01542.x.

Vankosky M. A. 2011. Integrated pest management of *Sitona lineatus* L. (Coleoptera : curculionidae) in crops of *Pisum sativum* L. (Fabales : Fabaceae) in western Canada. 2011. Library and Archives Canada = Bibliothèque et Archives Canada. 200 pp

Vankosky, M. A., H. A. Cárcamo, and L. M. Dosdall. 2011a. Response of *Pisum sativum* (Fabales: Fabaceae) to *Sitona lineatus* (Coleoptera: Curculionidae) infestation: effect of adult weevil density on damage, larval population and yield loss. Journal of Economic. Entomology. 104: 1550–1560.

Vankosky, M. A., H. A. Cárcamo, R. H. McKenzie, and L. M. Dosdall. 2011b. Integrated management of *Sitona lineatus* L. (Coleoptera: Curculionidae) with nitrogen fertilizer, Rhizobium inoculation and thiamethoxam insecticide. Agronomy. 103: 565–572.

Vankosky, M., H. Carcamo, M. Evenden, S. Hartley, S. Meers, A. Wijerathna, D. Sjølie, and O. Olfert. 2018. Pea leaf weevil update. Agriculture and Agri-Food Canada.

Verkleij, F. N., P. A. M. van Amelsvoort, and P. H. Smits. 1992. Control of the pea weevil (*Sitona lineatus* L.) (Col., Curculionidae) by the entomopathogenic fungus *Metarhizium anisopliae* in field beans. Journal of Applied Entomology. 113: 183–193.

Velázquez De Castro, A. J., A. L. L. Friedman, and R. Borovec̆. 2010. *Sitonini* of Israel (Coleoptera: Curculionidae: Entiminae). Israel Journal of Entomology. 40: 71–108.

Wanner, K. 2016. Pea Leaf Weevil. Montana State University MontGuide. Pest Fact Sheets. Retrieved from: https://agresearch.montana.edu/wtarc/producerinfo/entomology-insect-ecology/PeaLeafWeevil/MontGuide.pdf [accessed 8 July 2019].

Westwood, J. O. 1840. Synopsis of the genera of British insects. *In* An introduction to the modern classification of insects, founded on the natural habits and cooperation organization of the different families, vol. 2. Longman, London.

White, C., and S. D. Eigenbrode. 2000. Effects of surface wax variation in *Pisum sativum* on herbivorous and entomophagous insects in the field. Environment Entomology. 29: 773–780.

Williams, L., L. E. O’Keeffe, and D. J. Schotzko. 1991. Chickpea, *Cicer arietinum*: a new host for the pea leaf weevil, *Sitona lineatus.* Field Crops Research. 27: 377–380. (https://doi.org/10.1016/0378-4290(91)90043-U).

Williams, L., D. J. Schotzko, and L. E. O'Keeffe. 1995. Pea leaf weevil herbivory on pea seedlings: effects on growth response and yield. Entomology Experimental Application. 76: 255-269.

Willsey, T., J. Patey, C. Vucurevich, S. Chatterton, and H. Carcamo. 2021. Evaluation of foliar and seed treatments for integrated management of root rot and pea leaf weevil in field pea and faba bean. Crop Protection. 143. https://doi.org/10.1016/j.cropro.2021.105538.

Witzgall, P., P. Kirsch and A. Cork. 2010. Sex pheromones and their impact on pest management. Journal of Chemical Ecology. 36: 80-100.

Wojciechowicz-Zytko, E., and M. Młynarczyk. 2002. The preference of different broad bean cultivars by *Sitona lineatus* L. (Coleoptera: Curculionidae). Journal of Plant Protection Research. 42: 81–9.

Wolfson, J. L. 1987. Impact of Rhizobium nodules on *Sitona hispidulus*, the clover root curculio. Entomology Experimental Application. 43: 237-243.

