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The Diamondback Moth in Canola and Mustard: Current Pest Status and Future Prospects

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Summary
Populations of the diamondback moth, *Plutella xylostella* (L.), routinely infest crops of canola (*Brassica napus* L. and *Brassica rapa* L.) and mustard (*Brassica juncea* (L.) Czern. and *Sinapis alba* L.) in the western Canadian prairies. In most years the insect causes minor economic damage, but in some years populations reach outbreak densities and substantial crop losses occur. The insect may overwinter in the prairies, but not frequently or in large numbers, and instead migrates northward from infested regions in the southern or western U.S.A. or northern Mexico on wind currents. The composition and timing of influxes has immense bearing on the damage caused by diamondback moth: the species is multivoltine, capable of producing as many as four generations per year in the prairies, and early arrival times can therefore result in greater population build-up than later arrivals. Its principal natural enemy, the hymenopteran parasitoid *Diadegma insulare* (Cresson), is not known to overwinter in the prairies and is believed to be carried northward along with its hosts. Consequently, whether invasions occur by one or both species has considerable effect on field densities of diamondback moth later in the season. Larvae may feed on all above-ground plant structures, but are particularly damaging when leaves senesce late in the season and they feed on pericarp of canola pods, preventing ripening, and so reducing yield. Brassicaceous weeds can provide important bridge hosts for diamondback moth, and among cultivated prairie crops, white mustard (*S. alba*) is most preferred followed by *B. rapa*, *B. juncea*, and *B. napus*. Soil fertility affects susceptibility of canola to infestation by diamondback moth. Females prefer to oviposit on plants fertilized at the rate recommended for canola production rather than on plants fertilized at higher or lower levels. Canola high in sulfur is particularly attractive, and field distributions of the insect were correlated with the highest levels of sulfur content in canola leaves. Nutrient levels in the leaves of plants fed upon by diamondback moth larvae also affect the *D. insulare* parasitoid which develops most rapidly in larvae that feed on leaves highly fertilized. The main control tactic for this pest currently involves chemical insecticide application when parasitoid populations are not abundant, but good potential exists for exploiting other control strategies, such as a bioinsecticide derived from the bacterium, *Bacillus thuringiensis* Berliner, or implementing agronomic practices that enhance the effectiveness of diamondback moth parasitoids and predators.

Introduction
The Canadian prairie provinces harbor a diverse fauna of insect pest species but none is as widespread on a worldwide basis as the diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) (Figure 1). Diamondback moth is restricted in its host range to plants of the family Brassicaceae. In most other regions of the world it attacks crops of cabbage (*Brassica oleracea* L. var. capitata), cauliflower (*B. oleracea* var. botrytis), broccoli (*B. oleracea* var. italica), kale (*B. oleracea* var. alboglabra), and many others, but these crops are rarely grown commercially in western Canada, and if so, over relatively small production areas. Canola (*Brassica napus* L., *Brassica rapa* L.) and mustard (*Brassica juncea* (L.) Czern., *Sinapis alba* L.) crops, however, are plentiful in the prairie provinces and can serve as hosts for this insect. In addition, diamondback moth can feed and reproduce on a number of brassicaceous weeds that are common across the prairies[1,2]. On a worldwide scale, diamondback moth has been considered responsible for over $1 billion (U.S.) annually in economic losses[3]. In western Canada, crop losses vary considerably from year to year. In some years the population densities and economic importance of diamondback moth can be negligible, but in other years the pest can cause many millions of dollars in lost revenue[4,5].

Figure 1. Adult of diamondback moth on canola. Photo credit: Lloyd Dosdall.

A number of factors are responsible for the exceptional pest status of diamondback moth. Its host plants in the Brassicaceae are abundant and diverse, comprising 350 genera and more than 3,500 species worldwide[6]. Brassicaceae are also widely distributed geographically, and because they contribute such an important food source for humankind, they are often grown very abundantly. For instance the vast monocultures of canola and mustard in the Canadian prairies encompass some 6.1 million ha annually[7], and the area devoted to production of these crops is expected to increase in future years[8]. Diamondback moth has enormous reproductive potential, enabling it to rapidly increase its population size and to acquire the genetic mutations necessary to withstand environmental change and to develop resistance mechanisms to a wide range of insecticides with diverse modes of action[3]. Diamondback moth is not known to undergo diapause, but rather is multivoltine and can produce as many as four and 20 generations per year in temperate and tropical regions, respectively[9,10].

