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Reoccurrence of new pest - pea weevil in Montana *(Cropland Insects)*

Description:

The pea weevil *Bruchus pisorum* L. (Coleoptera: Chrysomelidae), not to be confused with the more common pea leaf weevil, is one of the most problematic insect pests on field peas particularly in US Western States. Attached is more information.

Gadi Reddy, Western Triangle Agricultural Research Center, Conrad, MT

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Monday, January 15, 2018

Reoccurrence of new pest - pea weevil in Montana

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The pea weevil *Bruchus pisorum* L. (Coleoptera: Chrysomelidae), not to be confused with the more common pea leaf weevil, is one of the most problematic insect pests on field peas particularly in US Western States. The larvae feeding inside the developing dry pea seed cause damage. Weevil infestations ranges between 30–70% in untreated crops with high level-presence of the pest already. Affected peas are unfit for human consumption and their seed germination rate decreases, which in turn diminishes the market value.

In Montana, damage by this weevil was reported for the first time in the Hi-Line area in 2014, which alarmed pea growers and stakeholders because this pest could easily spread to neighboring pea-growing areas. Consequently, with the funding from USA Dry Pea and Lentil Council, pea weevil surveys were carried out during 2016 and 2017 in 33 field sites, five elevators and 16 farm bins in the Golden Triangle Area including Hi-Line area by WTARC staff. The primary objective was to determine the damage potential and distribution of the pea weevil. Although, no incidence of weevil was noticed in the surveys of 2016–2017, damaged seeds with live pea weevils were confirmed from the Chester area (December, 2017) by the State Grain Lab. This incidence indicates the necessity of continuing the survey work.

In an event of significant levels of crop damage and noticeable population levels, efforts will be undertaken to obtain a USDA-APHIS permit to introduce the pea weevil egg parasitoid *Uscana senex* (Hymenoptera: Trichogrammatidae) into Montana. This parasitoid, is reported to show up to 82% of parasitism rate. Detailed information on the biology, ecology and management of pea weevil was recently reviewed and published by our team.

Fig. 1. Damaged peas with live pea weevil collected from Chester area. All peas shown adult exit hole in the seeds that are commonly found in the stored product.

Fig. 2. Brown colored, globular shape adult *Bruchus pisorum* with white patches. Scale – 1mm.

If anyone has noticed peas with holes, please send the samples (preferably one to two lbs) to Ms. Rama Gadi, Western Triangle Ag Research Center, Montana State University, 9546 Old Shelby Rd., P. O. Box 656, Conrad, MT 59425 or contact for pick up the samples; Phone: 406-278-7707 (office); 406-450-1835 (mobile); E-mail: ramadevi.gadi@montana.edu

For pest biology, ecology, thresholds, chemical control and other management options, please refer to attached reference materials.

Further Reading

Reddy, G.V.P., A. Sharma and R.L Gadi. 2017. Biology, ecology, and management of the pea weevil, *Bruchus pisorum* (Coleoptera: Chrysomelidae). *Annals of the Entomological Society of America*, doi:10.1093/aesa/sax078

Pea weevil

***Bruchus pisorum* (L.), the pea weevil,** is not a true weevil, but is a serious pest of pea crops. Adults lay eggs in the developing pea in the field, but larvae complete development in the grain bin. For this reason the pea weevil is strictly speaking not a stored grain pest, though most of its damage is caused while it is in the bin. Larvae excavate the center of the pea and construct a circular exit hole (Figure 1). Damage from this insect is most often discovered at the elevator. Up to 70% of grain weight loss occurs in the storage bin due to continued larval feeding.

The adult pea weevil can be surveyed in the field using a sweep net. Adults are thick brown beetles with white spots on the elytra. The abdomen extends beyond the elytra and has white tips. The adults are measure 5mm in length.

Assessing

Sweep netting for adults in the summer after peas flower is a good way to survey populations. Beetles are more common near field borders.

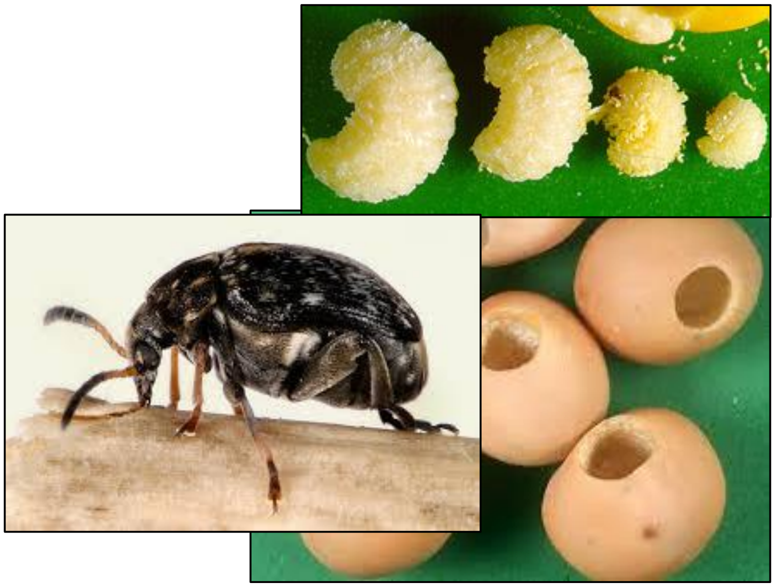

Figure 1. a) Pea weevil adult, larvae and damage to peas.

Control

Sheep may be used to graze out crop residues, either eating the larvae from shattered pods or exposing them to direct sunlight. Chemical control may be used for the adults when they are in flight. Threshold for spraying is 2 beetles/25 sweeps (Dun) & 1 beetle/25 sweeps (White).

Research

This is a new pest in Montana. WTARC is investigating monitoring methodologies to assess the presence and extent of pea weevil in Montana. As more information accumulates about this pest control programs will be initiated.

Dry Peas

Pea weevil

Sue Blodgett

Identification (and life cycle/seasonal history)

Adults are small 1/16 inch gray-brown weevil flecked with light and dark irregular patches. Tip of the abdomen protrudes beyond the wing covers. Adult pea weevils overwinter and emerge about the time that peas are blooming. Adults feed on flowers, leaves or pods, congregating on pea flowers at early bloom. They will mate following a pollen meal. Females lay 1 or 2 eggs on the outside of the pea pod. Larvae hatch within 1 – 2 weeks and burrow into the pod. Larvae are C-shaped, legless with a brown head and creamy white colored body. Larvae develop within developing seed with each developing pea seed supporting a single weevil larva. Larvae feed within pods, and emerge from threshed pea seed as much as one month after harvest to pupate. There is one generation

Sweep net is used to sample adults. One weevil in 25 sweeps can result in 10% infestation at harvest. The threshold is considered to be 2 adults per 25 -180 degree sweeps.

Plant Response and Damage

Weevil infested seed can result in decreased seed weight, yield reduction and dockage at point of sale.