Xiao, J. X., Y. A. Zhu, W. L. Bai, Z. Y. Liu, T. A. N. G. Li, and Y. Zheng. 2021. Yield performance and optimal nitrogen and phosphorus application rates in wheat and faba bean intercropping. Journal of Integrative Agriculture. 20: 3012–3025. https://doi.org/10.1016/S2095-3119(20)63489-X.

Yadav, S. S., A. H. Rizvi, M. Manohar, A. K. Verma, R. Shrestha, C. Chengci, G. Bejiga, W. Chen, M. Yadav, and P. N. Bahl. 2007. Lentil growers and production systems around the world. *In*: Yadav, S.S., D. L. McNeil, P. C. Stevenson. (eds) Lentil. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6313-8_23.

Yates, F. 1954. The analysis of experiments containing different crop rotations. Biometrics. 10: 324–346.

Zhou, R., B. Hyldgaard, X. Yu, E. Rosenqvist, R. M. Ugarte, S. Yu, Z. Wu, C. O. Ottosen, and T. Zhao. 2018. Phenotyping of faba beans (*Vicia faba* L.) under cold and heat stresses using chlorophyll fluorescence. Euphytica. 214: 68 pp.

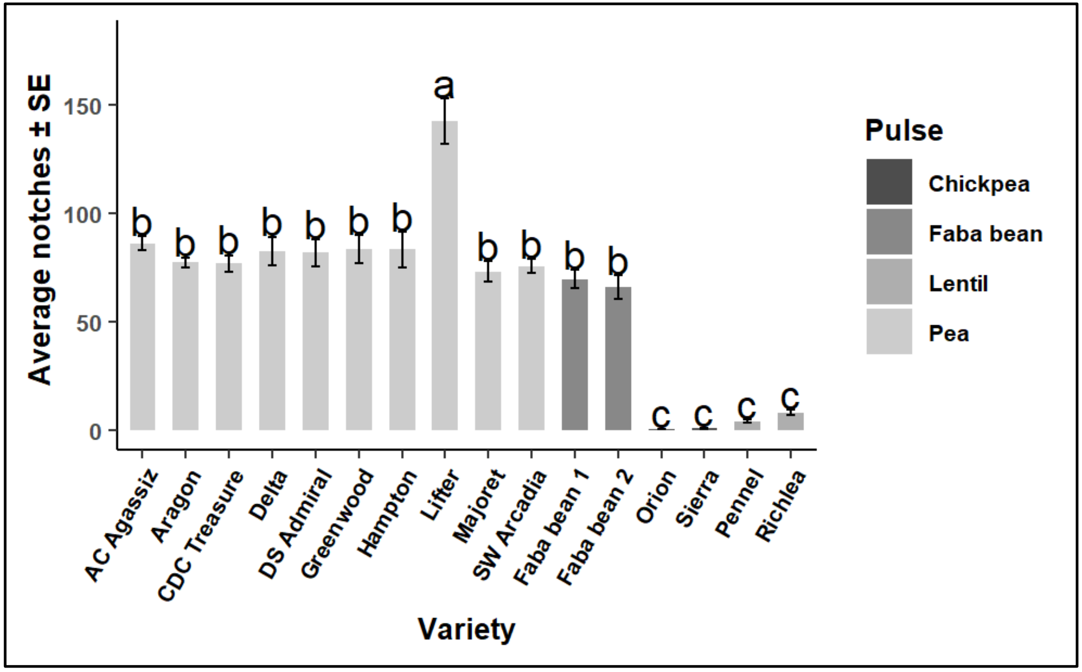
Zohary, D. 1972. The wild progenitor and the place of origin of the cultivated lentil. Economic Botany. 26: 326–332.