Origins of Diamondback Moth in the Canadian Prairies

Diamondback moth is not known to overwinter in western Canada, at least not in large numbers or frequently. In one study in central Alberta, several cages placed onto canola stubble from the previous growing season very early in spring, as soon as frost had thawed from the soil but before development of any host plants occurred, were later found to contain living specimens of diamondback moth[11]. The traps were sealed to the outside, and the only realistic explanation was that the species had overwintered at the site. The occurrence of a heavy, insulating snowfall in early fall preceding the collections was thought to help explain these observations. However, subsequent attempts to overwinter diamondback moth were unsuccessful regardless of location (Saskatoon, SK and Vegreville, AB), soil organic residue levels, or the insect life stage used[12].

Diamondback moth populations in western Canada in spring and early summer are then best explained by influxes of migrant moths from source regions in the U.S.A., and substantial circumstantial evidence exists to support this conclusion. Dosdall et al.[12] reported that high densities of diamondback moth throughout the prairies in May 2001 coincided with strong air flow from the southern U.S.A. in Texas, and this was corroborated by researchers in northwestern Texas who observed massive emergences of the insect from brassicaceous crops and weeds at the same time. Backward trajectories that modeled airflow during this period further supported this hypothesis[12]. Hopkinson and Soroka[13] used a network of pheromone traps and back trajectories of air flow from a number of possible source regions in 1997 and 1998, and successfully explained some observed moth populations from air flow originating over southern Texas prior to moth occurrence in the eastern prairies. However, the trajectory analysis failed to explain Alberta's moth populations, suggesting a unique source, perhaps California or the Pacific northwest[13]. The wind trajectory project has continued to expand the number of sites being monitored both in the U.S.A. and Mexico as well as in Canada. The models are implemented annually during the growing season, together with a network of sentinel sites with pheromone traps, to provide an early-warning system for the potential arrival of diamondback moth populations into canola production areas of the prairies[14] (Anonymous 2011). Vigilant monitoring can alert growers to threat from diamondback moth attack, and can help detect multiple invasions from air flow.

Life Cycle, Damage, and Crop Loss by Diamondback Moth

Diamondback moth eggs are laid mainly on upper leaf surfaces[15] (Justus et al. 2000) and hatch in four to eight days. First-instar larvae bore through the leaf epidermis and feed on cells of the leaf mesophyll[16] (Harcourt 1957). The three subsequent larval instars are surface feeders, and consume leaves, buds, flowers, or pods (Figure 2). An average duration of 4.0, 3.6, 3.4, and 4.2 days were required for completion of the first to fourth larval instars, respectively, and 7.8 to 9.8 days were required for pupation under field conditions in Ontario[16] (Harcourt 1957).

Figure 2. Diamondback moth larva. Photo credit: Lloyd Dosdall.

Damage inflicted by diamondback moth occurs through larval feeding, and can affect all crop developmental stages and all above-ground plant parts. Much depends on the arrival time of the adults. An influx of adults early in the season can be associated with damage to seedlings by the larvae they produce, sometimes even plants in the early true-leaf stages. In most instances, however, moth invasions of western Canadian canola and mustard crops occur later, when crops are in the rosette stage. An arrival time of moths in mid May can enable the species to complete three or four generations by the time crops are in the pod development stages, and most vulnerable to attack[17] (Philip and Mengersen 1989). Larval feeding damage to canola leaves is usually considered to have a minor effect on yield, but larval feeding on buds and flowers can be more damaging, especially when plants are under abiotic stress (e.g., drought) and cannot compensate by producing new buds and flowers (Figure 3). In the pod stages, leaves senesce, and even though larvae may prefer to feed on leaves, they must subsist by stripping pod pericarp, preventing eventual seed maturation. In prairie fields under severe attack by diamondback moth, yield losses can be extreme (Figure 4).

Figure 3. Diamondback moth feeding damage to canola buds. Photo credit: Lloyd Dosdall.

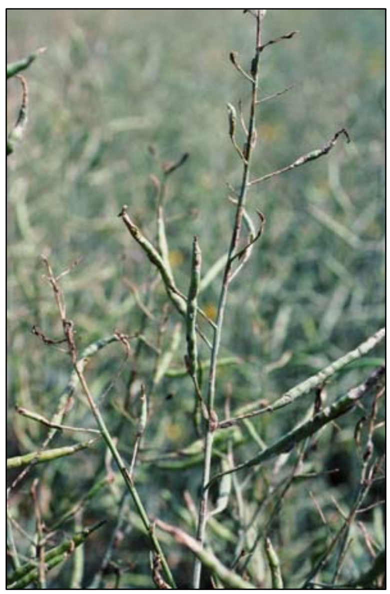

Figure 4. Canola severely damaged by diamondback moth feeding. Photo credit: Lloyd Dosdall.