Monitoring and Economic Threshold

A sweep net is used to sample adults. One weevil in 25 sweeps can result in 10% infestation at harvest. The threshold is considered to be 2 adults per 25 (180 degree) sweeps.

Management

Although pea weevil resistance is available there are currently no resistant varieties available in the US.

Cultural Control

Field sanitation, by destroying crop residues, preventing shattering at harvest, eliminating volunteer plants and planting uninfested seed can reduce infestation. Early planting and harvest is desirable

Chemical Control

Product List for Pea Weevil:

Insecticide	**Lbs Active Ingredient per Acre (Fl oz. or oz. product)**	**Preharvest Interval, remarks**
Carbaryl 4L, 80S, XLR[1,2]	1 – 1.5 qt (4L) 1 ¼ - 1 7/8 lbs (80S) 1 – 1.5 qts (XLR)	PHI 14 days grazing or harvest for forage, 21 days harvest dry seed. Do not apply more than 6 qts (4L or XLR) or 7.5 lbs (80S)/A/ season.
Fury 1.5[R]	3 – 4.3 oz	PHI 21 days. 12 hr REI. Do not apply more than 24 oz per season.
Imidan 70 WP[1]	1 – 1.3 lbs	PHI 7 day. 10 days for hay or 7 days for forage. Pacific Northwest only. Do not apply more than 4 lbs/A/season. Minimum tank mix of 5 gal/A.
Malathion[2]	1 – 2.5 pts (8EC)	PHI 3 days. 12 REI. Do not graze or feed treated vines.
Mustang Max1.5EC[R]	2.72 – 4. oz	PHI 21 days. 12 hr REI. Do not apply more than 24 oz per season.

R Restricted Use Pesticide
1 Labeled for chemigation
2 Several formulations

Categories: Dry Peas, Insects, Pea Weevil, Bruchus pisorum

Date: 04/29/2006

Annals of the Entomological Society of America, XX(X), 2017, 1–11
doi: 10.1093/aesa/sax078
Review

OXFORD

Review

AQ1 Biology, Ecology, and Management of the Pea Weevil (Coleoptera: Chrysomelidae)

AQ2 **Gadi V. P. Reddy, Anamika Sharma, and Ramadevi L. Gadi**

Montana State University-Bozeman, Department of Research Centers, Western Triangle Agricultural Research Center, 9546 Old Shelby Road, P.O. Box 656, Conrad, MT 59425 and [1]Corresponding author, e-mail: reddy@montana.edu Subject Editor: Peijian Shi

Received 2 September 2017; Editorial decision 4 October 2017

Abstract

The pea weevil, *Bruchus pisorum* (L.; Coleoptera: Chrysomelidae), is a seed-feeding chrysomelid beetle. It is a strictly monophagous pest of *Pisum sativum* (L.; Fabales: Fabaceae), and is a major pest of peas in the world, including the United States, Australia, Europe, Ethiopia, and parts of Asia. The genetically diverse U.S. population of *B. pisorum* suggest the introduction of *B. pisorum* individuals from several distinct populations. Infestations destroying ranges from 0 to 90% in various parts of United States. *B. pisorum* is univoltine and each generation takes 50–80 d from oviposition to adult emergence. Adults overwinter adjacent to fields and colonize pea fields at bloom. Volatile cues from pea plants attract *B. pisorum* females to oviposit. Cultural methods to control *B. pisorum*, including early planting and harvesting, are effective. Chemicals such as acetamiprid, pyrethroids, and organophosphate insecticides are commonly used as contact insecticides. Parasitoid *Uscana senex* (Grese; Hymenoptera: Trichogrammatidae), through augmentative releases seems promising for control of *B. pisorum*, and such efforts have met with success in Russia and Chile. In terms of plant resistance, the α-AI-1 gene, an α-amylase inhibitor, can control of *B. pisorum* in both outdoor and greenhouse pea crops. The neoplasm gene (*Np* allele) is an inducible form of resistance whose expression is induced by natural products of lipid origin found in *B. pisorum.* Expression of the neoplasm gene in resistant
AQ3 pea may be a possible approach for reducing *B. pisorum* infestation. Integrated pest management (IPM) strategies include cultural control, biological control, and planting of resistant pea varieties.

Key words: integrated pest management, life-cycle, field pea, chemical control, resistance

Pest Origins and Distribution

Species of *Bruchus* (Bruchinae, formerly considered a distinct family, the Bruchidae) (Kergoat et al. 2007) are chrysomelid beetles whose larvae develop inside seeds. *Bruchus* spp. are most common in the Palearctic region, but some species occur in North America, Africa, and Australia as introduced species. Several species are agricultural pests of legume seeds (Kergoat et al. 2004, 2007).

Bruchus pisorum (L.; Coleoptera: Chrysomelidae), commonly known as the pea weevil, is strictly monophagous on field pea, *Pisum sativum* (L.; Fabales: Fabaceae). *B. pisorum* is a major pest of *P. sativum* in most regions of the world where field peas are grown (Clement et al. 1999). Peas are an important source of protein for people in several parts of the world and are also used as animal fodder (Teshome et al. 2014). *B. pisorum* was first described in 1752, but was known as an important pest of dry peas in North America as early as the 1740s (Bridwell and Bottimer 1933). Pea weevil arrived in North America as early as 1628 (Bain 1998) in shipments of dry pea seeds shipped to the Massachusetts Bay Colony in 1628 from Europe and became a field pest there by 1675 (Bain 1998). It was first observed near Philadelphia, Pennsylvania in the 1740s, and in nearby states in the 1750s. By the 1890s, pea weevil had spread across North America (Afonin et al. 2008). Genetic sequence data (the Cytb gene) (Scheepers 2012) show that the US population of *B. pisorum* is the most diverse pea weevil population in its invaded range, including Australia, Europe, and Ethiopia. Such high diversity in the United States could indicate that multiple introductions of *B. pisorum* occurred, from several genetically distinct populations. The native range of *B. pisorum* is not certain, but it likely evolved in the same geographical region as its host, *P. sativum* (Byrne 2005). The origin of peas is believed to be the middle Asia, including northwest India and Afghanistan and also a second area of development lies in the Near East, and a third includes the plateau and mountains of Ethiopia (Byrne 2005, Afonin et al. 2008). Currently, *B. pisorum* is found throughout the United States and southern Canada, and most temperate areas of Asia, Europe, North Africa, and Australia. Other important regions with pea weevil infestations are Central

Asia, the Western Russia, the northern part of Kazakhstan, Moldova, and Ukraine (Afonin et al. 2008). In Montana, in the United States, pea weevil is one of the most damaging pests of peas (Larson 1931), even though it is a relatively new pest in most of the state compared to other parts of United States. The first report of the species in Montana was in Gallatin county in 1912 (Cooley 1912).

