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Profile

Ecology and Management of the Western Bean Cutworm (Lepidoptera: Noctuidae) in Corn and Dry Beans—Revision With Focus on the Great Lakes Region

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Abstract

The western bean cutworm, *Striacosta albicosta* (Smith) is a native North American pest of corn and dry beans. The historical geographic range of the western bean cutworm covered the western Great Plains states including Colorado, Nebraska, and Wyoming. Since 1999, the geographic range of the western bean cutworm has rapidly expanded eastward across the U.S. Corn Belt and eastern Canada, causing significant and economic damage to corn *Zea mays* (L.) and dry edible beans *Phaseolus* spp., in parts of this region. Since 2010, increasing challenges related to managing this pest in its new range prompted numerous research studies that provided new insights into the biology and management of western bean cutworm. This revision of a previous Journal of IPM profile summarizes new information regarding the ecology and biology of western bean cutworm, and discusses updated recommendations for scouting and management in corn and dry beans, with an emphasis in the expanded geographic range of the Great Lakes region.

Key words: western bean cutworm, corn pest, dry bean pest, management, mycotoxin

This article is a revision of the profile 'Ecology and Management of the Western Bean Cutworm (Lepidoptera: Noctuidae) in Corn and Dry Beans', published in the inaugural issue of the Journal of Integrated Pest Management in 2010 (Michel et al. 2010). At that time, profiles were envisioned as summarizing key information on a pest for a general audience, with the added incentive that authors could revise their article at some point in the future. In 2010, western bean cutworm (*Striacosta albicosta* (Smith), Lepidoptera: Noctuidae) was in the process of establishing in the Great Lakes region after a dramatic range expansion from the western United States. Most information on its biology, host range, damage, and management was gathered before the range expansion. This information, with limited new observations from Michigan, Ohio, and Ontario, was summarized in the initial profile.

Since 2010, western bean cutworm has been the focus of a considerable work, prompting this first-ever revision of a J-IPM profile. Western bean cutworm continued to expand its range eastward in the United States and Canada. Field and lab studies in both the western and eastern Corn Belt resulted in newer or better information on its life cycle, overwintering, movement, and injury. Yield and quality impacts were documented in both field corn and dry beans, and management recommendations (especially in the Great Lakes region) were adjusted in both crops. Finally, field-evolved resistance developed to the main Bt toxin deployed to manage this pest, resulting in changes to Bt corn labels. The new information from the last decade plus additional figures were integrated into the original 2010 article to create this updated profile.

The western bean cutworm is native to North America, first described in 1887 from a collection of Arizona moths (Smith 1887). It was first mentioned as a pest of dry edible beans, *Phaseolus* spp., in Colorado in 1915 (Hoerner 1948) followed by corn, *Zea mays* L., in Idaho in 1957 (Douglass et al. 1957). Since its initial description, the range and distribution of the western bean cutworm have expanded, first northward and then eastward (Fig. 1). The range expansion between the 1940s and early 2000s was relatively slow. In the mid-1950s, Crumb (1956) described the distribution to include Idaho, Kansas, Nebraska, Iowa, Utah, Colorado, Arizona, New Mexico, Texas, Alberta, and Mexico. Pohl et al. (2010) since determined that the Alberta report was a misidentification. Between 1970 and 1980, the distribution was extended to include Oklahoma, South Dakota, and Wyoming (Blickenstaff and Jolley 1982).