Species of Brassicaceae differ in their susceptibilities as hosts for diamondback moth. Sarfraz et al.[18] compared site selection for egg-laying, larval and pupal developmental times, quantity of leaf tissue eaten, and several parameters of F_1 individuals reared as larvae on *B. napus*, *B. rapa*, *B. juncea*, *Brassica carinata* L., *B. oleracea* and *S. alba*, and found that ovipositing females preferred *S. alba* and *B. rapa*, and development times of larvae and pupae were most rapid on *B. juncea* and *S. alba*. Differences in preference and performance of diamondback moth were also found among some common brassicaceous weed species. Sarfraz et al.[2] (2011) found that females greatly preferred wild mustard, *Sinapis arvensis* L., for egg-laying compared with wormseed mustard, *Erysimum cheiranthoides* L., and Shepherd's-purse, *Capsella bursa-pastoris* (L.) Medicus. In addition, survival was higher, development was faster, and leaf consumption was greater for larvae reared on wild mustard than on the other two weed species[2]. Spiderflower, *Cleome hassleriana* Chod. (Capparaceae), and garden nasturtium, *Tropaeolum majus* L. (Tropaeolaceae), are not members of the Brassicaceae, but they contain glucosinolates in their leaf tissues, and glucosinolate compounds are characteristic of brassicaceous plants. Although *C. hassleriana* and *T. majus* were not preferred as host plants for egg-laying by females, diamondback moth larvae could complete their development on both species[1].

Development of diamondback moth can also be influenced by varieties within species. Although survival of diamondback moth did not vary for individuals reared from egg to pupa on the *B. napus* varieties Q2, Liberty, and Conquest, females laid significantly more eggs on Liberty than on Q2 or Conquest[18]. Developmental time of females from larva to prepupa tended to be faster on Liberty and Conquest than on Q2, but female body weight was greater for individuals reared as larvae on Q2 than on Liberty[18].

Host plant selection and larval development of diamondback moth is also affected by the nutrient content of canola leaf tissue. For egg-laying, females selected plants that received quantities of soil fertilizer that corresponded to the level recommended for canola production, compared to unfertilized plants or plants that received three and five times the recommended levels of fertilizer[19]. Similarly, larval survival was greatest and larval development was fastest on plants grown at intermediate levels of soil fertility[19].

Among the different plant nutrient constituents, sulfur appears to have the greatest influence on diamondback moth. Gupta and Thorsteinson[20] found that diamondback moth females laid significantly more eggs on sulfur-fertilized plants than on plants grown in soil deficient in sulfur, and Marazzi et al.[21] found that females laid more eggs on artificial leaves treated with extracts of plants grown in soil containing sulfur than on artificial leaves sprayed with extracts that did not contain sulfur. In canola in southern Alberta, Sarfraz et al.[22] found that distributions of diamondback moth were correlated with leaf sulfur content in one of three fields studied, and suggested that plants grown in soil high in sulfur content could serve as hot spots for diamondback moth infestations.

B. napus, *B. rapa*, and *S. alba* can respond to larval feeding by increasing their root biomass, presumably as a strategy to enable them to compensate for herbivory through the uptake of greater quantities of soil water and nutrients[18]. However, the magnitude of root mass increase is dependent on variety and species. For instance, *B. napus* cv. Q2 produced approximately two-fold more root biomass when infested with 10 larvae per plant, but root mass increase by *B. napus* cv. Conquest was less, only 1.5-fold more when infested, and *B. napus* cv. Liberty produced root mass quantities that were similar among infested and noninfested plants[18]. Root biomass of *B. juncea* did not vary for infested and noninfested plants. The degree of root biomass increase is also related to soil nutrient content. Sarfraz et al.[19] found that the greatest increase in *B. napus* root biomass occurred to plants treated with intermediate levels of fertilizer (i.e., the rate recommended for canola production) rather than low or high fertilizer applications.

Monitoring of Diamondback Moth

Monitoring of diamondback moth is conducted in several ways: with pheromone traps, sweep net sampling, and individual plant examinations. Traps baited with sex pheromone have been developed for canola crops in the prairies using a blend of four components[23]. In a study to improve the efficiency of this practice, Evenden and Gries[24] found that lures designed to release pheromone at a high rate were less attractive to male moths in field trials than lures that released pheromone at a low rate, and that older lures were more attractive to diamondback moth than fresh lures. Pheromone traps set out early in the season can provide an early warning of moth invasions and risk to crops, although the predictive capability of trap catches with field larval densities can be inconsistent[25].