Most studies of pea weevil damage are from Ethiopia, Europe, Australia, and the United States. In Ethiopia, *B. pisorum* was introduced in the mid-1970s (Ali et al. 2009), and the occurrence of *B. pisorum* was first documented in 1985 and later on in 1992 it was reported as an important pest of field peas (Esmelealem and Adane 2007). In Ethiopia, during early August *B. pisorum* can cause crop losses there of 45–85% (Scheepers 2012). In Australia, *B. pisorum* was first reported in 1931 in Western Australia, from where it spread to other temperate parts of Australia. By the 1960s, significant economic losses to this pest were reported in Australia (Waterhouse and Sands 2001). In Europe, *B. pisorum* was first recorded in 1850 and today it is found throughout Europe, except in the coldest areas (such as Palermo and parts of Denmark) (Byrne 2005, Scheepers 2012, Stejskal et al. 2014).

Impact and Economic Thresholds

Adult *B. pisorum* leave an exit hole about 2–3 mm in diameter when they emerge from seeds, which renders the peas unfit for human consumption and also reduces germination rates, both of which diminish the crop's market value (Pesho et al. 1977, Southgate 1979, Horne and Bailey 1991). Live insects (larvae, pupae, adults) and their excrement contain the toxic alkaloid cantharidine, and therefore damaged pea seeds are hazardous to both human health and that of domestic animals (Grigorov 1976). Gas chromatography–mass spectrometry (GC–MS) analysis of *B. pisorum* showed 19 compounds, one of which (isopropyl tetradecanoate) is used for to treat head lice and another (2, 5-Hexanedione, 3, 4- dimethyl) is neurotoxic (Verma et al. 2015). Larvae feeding in the developing pea seed (see uspest.org) are the main cause of damage to peas, and this damage is often only discovered when the product reaches the crop storage elevators. Worldwide infestations levels range from 10 to 90%. In the U. S. Pacific Northwest, Burns and Bragg (2001) documented seed damage ranging from 42 to 82%.

Economic thresholds for pea weevil vary across the world. In the northwest United States (Oregon, Washington, Idaho), one weevil per 25 sweeps can result in 10% infestation at harvest, and consequently, the economic threshold in this region is considered to be two adults per 25 sweeps (Blodgett 2006). Infestation levels of 30–70% occur in untreated crops in the northwestern United States (uspest.org). In a study done in 1986 and 1988 in Australia, the development of *B. pisorum* and the weight loss of infested field pea seed were examined in relation to the damage thresholds for pesticide application and the timing of harvest. At the earliest possible harvest date, most pea weevils were late instar larvae (3rd and 4th) and at that point in time, crop loss was usually below 4% (by weight), which was equivalent to the cost of controlling adults with insecticide. When harvested 1–3 wk after the earliest possible harvest date, weight loss exceeded than 4% (Smith 1990). In another study in southern Australia, the economic injury level depended on the relative value of undamaged peas for human consumption, and most pea farmers attempted to limit damage within 50 m from the edge of the pea crop (the part of the crop most susceptible to *B. pisorum* damage) to <5% of pea seeds (Horne and Bailey 1991).

Weight loss and reduced germination are the key damage effects of pea weevil. Both of these losses increase with as immature pea weevil stages develop, reaching their maximum when bruchid larvae are mature. Early harvesting and fumigation of pea seed immediately after harvesting can protect germination (Brindley and Hinman 1937, Baker 1998, Mihiretu and Wale 2013). The effect of *B. pisorum* on the germination of *P. sativum* seed varies by varieties, with some studies finding losses in germination as high as about 58% compared to other varieties where loss can be about 16% (Nikolova and Georgieva 2015a). Similarly, *B. pisorum* infestation has been associated with a decrease in length and weight of primary radicles (the embryonic root) by 34.1 and 36.2% and with reduction of the length and weight of plumules (stems of embryonic plants) by 31.8 and 34.3%. The vigor index of the primary radicle and plumule is reduced 81.1 and 82.1%, the germination index reduced by 83.1% in infested seeds (Nikolova and Georgieva 2015a).

Life-Cycle and Ecology

Adults of *B. pisorum* are 6 to 7 mm long and 2.5 mm wide, globular in shape with long legs. In general, pea weevils have a brownish color with grey or white or black patches (McDonald 1995). Elytra do not cover the end of the abdomen, which leaves the last terga exposed (Fig. 1). The last abdominal is covered with black and white setae and the inner ridge of the ventral margin of the hind femur has a single spine. Females are slightly bigger in size than males. A tiny spine located on the distal end of the tibia of the middle leg distinguishes males from the females (Larson et al. 1938). The antennae of the *B. pisorum* is as long as one third of its whole body length. Larvae can grow as long as 5 mm and are C-shaped, with a brown head and creamy white colored body with reduced legs. The eggs are bright orange and about 1.5 mm in length (Newman 1932, Hardie 1992, Baker 1998, Gari 2015).

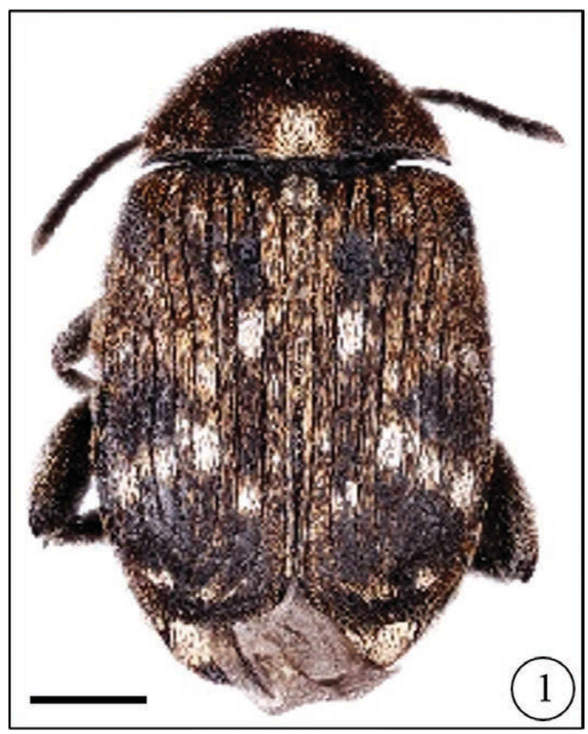

Fig. 1. Brown colored, globular shape adult *Bruchus pisorum* with white patches. Elytra do not cover the end of the abdomen and leave the last terga exposed. Scale: 1 mm.