APPENDICES

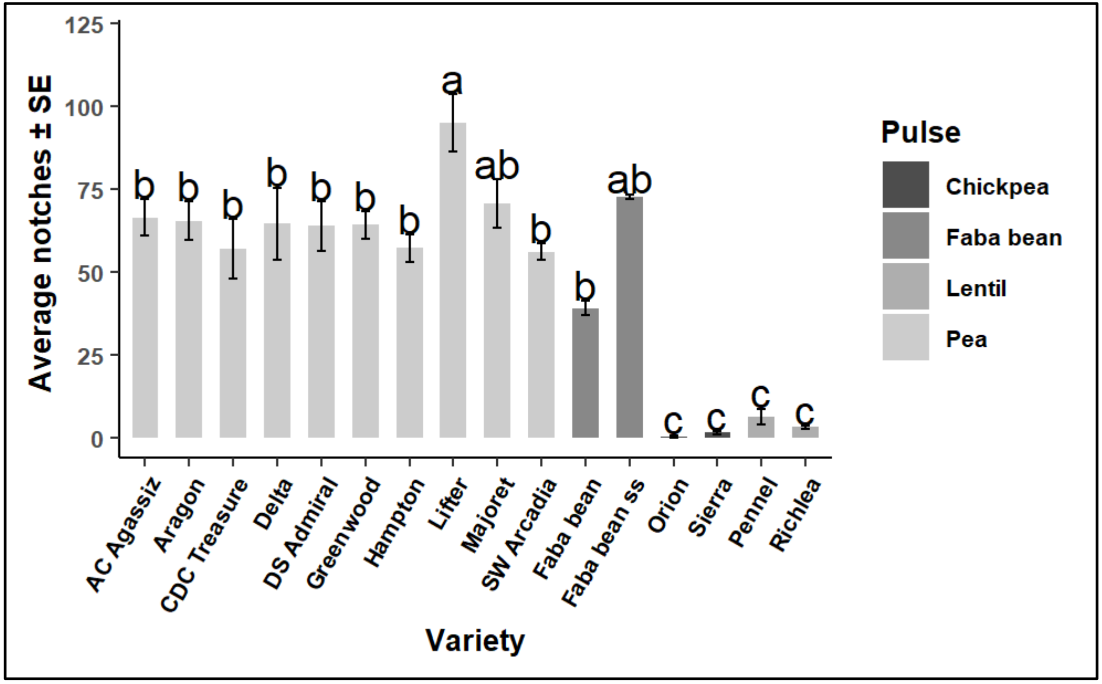
APPENDICES A

FIGURES FOR ADULT DAMAGE ASSESSMENT

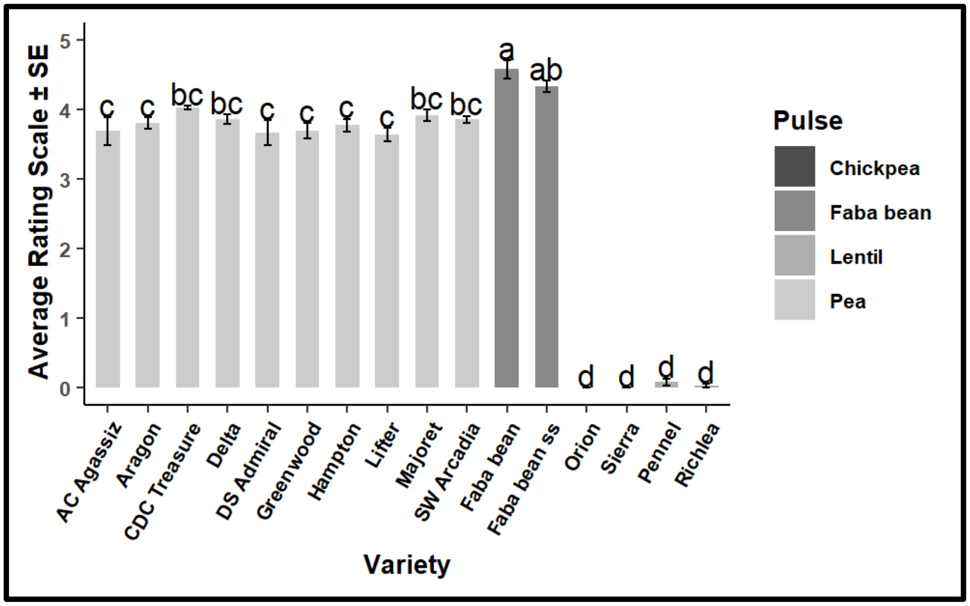
Appendix A1 Figure. Bar-graph of average notches per plant without notches in clam leaf with the standard error of different variety of four different pulse crops in June 2020.