Sweep net sampling can determine the presence and general abundance of the species in the field, but does not provide a good estimate of larval density because no correlative studies have been conducted to relate sweep net captures with density. Nevertheless, high population counts in sweep sampling can prompt producers to perform more accurate counts of densities per unit area (Figure 5). The most accurate method of estimating diamondback moth population density in canola is then to perform counts of diamondback moth specimens per plant over a given area of a field.

Figure 5. Sweep net collection of canola insects, primarily diamondback moth larvae. Photo credit: Lloyd Dosdall.

Control of Diamondback Moth

In western Canada, control of diamondback moth is achieved by chemical and biological means; no cultural control strategies are currently employed in canola and mustard cropping systems. Both organophosphate and pyrethroid compounds are currently registered for foliar applications, and chemical intervention is recommended in canola when larval populations exceed 100 to 150 per m^2 in immature to flowering plants and 200 to 300 per m^2 in plants with flowers and pods[26]. For seedlings, control is recommended when 25 to 33% of the cotyledons or true leaves are defoliated. These economic threshold recommendations are nominal, without basis in replicated experimental studies. Although foliar applications with formulations of bioinsecticide containing the delta-endotoxin of the bacterium *Bacillus thuringiensis* (*B*. *t*.) subspecies *kurstaki* are proven to be effective and less damaging to non-target organisms than chemical insecticides[3,27], *B*. *t*. is not registered for application in canola in Canada. Canola transgenic for expression of the cry1Ac gene has been developed and provided protection from diamondback moth infestation[28], but no such transgenic crops are registered.

Natural enemies of diamondback moth are important for biological control, and comprise both parasitoids and predators. The three main parasitoids of diamondback moth in the prairies of western Canada belong to two families of Hymenoptera. The wasps *Diadegma insulare* (Cresson) and *Diadromus subtilicornis* (Gravenhorst) are members of the Ichneumonidae, and *Microplitis plutellae* (Muesbeck) is in the Braconidae[29,30]. *D*. *insulare* and *M*. *plutellae* attack larvae of diamondback moth, and *D*. *subtilicornis* parasitizes pupae[7,30]. Among these species, *D*. *insulare* is considered the most important for biological control (Figure 6). For instance, in Alberta *D*. *insulare* parasitized 45% of diamondback moth individuals in 1992; by comparison, *M*. *plutellae* and *D*. *subtilicornis* were each responsible for approximately 15% parasitism[29]. Similarly, in Saskatchewan *D*. *insulare* accounted for 30% of diamondback moth parasitism, with about 15% parasitism by *D*. *subtilicornis* and *M*. *plutellae* combined[29].

Figure 6. Adult female of the diamondback moth parasitoid, *Diadegma insulare*. Photo credit: Lloyd Dosdall.

D. insulare is native to the neotropics[30,31], and this appears to explain its inability to tolerate cold conditions: at temperatures of only 4°C, its pupae soon die[32]. Consequently western Canadian populations are believed to migrate northward in spring with their diamondback moth hosts. *D. insulare* can parasitize all four larval instars of diamondback moth and the parasitoid emerges as a final instar when its hosts reach their prepupal stage. Adults require a nutrient source for survival, and as a result they spend more time in habitats where flowering plants are abundant so they can feed[33]. Flowering plants like alyssum, *Lobularia maritime* (L.) Desv. (Brassicaceae), can provide food sources for adults of *D. insulare*, and the parasitoid is attracted to plant tissue damaged by diamondback moth larvae[34]. This appears to explain why field populations of *D. insulare* can be clustered, often in patches correlated with high populations of diamondback moth[35,22].

The development of *D. insulare* can be affected by the plant species upon which its diamondback moth hosts feed, and the effectiveness of *D. insulare* for parasitizing its hosts is also dependent on host plant species[36,37]. Parasitized larvae of diamondback moth consumed less foliage than their non-parasitized counterparts[36,37]. Plant quality also affected development of *D. insulare*. Sarfraz et al.[38] found that parasitism and survival of larvae of *D. insulare* were favored when their host larvae were reared on plants treated with three- to five-fold more fertilizer than is currently recommended for canola production, and that developmental rate from egg to pre-pupa tended to be slower when larvae were reared at the recommended soil fertility rate than at higher or lower levels.

The parasitoid *M. plutellae* has a transcontinental distribution in North America[29,30]. Unlike *D. insulare*, *M. plutellae* overwinters in western Canada, and can be present early in the season to parasitize hosts[39]. However, *M. plutellae* is generally less abundant than *D. insulare* in canola fields, and distribution of the species does not appear to be correlated with leaf sulfur content[22].