B. pisorum is univoltine. Adults emerge about the time that peas are blooming but weevils do not appear on vines in large numbers until shortly after blooming begins. Adults first feed on pollen of pea flowers, mate, and oviposit (Brindley 1933, Blodgett 2006). Pollen is necessary for *B. pisorum* before oviposition. Upon leaving hibernation, only the male is sexually mature. Ovaries of females remain undeveloped for 6 mo, and the female must feed on pollen before she can lay eggs on green pea pods. After pollen feeding, females require 7–8 d for maturation of their ovaries. In addition, males increase their mating frequency after pollen feeding (Pajni 1981, Pesho and Van Houten 1982, Ceballos et al. 2015). Pollen of other members of Fabaceae such as *Lathyrus sativus* (L.; Fabales: Fabaceae) and *Phageolus vulgaris* (L.; Fabales: Fabaceae) are also suitable for adult male and female sexual development and it appears that it is pollen quantity, not quality that drives oocyte development (Annis and O'Keeffe 1984a). Females furthermore lay eggs on resistant varieties of peas as well as once susceptible to feeding (Clement et al. 1996). Adults also feed on petals, the calyx, and nectar (Clement et al. 2002), although pods which have nearly reached their maximum size but are still tender are preferred. Eggs are laid on pods of all sizes (Brindley 1933). Volatile cues from pods are responsible for attracting *B. pisorum* females more than other phenological stages (Ceballos et al. 2015), while the number of eggs laid on each pod depends largely on the local weevil population size. The greater the number of adults that are present, the greater the number of eggs laid per pod. As many as 126 eggs have been found on a single pod (Brindley 1933). Eggs can be found on every part of the pea pod and flower. Pea plantings as a whole were found to have pods suitable for oviposition for a maximum of 25 d (Brindley 1933). Eggs hatch within 1–2 wk and larvae burrow directly through the chorion of the egg at the point where it is attached through the pod into the maturing seeds, where larvae consume the pea seeds and complete their development (Clement 1992). Often, the larva does not make its way directly into the seed, but mines the wall of the pod before penetrating a seed. Larval development takes 4–8 wk, and most larvae develop in 41 d. At the end of this stage, the mature larvae cut through the seed coat, leaving the characteristic circular caps or 'windows' over the cavities (Chamberlin and Gray 1938). Several larvae often enter the same seed, but only one adult has been observed to emerge, and while the reasons for this are not completely explored, density dependent mortality seems to occur in the third instar (Smith and Ward 1995). When two insects in one seed reach the adult stage, only one emerges (Brindley 1933). Late pupating larvae emerge from threshed pea seeds about 30 d after harvest (Blodgett 2006). Pupae become adults in about 2 wk, and total developmental time from egg laying to adult emergence is 7–12 wk (Fig. 2). *B. pisorum* does not reproduce in dry seeds (Chamberlin and Gray 1938). The optimal temperature for development of larvae and pupae is 32–41°C. While early instars (first [41.8°C] and second [34.0°C]) can tolerate relatively higher temperature, late instars and pupae prefer relatively lower temperatures (third instar [34.4°C], fourth instar [34.2°C], and pupae [32.7°C]) (Smith and Ward 1995). Temperature also plays a major role in pre-emergence adult survival, and air temperatures >40°C cause significant mortality (Smith and Ward 1995).

Adult *B. pisorum* overwinter in peas, if seed is stored in a cool, dry place (Chamberlin and Gray 1938). Upon emerging adults seek shelter in rubbish, old buildings and in lichens on the bark of local trees, and thus such habitats near pea fields promote higher infestations (Larson and Hinman 1931, Hardie et al. 1995). Pea seeds imported without fumigation, peas left on the vine after the main crop has been harvested, peas which, because of disease or other unfavorable conditions, have been left unharvested, peas which have been grown for hay, volunteer peas which are not harvested, screenings cleaned from the main crop of peas, and all peas wasted in the process of harvesting and cleaning the crop can be major sources of infestation (Larson et al. 1933). Adult *B. pisorum* cannot persist in storage as they cannot re-infest stored seed, and therefore the source of new field infestations is not, as is commonly supposed, adults in planted seeds, but rather the insects overwintering in field margins (Whitehead 1930).

Adults in autumn can fly up to 70 feet above the ground in cultivated areas and 50 feet in forested margins and can travel up to three miles to shelter in the barks of trees (Wakeland 1934). Most weevils are found, however, near the edges of pea fields. Autumn flights of *B. pisorum* occur soon after the adults emerge from the peas and last for 2 mo. Most adults fly at the onset of autumn rains because the mature pea pods crack open after drying following the first rain and this allows the escape of adults (Wakeland 1934).

B. pisorum Management

Many farmers mistakenly think of *B. pisorum* as just a storage pest. A study by Mendesil et al. (2016a) found most farmers surveyed in northern and north-western Ethiopia considered *B. pisorum* to be solely a post-harvest pest, because of the presence of the adult exit 'hole' in the seeds, which is most commonly found in the stored product (Fig. 3). In fact, when exit holes are observed in infested seeds, it is too late to apply post-harvest management practices to control the weevils. Similarly, a study in Australia showed that if the peas are harvested at the earliest possible harvest date, weight loss can be minimized, and seed quality maximized (Smith 1990). For monitoring and sampling *B. pisorum*, direct counts, levels of insect damage, and sweep netting of adults are considered to be the most reliable methods (Sharma et al. 2005). A cost effective statistical sampling plan for eggs was developed by Smith and Hepworth (1992). While accurate assessment of *B. pisorum* density is necessary for effective control, detecting immature stages inside dried peas is difficult. However, soaking peas in water allows them to swell and soften, and facilitates cutting and checking peas internally for immature stages of *B. pisorum*. This increases the efficiency of detection compared to visual examination of unopened, dry peas (Somerfield 1989). Variogram (hyperspectral) imaging can also be used to identify internal seed defects caused by *B. pisorum* (Nansen et al. 2014).

Cultural Control

Cultural controls are preventive methods to keep the incidence of pea weevil infestation low (Mihiretu and Wale 2013). Field sanitation by destroying crop residues, preventing shattering at harvest and eliminating volunteer plants can reduce infestation (Blodgett 2006). Early planting and harvesting is likewise recommended (Smith 1990, Mihiretu and Wale 2013, Mendesil et al. 2016a) and is effective because of a general lack of other host plants. Grazing by sheep can be used to clean up crop residues immediately following harvest. Heavy grazing also enables the reduction of volunteer peas which adult *B. pisorum* can use as host to survive during winters (McDonald 1995, Mihiretu and Wale 2013). Other cultural control practices such as crop rotation and intercropping can help in the increment in the productivity (Mendesil et al. 2016a). Border trap crop strips can also be a valuable addition in cultural control of *B. pisorum* management, nevertheless more research is needed to explore this option (Michael et al. 1990, Sharma et al. 2005). Trap cropping using surrounding buffer strips or intercropping pea fields with non-crops species or pea varieties that are highly attractive