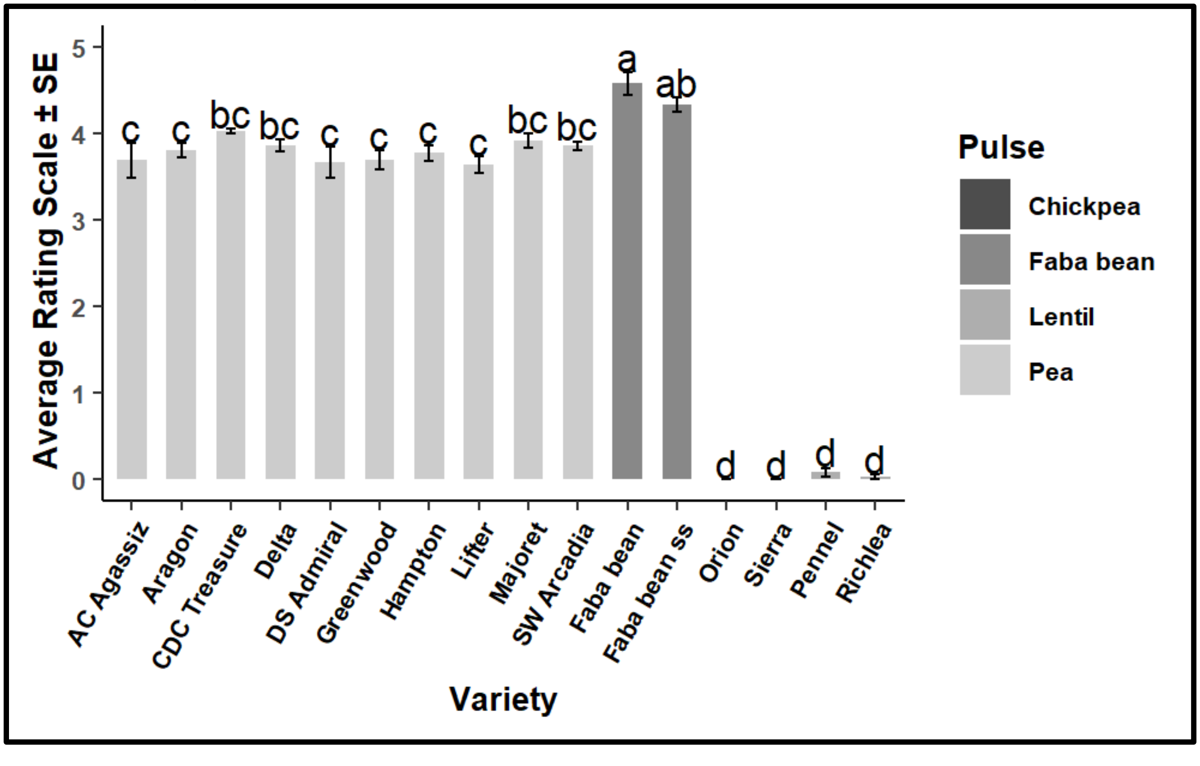
Appendix A2 Figure. Bar-graph of average notches per plant without notches in clam leaf with the standard error of different variety of four different pulse crops in June 2021.



Appendix A3 Figure. Bar-graph of average rating scale per plant with the standard error of different variety of four different pulse crops in June 2020.