Very little is known of the biology of *D. subtilicornis* in the prairies of western Canada. It is a solitary pupal endoparasitoid of the diamondback moth. Females oviposit in prepupae or in pupae, but much more frequently in newly formed versus older pupae[40]. Females of *D. subtilicornis* can use their mouthparts to enlarge wounds made by the ovipositor during egg-laying, and may then feed on fluid oozing from the wound[40].

The contribution of predators to biological control of diamondback moth in the prairies is unknown. Canola and mustard crops harbour a diverse fauna of predators, comprised mainly of various species of carabid beetles (Coleoptera: Carabidae), lady beetles (Coleoptera: Coccinelidae), syrphid flies (Diptera: Syrphidae), lacewings (Neuroptera: Chrysopidae), rove beetles (Coleoptera: Staphylinidae), and several families of spiders (Araneae). However, with the exception of the Carabidae, little research on this fauna has been undertaken. A number of studies have used species of carabids as indicators of treatment effects in agro-ecology (e.g. [41,42,43]) and consequently this group is among the most well known of the predators in canola. For example, Broatch[44] documented 59 species of carabids in canola from a single site in central Alberta over three years of collections. However, no studies have focused specifically on predation of diamondback moth in the prairies. In view of the importance of predatory insects for reducing pre-imaginal populations of diamondback moth in some other cropping systems (e.g.[45]), it is evident that further study is warranted to better resolve this important gap in our knowledge of mortality factors that can impact diamondback moth populations in prairie agro-ecosystems.

Prospects for Improved Management of Diamondback Moth

There is much opportunity for optimizing monitoring and control strategies for diamondback moth, and success in this area would depend upon the research effort that can be focused on these aspects. A primary need is to develop more accurate economic thresholds, based on replicated studies for different crop developmental stages, and incorporating population densities of natural enemies into those threshold determinations.

Previous studies to determine the species composition and relative abundances of diamondback moth parasitoids are now dated, and the original studies did not extend across a sufficiently broad geographical area to provide representative information on the fauna or faunal differences among eco-regions. For example, the survey data reported by Braun et al.[29] represented samples from fewer than 30 commercial fields of canola in central Saskatchewan and Alberta, with no data from mustard crops, from the Peace River region of Alberta and British Columbia, and with no data from Manitoba. More extensive sampling is needed to provide researchers with improved understanding of diamondback moth parasitoid biodiversity and faunal variation among eco-regions and between years, so that biological control strategies can be tailored to accommodate different cropping systems and locations. As stated earlier, predators of diamondback moth have not been well studied in prairie agro-ecosystems, and probably represent an important resource that could be better exploited by farmers for biological control. Research is needed to determine the characteristics of cropping systems that can enhance their effectiveness.

Cultural strategies for diamondback moth management have been inadequately studied, yet may hold promise for mitigating infestation levels. Dead-end trap cropping for diamondback moth control, as proposed by Shelton and Nault[46], may not be practical in prairie agriculture because it is not possible to predict years in which diamondback moth invasions will occur. Farmer adoption of planting strips of the susceptible weed, *Barbarea vulgaris* R. Br. (Brassicaceae), could be difficult since the pervading mentality is to remove weeds, not plant them. However, other possibilities exist. The positive attraction of diamondback moth adults for plants high in tissue sulfur content could perhaps be exploited to draw in moths in a trap crop system, or perhaps sulfur additions could be combined with planting susceptible trap borders of *B*. *rapa* around a main *B*. *napus* crop. Spraying the trap crops with insecticide rather than the entire crop would reduce environmental damage and economic costs.

The importance of weed management should be investigated for optimizing control of diamondback moth. Anecdotal reports have documented the arrival of migrant adults in western Canada in spring before canola and mustard crops are even planted, and it is probable that the early migrants are being sustained on brassicaceous weeds, such as flixweed (*Descurainia sophia* (L.) Webb) and shepherd's purse (*Capsella bursa-pastoris* (L.) Medicus), that overwinter as seedlings. Management of these host plants could be important for reducing diamondback moth infestations later in the season.

Research on the use of intercropping in prairie agriculture has recently drawn interest as an alternative agronomic practice for increasing crop diversity and yields, and for controlling pests. For instance, Hummel et al.[47] found that intercrops of canola and wheat resulted in reduced infestations of root maggots (*Delia* spp.), and in a vegetable cropping system, Buranday and Raros[48] found that infestations of diamondback moth were significantly lower when collards were intercropped with tomatoes than when collards were planted in pure stands. The potential application of this strategy for reducing infestations of diamondback moth in prairie oilseed crops is worthy of investigation.