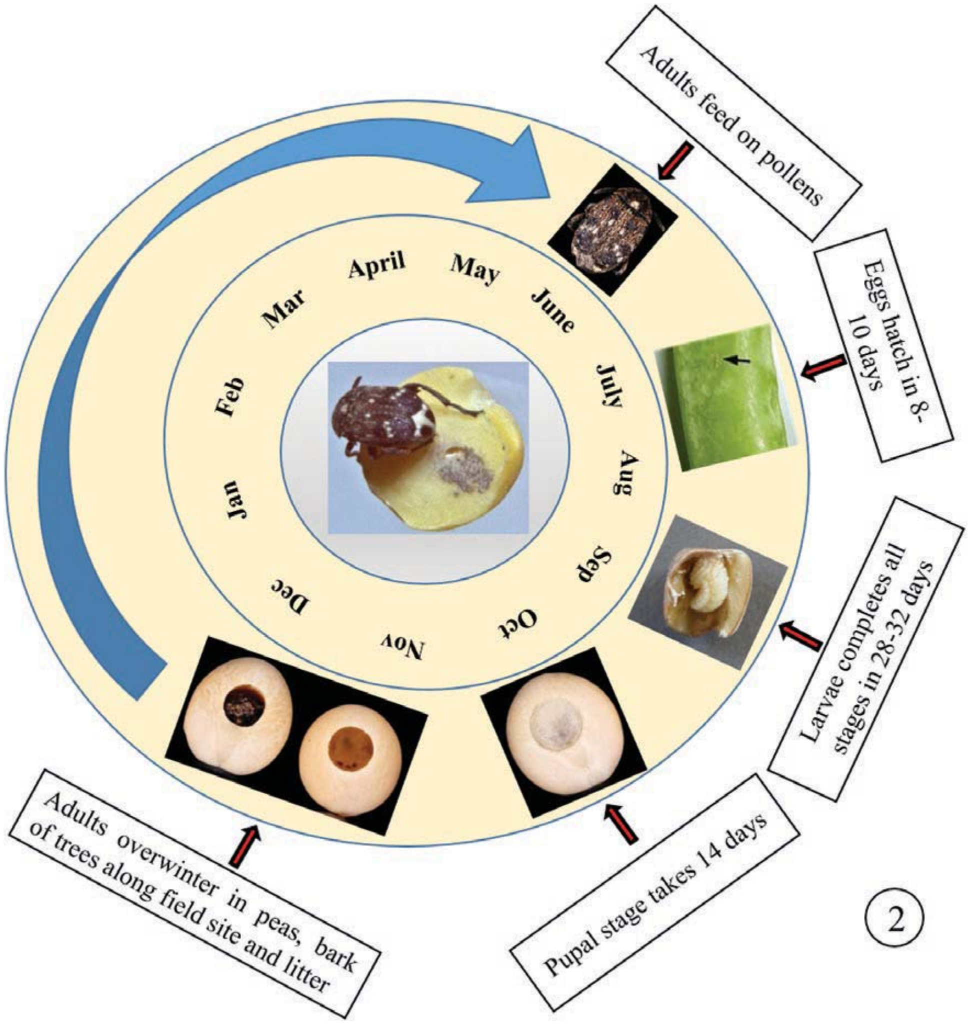

Fig. 2. General life cycle and ecology of *Bruchus pisorum*. Egg and larvae images: copyright: Radoslav Andreev and I. Manolov, Agricultural University, Plovdiv, Bulgaria; 2014 Department of food and agriculture, Western Australia, DAFWA.

Fig. 3. Infested seeds of *Pisum sativum*. All show the adult exit hole in the seeds, which most commonly is found in the stored product. Scale: 1 mm.

to *B. pisorum* might, therefore, be useful in managing *B. pisorum* (Mendesil et al. 2016b).

To prevent the persistence of infested seeds, pea hay should be cut soon after the beginning of flowering (Baker 1998, Scheepers 2012). Destruction of infested stored peas is an additional cultural measure that can be useful. A temperature of 21°C is best for treating seeds with bisulfide of carbon. Seed can be treated by immersing infested seeds in water previously heated to 50–55°C for 2–3 min and later drying the seeds with hot air at 50°C. As such a heat treatment poses some risk of reducing germination, in colder regions seeds may be left at −17°C overnight to kill all stages of *B. pisorum* without influencing the germination rate of seeds (Garman 1917, Larson et al. 1935). Stoyanova (1984) studied the effect of cooling, to 5, −2, −9 or −16°C on the time required for mortality of stored grain pests and found that under laboratory conditions, *B. pisorum* showed the lowest mortality at 5°C, while 99.9% mortality of *B. pisorum* was observed after 16 d at −16°C. Female *B. pisorum* were also found to discriminate between host and non-host plants during oviposition trials (Mendesil et al. 2016b).

Chemical Control

The feeding location of pea weevil larvae within the seed makes infestation levels in crops difficult to monitor. Control of adults is most effective if pesticides are applied before females lay eggs, which starts when the crop comes into bloom (Horne and Bailey 1991, Baker 1998, Clement et al. 2000, Scheepers 2012). However, adults are present in pea fields for a long period, and repeated chemical applications are required to prevent seed infestation (Baker 1998). Fumigation of harvested peas in storage can prevent further damage by *B. pisorum* larvae in seeds (Baker 1998, Clement et al. 2000).

Periodic application of contact-pesticides to pea fields or fumigation of the harvested seed are the most common strategies for chemical control of *B. pisorum* (Aryamanesh et al. 2012). Organochlorine insecticide-DDT, which is no more in use now was found effective to control for *B. pisorum* (Brindley and Chamberlin 1952) in the experiment conducted from 1944 to 1946 (Schopp et al. 1948). A variety of pesticides, in different chemical groups, have been found to be effective against pea weevil (Chamberlin and Gray 1938, Brindley 1939, Smith 1990, Horne and Bailey 1991, Blodgett 2006) (Table 1). Between two pyrethroids (lambda-cyhalothrin, alpha-cypermethrin) and two neonicotinoids (acetamiprid, thiacloprid) used on *B. pisorum* eggs, pyrethroids showed the higher effectiveness, while the acetamiprid, a neonicotinoid, was the least effective at killing eggs and larvae (Seidenglanz et al. 2011). Another study found neonicotinoids to be significantly more effective than pyrethroids in reducing the survival and efficacy of pea weevil eggs (Nikolova 2014). Acetamiprid and zetacypermethrincan produced suitable results when sprayed at the first detection of eggs on pea pods (Nikolova 2015a). Meanwhile, phosphine was used as a fumigant by Waterford and Winks (1994), who found that long exposure times were required to control all stages of the weevil. However, when phosphine was applied in sealed containers, relatively low concentrations were sufficient to kill all *B. pisorum* life stages if held in place for 21 d. Most failures of phosphine fumigation were caused by inadequate container tightness and consequent escape of the gas. Absorbed phosphine desorbs readily from peas, making phosphine fumigation good for controlling *B. pisorum* (Williams and Whittle 1994).