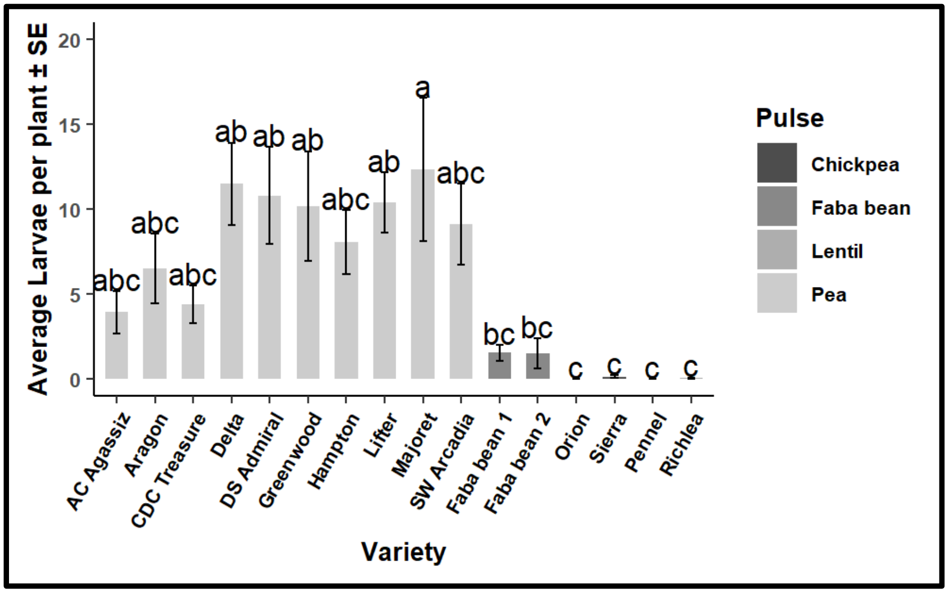
Appendix A4 Figure. Bar-graph of average rating scale per plant with the standard error of different variety of four different pulse crops in June 2021.