B.t.-transgenic canola, engineered to express one or more genes for resistance to diamondback moth, has proven effectiveness against this pest[28], but it is not likely to comprise a component in future management. There is considerable public reluctance to adopt *B.t.* transgenic technology for crops with food uses. For example, *B.t.* potatoes were registered but soon withdrawn from production in Canada. Secondly, there will be additional costs associated with the purchase of *B.t.*-transgenic seed, and because diamondback moth is an irregular pest on the prairies, it is probable that farmers would forego this input cost in favor of foliar applications of insecticide if economically significant populations of the pest develop. A more realistic future development would be the registration of *B.t.* as a foliar spray, which has been a successful strategy in Australia for *P. xylostella* management in canola[49].

Conclusion

Diamondback moth is virtually certain to remain a major component of the insect pest fauna of the prairies in future years. The demands of an ever-increasing human population for edible oil, as well as the need for biofuel production to reduce the use of non-renewable energy, is predicted to result in increases in the area devoted to production of brassicaceous oilseed crops across the prairies[8]. The efforts of canola producers to increase yields will provide an abundance of diamondback moth host plants grown in resource-rich soils – conditions that are ideal for diamondback moth development and reproduction. Moreover, even relatively conservative climate change scenarios are predicted to result in northerly increases in the latitude in North America where diamondback moth can survive and reproduce continuously, and climate change is also predicted to increase the number of generations per year that the species can accomplish in the prairies[5]. Nevertheless, the vulnerability of this species to biological control agents and to bioinsecticides offers important opportunities for managing this pest in a manner that enhances environmental and economic sustainability.

References

1. Sarfraz, M., L.M. Dosdall, and B.A. Keddie. 2010a. Performance of the specialist herbivore *Plutella xylostella* (Lepidoptera: Plutellidae) on Brassicaceae and non-Brassicaceae species. Can. Entomol. 142:24-35.
2. Sarfraz, M., L.M. Dosdall, B.A. Keddie, and J. Myers. 2011. Larval survival, host plant preferences and developmental responses of the diamondback moth *Plutella xylostella* (Lepidoptera: Plutellidae) on wild brassicaceous species. Entomol. Sci. 14: 20-30.
3. Talekar, N. S., and A.M. Shelton. 1993. Biology, ecology, and management of thediamond back moth. Ann. Rev. Entomol. 38:275-301.
4. Western Committee on Crop Pests. 1995. Minutes of the 34th Annual Meeting, 20-21 October 1995. Victoria, BC, Canada.
5. Dosdall, L.M., R.M. Weiss, O. Olfert, P.G. Mason, and J.J. Soroka. 2008. Diamondback moth, *Plutella xylostella* (L.), as a pest of canola in Canada: Its historical impact on the crop and predicted effects of climate change on its pest status. Pages 112-121 *In*: A.M. Shelton, H.L. Collins, Y. Zhang, and Q. Wu (eds.), Proceedings of the Fifth International Workshop on the Management of Diamondback Moth and Other Crucifer Pests, Beijing, China, 24-27 October 2006.
6. Warwick, S. I., A. Francis, and G. A. Mulligan. 2003. Brassicaceae of Canada. Government of Canada. http://www.cbif.gc.ca/spp_pages/brass/index_e.php
7. Statistics Canada. 2007. Field Crop Reporting Series, Catalogue number 22-002-XIE.
8. Canola Council of Canada. 2010. Canadian canola industry. http://www.canolacouncil.org/canola_boost.aspx
9. Harcourt, D.G. 1986. Population dynamics of the diamondback moth in southern Ontario. *In*: Talekar, N.S. (ed.), Proc. First International Workshop on the Management of Diamondback Moth and Other Crucifer Pests, Tainan, Taiwan, 11-15 March 1985, pp. 3-16.
10. Vickers, R.A., M.J. Furlong, A. White, and J.K. Pell. 2004. Initiation of fungal epizootics in diamondback moth populations within a large field cage: Proof of concept of auto-dissemination. Ent. Exp. Appl. 111:7-17.
11. Dosdall, L.M. 1994. Evidence for successful overwintering of diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), in Alberta. Can. Entomol. 126:183-185.
12. Dosdall, L.M., P.G. Mason, O. Olfert, L. Kaminski, and B.A. Keddie. 2004. The origins of infestations of diamondback moth, *Plutella xylostella* (L.), in canola in western Canada. Pages 95-100 *In*: N.M. Endersby, and P.M. Ridland (eds.), Proceedings of the Fourth International Workshop on the Management of Diamondback Moth and Other Crucifer Pests, Melbourne, Australia, 26-29 November 2001.
13. Hopkinson, R.F., and J.J. Soroka. 2010. Air trajectory model applied to an in-depth diagnosis of potential diamondback moth infestations on the Canadian prairies. Agric. Forest Meteorol. 150:1-11.