Alternatives to conventional pesticides include botanical products such as NeemAzal and pyrethrum. However, these materials, when applied in combination with Biofa (a product combining organic matter, natural plant hormones, alginic acid, potassium, phosphorous and nitrogen), which works as organic growth promoter, at the bud and flowering stages of pea, gave better results in comparison to applying NeemAzal and pyrethrum alone. Pea stands treated with NeemAzal and pyrethrum with Biofa showed biochemical changes related to increased content of crude protein and phosphorus contents of seeds when compared to applied alone (Nikolova and Georgieva 2015a,b).

Physiological inhibition of oviposition is an alternative method of population control, separate from reducing oviposition by killing adults. Treatment of green pea pods with a Bordeaux mixture, CaSO4.Cu(OH)z.3Ca(OH) complex, almost totally inhibited oviposition (Jermy and Szentesi 1978). It may be possible to find compounds capable of controlling pea weevil by interfering with egg-laying behavior (Jermy and Szentesi 1978).

Conventional insecticides are often unaffordable for small-scale farmers in developing countries. Moreover, such insecticides may have adverse effects on human health or the environment. Mendesil et al. (2016a) documented the improper use of insecticides among field pea growers in Ethiopia, which exposed them to water, soil, and air contamination from leaching, runoff, and spray drift. The same study also documented detrimental effects on wildlife, fish, plants, and other non-target organisms.

Plant extracts have potential for use as pesticides against pea weevil. The oil of *Putranjiva roxburghii* seeds wall effectively repelled *B. pisorum* adults from infesting seeds of *Dalbergia sissoo* Roxb. (Kumar 2014). Oils of several aromatic plants, such as *Thymus vulgarus* (L.; Lamiales: Lamiaceae), *Santolina chamaecyparissus* (L.; Asterales: Asteraceae) and *Anagyris foetida* (L.; Fabales: Fabaceae), control *Callosobruchus chinensis* (L.; Coleoptera: Chrysomelidae), another seed-infesting beetle, suggesting that such oils used against *B. pisorum* (Righi-Assia et al. 2010). Plant extracts such as pyrethrum (a neurotoxin), *Acanthrospernum hispidum* D.C. (Asteraceae) (antifeedant), *Trichilia heudelotii* (antifeedant), *Vernonia* spp. (contains the neurotoxin pyrethrin), *Lippia adoensis* (contains a neurotoxin), *Piper guineanse* (a fumigant) and garlic (a repellant) can be AQ5 used against *B. pisorum* before egg laying occurs (Olaifa 2000).

Biological Control

Several studies have documented potential biological control agents for *B. pisorum*, such as *Eupteromalus leguminis* (Gahan; Hymenoptera: Pteromalidae). Study done in Northwest United States showed that the survival of *E. leguminis* depends on development of *B. pisorum* to the fourth instar but no increase was found in individual plant fitness resulting from enhanced parasitoid activity (Annis and O'Keeffe 1987; Baker 1990a,b). *Triaspis thoracica* (Curtis; Hymenoptera: Braconidae), which attacks the early stage larvae of the pest within the seed, has been reported to attack about 15 species of *Bruchus* in France (Nikolova 2016a). In Russia, *T. thoracica* has been recorded to cause up to 80% parasitism of *B. pisorum* larvae (Khrolinskii and Malakhanov 1979). From 1935 to 1939, several attempts were made to introduce *T. thoracica* into the United States from Austria and France (Larson et al. 1938). More than 140,000 specimens were released in Idaho, Oregon, California, Pennsylvania, and North Carolina, but *T. thoracica* did not successfully establish. In 1942, a second attempt was made to release the parasitoid, which also failed. *T. thoracica* appears to oviposit in its host's eggs, which are embedded in plant tissue (Huis et al. 1990). *B. pisorum* may not be the natural host of *T. thoracica* and this factor may explain the failure of *T. thoracica* to establish as the parasitoid appears to have difficulty piercing the egg of *B. pisorum* (Turnbull and Chant 1961, Huis et al. 1990).

Several species of *Uscana* (Hymenoptera: Trichogrammatidae) are egg parasitoids of various families of Coleoptera (Huis et al. 1990). *Uscana senex* (Grese; Hymenoptera: Trichogrammatidae) is reported to cause 50–80% parasitism, and it reduced seed damage by 70% in Chile after its introduction in 1987 (Huis 1991, Hormazábal and Gerding 1998). In Chile, these parasitoids are released twice weekly at the beginning of flowering until the pea pods are completely filled. *U. senex* has also displayed a degree of dispersal ability, although distance certainly influences the level of parasitism and as the distance from the release point increases, the level of egg parasitism decreases (Hormazábal and Gerding 1998). In Russia, *U. senex* is also reported to be very effective, parasitizing up to 70% of *B. pisorum* eggs (Karpova 1950). *U. senex* can be reared in the eggs of the bean weevil, *Acanthoscelides obtectus* (Say), an easily reared alternative host (Vasiljev 1947). Moreover,

Table 1. Management practices used for the control of *Bruchus pisorum* in various countries in different time period

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	Chemical control			
	Trade name (constitute)	Rate per ha	Remarks	Reference
1	*Rotenone crystalline (Rotenone)	4 kg	—	Brindley and Chamberlin 1952
2	Carbaryl 4L, 80S, XLR (1-naphthyl methylcarbamate)	2.5–3.5 liters	PHI 14 d grazing or harvest for forage, 21 d harvest dry seed. Do not apply more than 5.6 qts (4L or XLR) or 3.4 kg (80S)/A/ season.	Blodgett 2006
3	Fury 1.5 (zeta cypermethrin)	75–250 ml	PHI 21 d. 12 h REI. Do not apply more than 700 ml per season.	Blodgett 2006, Nikolova 2015a
4	Imidan 70 WP (N-(Mercaptomethyl) phthalimide, S -(O,O-dimethyl phosphorodithioate)	450–650 gm	PHI 7 d. 10 d for hay or 7 d for forage. Do not apply more than 1.8 lbs/A/ season. Minimum tank mix of 18 L./A. Do not cut treated fresh pea forage for hay.	Blodgett 2006, Homan and O'Keeffe 1979
5	Malathion (organophosphate)	200–400 liters	PHI 3 d. 12 REI. Do not graze or feed treated vines.	Blodgett 2006, Homan and O'Keeffe 1979
6	Mustang Max1.5EC (S-Cyano (3-phenoxyphenyl) methyl cis/trans 3-(2,2-dichloroethenyl)-2,2 dimethylcyclopropane carboxylate)	200–300 liters	PHI 21 d. 12 h REI. Do not apply more than 700 per season.	Blodgett 2006
7	Parathion (Organothiophosphate)	15 ml	Do not apply within 10 d of harvest. Do not apply within 15 d of harvest for peas used for forage.	Homan and O'Keeffe 1979
8	*Methoxychlor (organochlorine)	450 gm	Do not apply within 7 d of harvest.	Homan and O'Keeffe 1979, Brindley and Chamberlin 1952
9	*5% DDT dust (crystalline organochlorine)	17–22 kg		Brindley and Chamberlin 1952
10	Fumigant Phosphine (hydrogen phosphide)	120–240 gm/liter	Longer exposure is required to kill all the stages.	Waterford and Winks 1994
11	Mospilan (acetamiprid)	3 kg	—	Nikolova 2015a
12	Pyrethroid (Lambda-cyhalothrin)	7.5 gm	—	Seidenglanz et al. 2011
13	Pyrethroid (Alpha-cypermethrin)	12.5 gm	—	Seidenglanz et al. 2011
	Cultural control			
1.	Field sanitation by destroying crop residues, preventing shattering at harvest and eliminating volunteer plants	—	—	Blodgett 2006
2.	Early planting and harvesting	—	—	Smith 1990, Mihiretu and Wale 2013, Mendesil et al. 2016a
3.	Hot (50–55°C) and cold (–17°C) treatment	—	—	Garman 1917, Larson et al. 1935
	Biological control			
1.	Release of *Uscana senex* Grese	—	~80% parasitism of *B. pisorum* larvae is found in Russia	Larson et al. 1938, Huis et al. 1990, Khrolinskii and Malakhanov 1979, Nikolova 2016a
2.	Establishment of resistant varieties	—	Adet, Glyans, Modus, Kamerton, Svit and Pleven 4 are few resistant varieties established around the world	Hardie and Clement 2001, Nikolova and Georgieva 2015b, Mendesil et al. 2016b, Nikolova 2016b