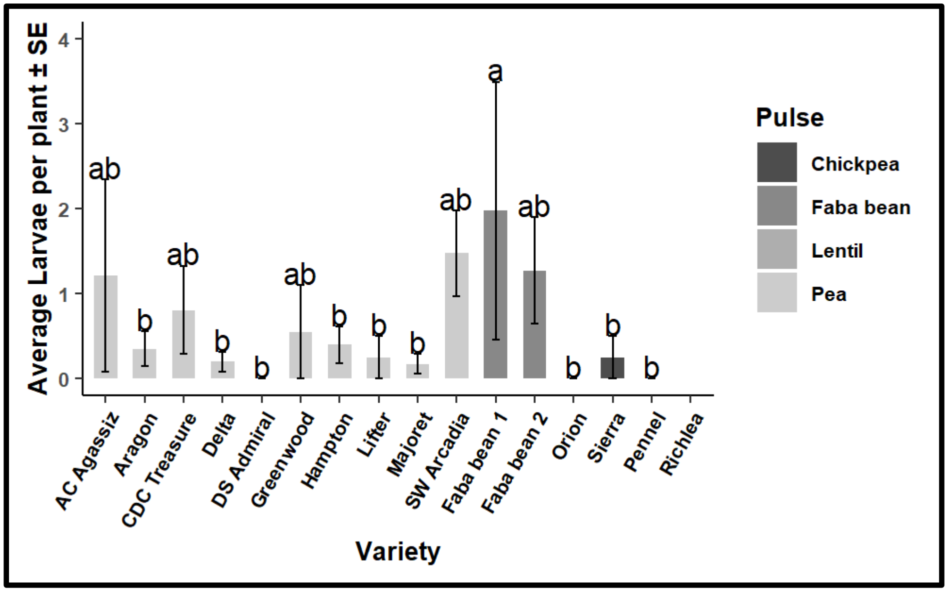
APPENDIX B

FIGURES FOR LARVAL DAMAGE ASSESSMENT

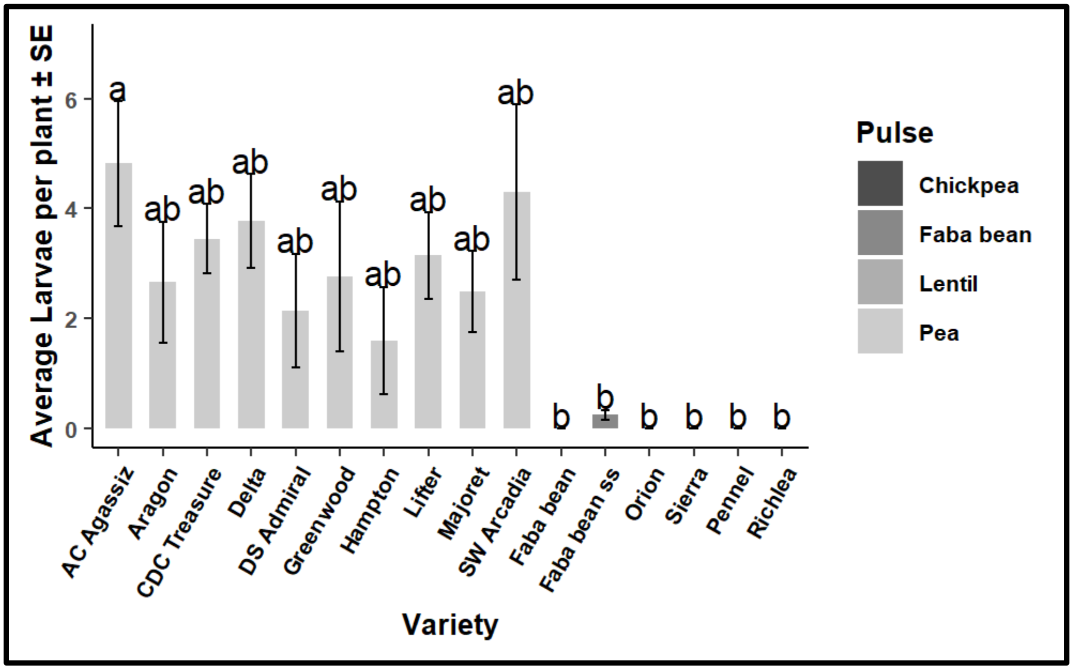
Appendix B1 Figure. Bar-graph of first larval damage assessment with the standard error of different variety of four different pulse crops in June 2020.



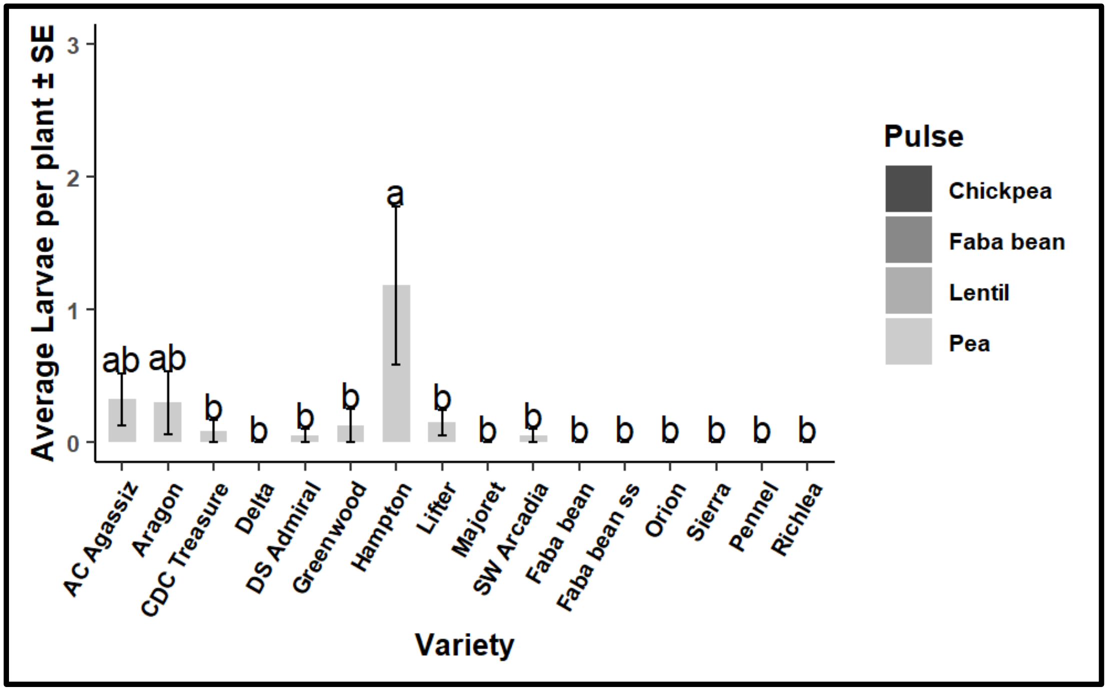
Appendix B2 Figure. Bar-graph of second larval damage assessment with the standard error of different variety of four different pulse crops in July 2020.