14. Anonymous. 2011. 2011 Diamondback moth forecast. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/prm13419
15. Justus, K.A., L.M. Dosdall, and B.K. Mitchell. 2000. Oviposition by *Plutella xylostella* (Lepidoptera: Plutellidae) and effect of phylloplane waxiness. J. Econ. Ent. 93:1152-1159.
16. Harcourt, D.G. 1957. Biology of the diamondback moth, *Plutella maculipennis* (Curt.) (Lepidoptera: Plutellidae), in Eastern Ontario. II. Life-history, behaviour, and host relationship. Can. Entomol. 12:554-564.
17. Philip, H., and E. Mengersen. 1989. Insect Pests of the Prairies. University of Alberta Press, Edmonton, AB. 122 pp.
18. Sarfraz, M., L.M. Dosdall, and B.A. Keddie. 2007. Resistance of some cultivated Brassicaceae to infestations by *Plutella xylostella* (Lepidoptera: Plutellidae). J. Econ. Entomol. 100:215-224.
19. Sarfraz, M., L.M. Dosdall, and B.A. Keddie. 2009a. Bottom-up effects of host plant nutritional quality on *Plutella xylostella* (Lepidoptera: Plutellidae) and top-down effects of herbivore attack on plant compensatory ability. Eur. J. Entomol. 106:583-594.
20. Gupta, P.D., and A.J. Thorsteinson. 1960. Food plant relationship of diamondback moth (*Plutella maculipennis* (Curt.)). II. Sensory regulation of oviposition of the adult female. Entomol. Exp. Appl. 3:305–314.
21. Marazzi, C., B. Patrian, and E. Städler. 2004. Secondary metabolites of the leaf surface affected by sulfur fertilization and perceived by the diamondback moth. Chemoecol. 14:81–86.
22. Sarfraz, R.M., L.M. Dosdall, A.J. Blake, and B.A. Keddie. 2010b. Leaf nutrient levels and the spatio-temporal distributions of *Plutella xylostella* and its larval parasitoids *Diadegma insulare* and *Microplitus plutellae* in canola. BioControl 55:229-244.
23. Chisholm, M.D., W.F. Steck, E.W. Underhill, and P. Palaniswamy. 1983. Field trapping of diamondback moth *Plutella xylostella* using an improved four-component sex attractant blend. J. Chem. Ecol. 9:113-118.
24. Evenden, M.L., and R. Gries. 2010. Assessment of commercially available pheromone lures for monitoring diamondback moth (Lepidoptera: Plutellidae) in canola. J. Econ. Ent. 103:654-661.
25. Miluch, C.E. 2010. Development of a Semiochemical-based Monitoring System for Diamondback Moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) in Canola in Alberta. M.Sc. Thesis, University of Alberta, Edmonton, AB. 113 pp.
26 Western Committee on Crop Pests. 2010. Guidelines for the control of insect pests. http://www.westernforum.org/Documents/WCCP/WCCP_documents/WCCP_Guidelines/WCCP_08/Oilseeds-WCCP-June09Revised.pdf
27. Kumar, K.P., and G.T. Gujar. 2005. Baseline susceptibility of the diamondback moth, *Plutella xylostella* (Linnaeus) to *Bacillus thuringiensis* Cry1A toxins in India. Crop Prot. 24:207-212.
28. Ramachandran, S., G. D. Buntin, J.N. All, P.L. Raymer, and C.N. Stewart. 1998. Greenhouse and field evaluations of transgenic canola against diamondback moth, *Plutella xylostella*, and corn earworm, *Helicoverpa zea*. Agron. J. 92:368-374.
29. Braun, L., O. Olfert, J. Soroka, P. Mason, and L.M. Dosdall. 2004. Diamondback moth biocontrol activities in Canada. Pages 144-146 *In*: A.A. Kirk, and D. Bordat (eds.): Improving Biocontrol of *Plutella xylostella*. Proceedings of the International Symposium, 21-24 October 2002, Montpellier, France.
30. Sarfraz, M., B.A. Keddie, and L.M. Dosdall. 2005. Biological control of the diamondback moth, *Plutella xylostella* (L.): A review. Biocontr. Sci. Technol. 15:763-789.
31. Wagener, B., A. Reineke, B. Löhr, C.P.W. Zebitz. 2006. Phylogenetic study of *Diadegma* species (Hymenoptera: Ichneumonidae) inferred from analysis of mitochondrial and nuclear DNA sequences. Biol. Control 37:131-140.
32. Okine, J.S., E.R. Mitchell, and G.Y. Hu. 1996. Low temperature effect on viability of *Diadegma insulare* (Hymenoptera: Ichneumonidae) and effect of this parasitoid on feeding rate of diamondback moth larvae (Lepidoptera: Plutellidae). Fla. Entomol. 7:503-509.
33. Idris, A.B., and E. Grafius. 2001. Evidence of *Diadegma insulare* (Cresson), a parasitoid of diamondback moth, *Plutella xylostella* (L.), present in various habitats. Pakistan J. Biol. Sci. 1:742-743.
34. Mitchell, E.R, G.Y. Hu, J.S. Okine, and J.E. Carpenter. 1999. Parasitism of diamondback moth (Lepidoptera: Plutellidae) larvae by *Cotesia plutellae* (Hymenoptera: Braconidae) and *Diadegma insulare* (Hymenoptera: Ichneumonidae) in cabbage fields after inundative releases of *C. plutellae*. J. Entomol. Sci. 34:101-112.
35. Ulmer, B.J., L.M. Dosdall, and G.A.P. Gibson. 2005. Spatio-temporal distribution patterns of the diamondback moth and its principal parasitoid, *Diadegma insulare*, in canola crops and the occurrence of hyperparasitism. Brassica 6:63-69.
36. Sarfraz, M., L.M. Dosdall, and B.A. Keddie. 2008. Host plant genotype of the herbivore *Plutella xylostella* (Lepidoptera: Plutellidae) affects the performance of its parasitoid *Diadegma insulare* (Hymenoptera: Ichneumonidae). Biol. Contr. 44:42-51.
37. Sarfraz, M., L.M. Dosdall, and B.A. Keddie. 2009b. Fitness of the parasitoid *Diadegma insulare* is affected by its host's food plants. Basic Appl. Ecol. 10:563-572.
38. Sarfraz, R.M., L.M. Dosdall, and B.A. Keddie. 2009c. Host plant nutritional quality affects the performance of the parasitoid *Diadegma insulare*. Biol. Contr. 51:34-41.