both *U. senex* and *Trichogramma* spp. are commercially reared for biological control of pea weevil in Brazil (Parra 2014).

Resistant Varieties

Developing resistant varieties, either by conventional plant breeding or genetic engineering, is another potential way to control pea weevil. Improved pea varieties developed through plant breeding for higher yield and better seed quality, however, are usually more susceptible to pea weevil because of their uniform genetics and the loss of inherent resistance traits, such as altered nutritional content, and reduced plant defenses (Chen et al. 2015, Mendesil et al. 2016b).

Source of Resistance

The mechanisms underlying resistance to *B. pisorum* act at both the seed (seed coat and cotyledons) and pod levels (Hardie 1992). The CsCl (30% caesium chloride) density separation method has been developed for screening large numbers of plants to efficiently separate infested seed from intact seed in order to produce several advanced pea weevil resistant lines (Aryamanesh et al. 2012). Molecular-marker screening or single-plant selection using a glasshouse bioassay are other ways to develop resistant varieties of peas (Aryamanesh et al. 2012).

A study by Dochkova and Ilieva (2000) found that cultivars and lines of pea containing condensed tannins in the pod, grain coat, or interior, were more resistant to attack by *B. pisorum*. *Lathyrus* species (Fabaceae) have also been considered a source of resistance in breeding programs for *P. sativum*. Pollen of species such as *Lathyrus tingitanus* provide required nutrition to female *B. pisorum* that promote ovarian development (Annis and O'Keeffe 1984a), but *Lathyrus* species are not preferred for oviposition because of their defenses against pea weevil attack, such as formation of callus (neoplasm) by *L. tingitanus* and *L. sativus* pods after oviposition by *B. pisorum*. Callus formation enables the plant tissue to prolong the period of exposure of larvae to toxic compounds in the plant tissue. Unknown chemical stimulant might occur from the ovipositional fluid used for oviposition, since callus formation also occurs on parts of the pod on which no eggs were laid. This indicates a diffusion of chemical stimulants throughout the pod from the point of oviposition to the other parts of pod in *L. tingitanus*. However, a different mechanism causes callus formation in *L. sativus*. In *L. sativus,* callus growth began only after larval emergence and occurred only beneath eggs. This suggests that physical damage due to emerging larvae or some larval secretion triggers callus formation (Annis and O'Keeffe 1984b). Formation of callus or neoplasm as an induced resistance is conditioned by the *Np* allele and mediated by a class of natural products of lipid origin that are found in *B. pisorum*. These compounds are long-chain α,ω-diols, esterified at one or both oxygens with 3-hydroxypropanoic acid. Doss et al. (2000) called them 'Bruchins'. They are potent plant regulators and caused neoplastic growth in small amounts on pods of all *P. sativum* lines tested (Doss et al. 2000). Mated and unmated females contain similar levels of callus-inducing compounds while males contain less (less than 10% of the activity of mature females). Thin layer chromatography partitioning showed that the stimulating component present in female *B. pisorum* is a nonpolar compound. This suggests that the *Np* allele probably conditions sensitivity to a nonpolar component of pea weevil oviposition as a mechanism of resistance to the weevil (Doss et al. 1995). Neoplasm formation is also found to be triggered by the absence of UV light. Furthermore, in order to enhance *Np* expression at the field level, *Np* genotypes of *P. sativum* were intercropped with sorghum, resulting in a threefold increase in the percentage of *Np* pods. Promoting *Np* formation under field conditions by intercropping is a means of managing *B. pisorum* appropriate for small scale farming systems (Teshome et al. 2016).

High levels of insect resistance has been reported in the wild relatives of peas (Clement 2002, Sharma et al. 2005) and wild species is a non-preferred plant as a site for oviposition by *B. pisorum* (Ali et al. 1994), therefore *P. fulvum* has been used as a source of resistance to *B. pisorum* in breeding programs (Byrne 2005). *P. fulvum* accessions have been screened under field conditions for their susceptibility to *B. pisorum* (Hardie et al. 1995), and variation in their levels of resistance to oviposition has been observed (Clement et al. 2002).

Responses of Resistant Varieties

Laboratory and glasshouse bioassays have been developed in Australia and the United States for evaluating *P. fulvum* accessions for resistance to *B. pisorum*. Swollen *P. sativum* pods and long pods (<10–20 mm) provide optimal oviposition substrates. Dual-choice and no-choice laboratory bioassays are now developed using these traits to screen *P. fulvum* accessions (Hardie and Clement 2001). Mendesil et al. (2016b) found that female weevils preferred 'Adet' (an improved variety of pea) for oviposition, likely due to differences in pod features such as trichome number, wax and pod wall thickness, when compared with non-host leguminous plants such as wild pea (*P. fulvum*) and grass pea (*L. sativus*). Nikolova (2016b) compared the response of five pea (*P. sativum*) varieties, viz. Glyans, Modus, Kamerton, Svit (Ukrainian cultivars) and Pleven 4 (Bulgarian cultivar) and found that the spring pea cultivar Glyans was only weakly preferred by *B. pisorum* for oviposition in breeding programs. Nikolova (2016b) found that, for spring pea cultivars, both healthy seeds and seeds with parasitoid emergence holes germinated and resultant plants showed good growth and development, while plants from weevil-damaged seeds had poor germination, reduced vigor and low productivity (Nikolova 2016b). Although pea weevil resistant varieties are available around the world, there are currently no resistant varieties available in the United States (Blodgett 2006). In 2008, Byrne et al., demonstrated that seed resistance to larval pea weevil attack is more sustainable than the pod resistance to pea weevil oviposition as an effective defensive trait in hybrid pea varieties. This is because pod resistance, which is quantitatively inherited in the F2 population, is greatly reduced in the F3 and subsequent generations, while seed resistance remains present and effective in the F4 and F5 generations. It has thus been proposed by Byrne et al. (2008) that the heritability of pod resistance is low but that seed resistance is conserved in progressive generations and that complete seed resistance in peas to *B. pisorum* is controlled by three major recessive alleles (pwr_1, pwr_2, and pwr_3) and complete susceptibility by corresponding dominant alleles (PWR_1, PWR_2, and PWR_3). Nevertheless, large numbers of recessive resistant plants are needed to introduce these recessive alleles into the current field pea cultivars through hybridization and repeated backcrossing (Byrne et al. 2008). However, in another study Clement et al. (2009) showed that while pod surface characteristics increased neonatal larval mortality, seed resistance was not broadly transferred to interspecific progeny. Total mortality of *B. pisorum* on pods and seeds of eight F2:3 families was 50–70%, demonstrating that resistance in a secondary gene pool can be transferred to interspecific progeny (Clement et al. 2009).