Appendix B3 Figure. Bar-graph of first larval damage assessment with the standard error of different variety of four different pulse crops in June 2021



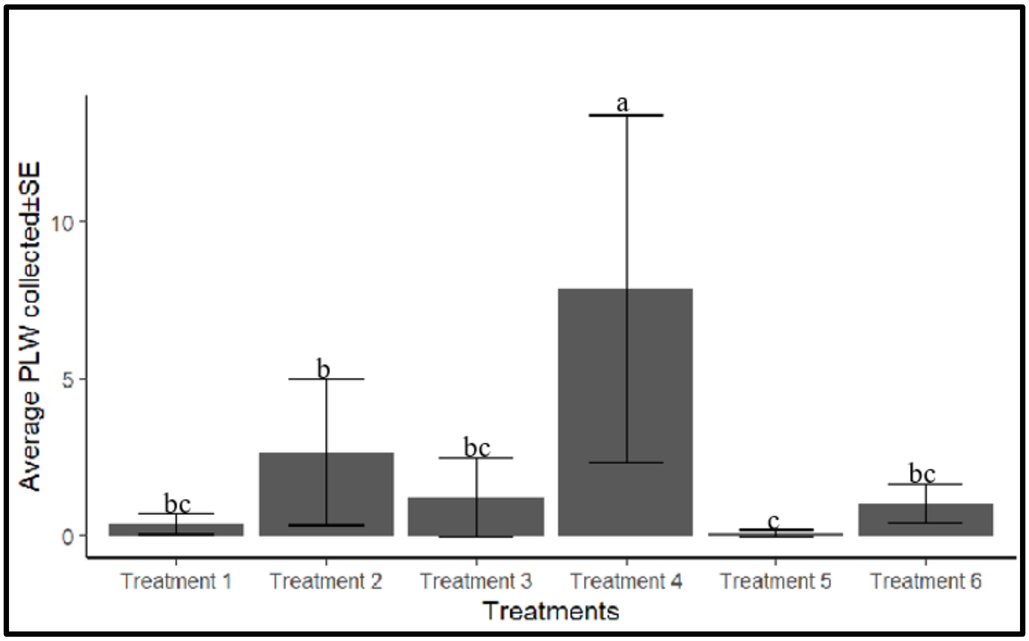
Appendix B4 Figure. Bar-graph of second larval damage assessment with the standard error of different variety of four different pulse crops in July 2021.



APPENDIX C

FIGRUE FOR ATTRACT AND KILL

Appendix C1 Figure Bar-graph of total number of PLW collected through attract and kill method in summer 2020.



Appendix C2 Figure. A) Pheromone septum in the pitfall trap **B)** Pitfall trap with pheromone pellets plus insecticide.