39. Putnam, L.G. 1978. Diapause and cold hardiness in *Microplitis plutellae*, a parasite of the larvae of the diamondback moth. Can. J. Plant Sci. 58:911-913.
40. Tran, T., and K. Takasu. 2000. Host age selection by the host-feeding pupal parasitoid *Diadromus subtilicornis* (Gravenhorst) (Hymenoptera: Ichneumonidae). Appl. Entomol. Zool. 35:549-556.
41. Cárcamo, H.A., and J.R. Spence. 1994. Crop type effects on the activity and distribution of ground beetles (Coleoptera: Carabidae). Environ. Entomol. 23:684-692.
42. Butts, R.A., K.D. Floate, M. David, R.E. Blackshaw, and P.A. Burnett. 2003. Influence of intercropping canola or pea with barley on assemblages of ground beetles (Coleoptera: Carabidae). Environ. Entomol. 32:535-541.
43. Bourassa, S., H.A. Cárcamo, F.J. Larney, and J.R. Spence. 2008. Carabid assemblages (Coleoptera: Carabidae) in a rotation of three different crops in southern Alberta, Canada: A comparison of sustainable and conventional farming. Environ. Entomol. 37:1214-1223.
44. Broatch, J.S. 2008. Root Maggot and Beneficial Insect Dynamics in Response to Weed Populations in Canola. Ph.D. Thesis, University of Alberta, Edmonton, AB. 255 pp.
45. Furlong, M.J., K.H. Ju, P.W. Su, J.K. Chol, R.C. Il, and M.P. Zalucki. 2008a. Integration of endemic natural enemies and *Bacillus thuringiensis* to manage insect pests of Brassica crops in North Korea. Agric., Ecosys. and Environ. 125:223–238.
46. Shelton, A.M., and B.A. Nault. 2004. Dead-end trap cropping: A technique to improve management of the diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae). Crop Prot. 23:497-503.
47. Hummel, J.D., L.M. Dosdall, G.W. Clayton, T.K. Turkington, N.Z. Lupwayi, K.N. Harker, and J.T. O'Donovan. 2009. Canola–wheat intercrops for improved agronomic performance and integrated pest management. Agron. J. 101:1190-1197.
48. Buranday, R.P., and R.S. Raros. 1975. Effects of cabbage-tomato intercropping on the incidence and oviposition of the diamond-back moth, *Plutella xylostella* (L.). Philipp. Entomol. 2:369–374.
49. Furlong, M.J., H. Spafford, P.M. Ridland, N.M. Endersby, O.R. Edwards, G.J. Baker, M.A. Keller, and C.A. Paull. 2008b. Ecology of diamondback moth in Australian canola: Landscape perspectives and the implications for management. Aust. J. Exp. Agric. 48: 1494-1505.