A recent 2012–2014 study (Nikolova 2015a) on the tolerance of five spring pea varieties (Ukrainian varieties Glyans, Modus, Kamerton and Svit and the Bulgarian variety Pleven 4), indicated that the duration of development of flowers and pod influenced the seasonal dynamics of *B. pisorum*. Varieties with the shortest duration of flowering and pod development had the lowest densities of pea weevil, and thus tolerance was directly related to earliness of the variety. Other research indicates that resistance in pea varieties may be related to pod length, thereby affecting oviposition (Hardie and Clement 2001). To generate variation between the phenological development of the host plant and the life cycle of *B. pisorum*, different markers can be used to create new pea varieties (Nikolova 2015a). In another study, the variety Glyans was found to be the most tolerant to damage in comparison to susceptible variety Pleven 4, while parameters related to germination and vigor of seeds were influenced in the lowest degree (Nikolova and Georgieva 2015b). Similarly, in Ethiopia, measurements of percent seed damage (PSD) of 602 pea accessions in 2011 found some promising accessions/genotypes (gene bank accessions 32454 and 235002), which showed 17–33% PSD at the site where earlier overall PSD ranged from 75 to 92%. These results can be used in pea breeding programs to develop new varieties (Teshome et al. 2014).

Seed quality is also influenced by insect infestation. Weevil adults seek out pea flowers and weevil larvae attack pea seeds at an early stage when plants (including seeds and pods) have fewer protective tannins and polyphenols. During development, larvae feed on cotyledon and influence carbohydrates, proteins and phosphorus. Infestation by *B. pisorum* induces chemical changes in seeds to increase defenses against the pest (Nikolova 2016c). One study found that infestation by *B. pisorum* is positively associated with lower protein and phosphorous levels in two pea varieties (Renata and Solara) (Marzo et al. 1997). The same study also found increased phytate and protein contents to be associated with a lower risk of infestation. Another study found that crude proteins, total phenols, water soluble sugars and phosphorous in seeds increase when seeds are fed on by *B. pisorum* (Nikolova 2016c), while calcium content and trypsin activity decreases. The increase in protein concentration in seeds is defense-related (Nikolova 2016c). Nevertheless, some authors also claim that the chemical components have no direct influence on a variety's tolerance to *B. pisorum*, but this question remains unexplored till date (Odagiu and Porca 2002).

Transgenic varieties of pea are also being developed. Although transgenic crops are not allowed in several countries, research in Australia has led to the development of a transgenic pea with resistance to *B. pisorum* through the expression of the α-amylase inhibitor (Schroeder et al. 1995, Morton et al. 2000, Sousa-Majer et al. 2004). However, it has also been proposed that, although highly resistant under well-watered and cooler conditions, these transgenic pea varieties may be relatively more susceptible in warmer regions. As high temperature reduces resistance in this transgenic pea, and the number of seeds per pod and pod wall weight decrease with increasing temperature (Sousa-Majer 2002, de Sousa-Majer et al. 2007). High temperatures (27–32°C) reduce the expression level of α-AI-1, which in turn reduces the protective capacity of transgenic peas (de Sousa-Majer et al. 2007). The potential of transgenic legumes expressing α-amylase inhibitor to control *B. pisorum* infestations has been confirmed in several studies (Moreno and Chrispeels 1989, Pueyo et al. 1993). Expression of α-AI-1 (a gene for α-amylase inhibitor), provided 100% control of *B. pisorum* under glass house conditions (Schroeder et al. 1995) and field conditions (Morton et al. 2000). Nevertheless, the effect of transgenic pea varieties on natural enemies is unknown (Lüthi et al. 2010). Also, genetically modified field peas which showed resistance against *B. pisorum* has been rejected due to problem of allergic asthma (Lee et al. 2011, Mendesil 2014).

Conclusions

Peas are an important crop in Montana and a major source of protein, making *B. pisorum* infestations an emerging problem for local farmers. Lack of awareness among farmers about the source and means of spread of pea weevil to their region might be a limiting factor taking the necessary actions to prevent the spread of *B. pisorum*. Cultural practices, including early planting, harvesting, and early fumigation, along with intercropping, are important preventative strategies. Farmers also need awareness about the appropriate timing to treat seeds. Other cultural methods such as hot and cold seed treatments can be used by small-scale farming systems. Cultural control practices such as crop rotation and intercropping can both increase the productivity of farmland and minimize the risk of crop failure and falling market prices. Adoption of integrated pest management (IPM) techniques including cultural methods (adjustments in planting and harvesting times), biological control, the use of tolerant and resistant pea varieties and, as a last resort, chemical application, should all be considered for controlling *B. pisorum*. Due to the environmental and health risks associated with chemical control, it should be used sparingly and after all other techniques have been employed. Further research on the relationship between the blossoming dates of the field border and the main field, on the type of plowing equipment used to plant the peas, and the use of insecticides in connection with the borders may make the use of border trap crop strips, a valuable addition in *B. pisorum* control. The development of specific genotypes expressing neoplasm formation (*Np* allele) when grown under shade (devoid of UV light), along with intercropping, is a promising new addition to IPM programs against *B. pisorum*. Further studies should also look into possibly introducing *U. senex*, the egg parasitoid of *B. pisorum,* into Montana. Finally, the introduction of resistant pea varieties is another possible tool for control of *B. pisorum* in Montana. Additional studies are required to examine the influence of pigments and amino acids on pea variety tolerance to *B. pisorum*. Other biological control strategies such as natural predators, entomopathogenic fungi, and nematodes also need to be explored, as does the use of natural plant extracts as repellents and anti-oviposition compounds against *B. pisorum*.

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