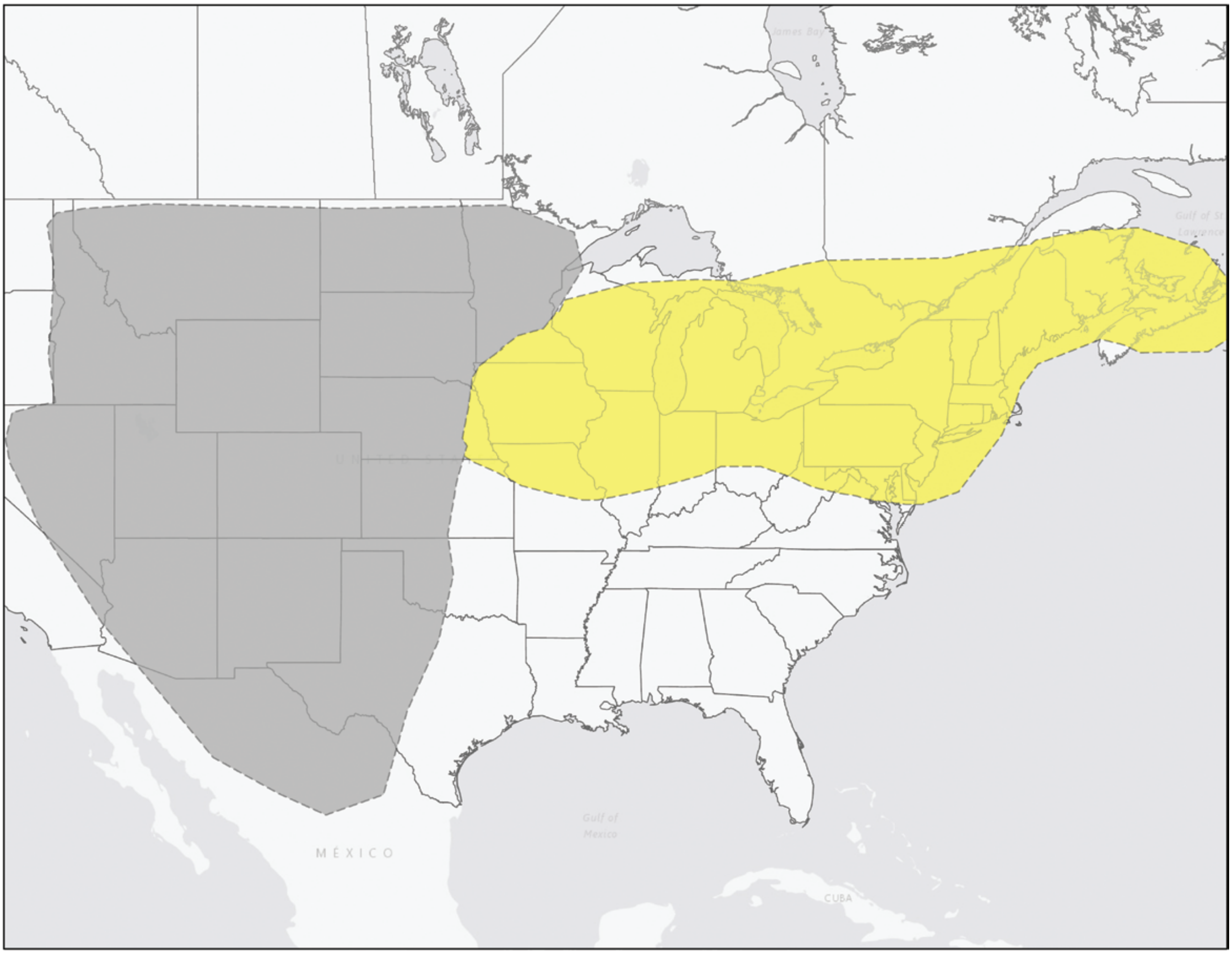

Fig. 1. Historic distribution (gray shading) and range expansion since 2000 (yellow shading) of western bean cutworm.

Western bean cutworm was only sporadically found in western Iowa before 2000 (Keaster 1999), and the first economic damage in Iowa cornfields was reported in 2000 (Rice 2000). After 2000, the eastward expansion accelerated. Western bean cutworm adults have now been collected in 22 additional states and provinces since 1999, spreading from western Iowa to the east coast of the United States and Canada (Fig. 2; see Table 1 for a list of dates and references). As of 2017, economic damage has been reported in Illinois, Indiana, Iowa, Michigan, Minnesota, New York, Wisconsin, Ontario, Quebec, and Nova Scotia. Hypotheses for the dramatic range expansion of western bean cutworm after 2000 include, but are not exclusive to, the widespread adoption of Bt transgenic hybrids leading to a reduction in either insecticide use or interspecies competition with other ear-feeding Lepidoptera such as European corn borer (*Ostrinia nubilalis* (Hübner)) and corn earworm (*Helicoverpa zea* (Boddie)) (Miller et al. 2009, Dorhout and Rice 2010, Hutchison et al. 2011).

Although the western bean cutworm is primarily a pest of field corn in its present range, other hosts include legumes, especially dry edible beans, where they are grown in abundance (Seymour et al. 2010). Economic infestations of dry beans now occur regularly in Michigan and Ontario. Soybean, *Glycine max* (L.) Merrill, is not a known host in the field, although Blickenstaff and Jolley (1982) reported that first or second instar western bean cutworm survived on soybean when transferred from corn. There are no records of western bean cutworm naturally feeding on soybean. Other hosts have been implicated as ancestral or primary, such as teosinte (*Zea mays* L. ssp. *parviglumis* Iltis and Doebley), tomato (*Solanum lycopersicum* L.), nightshade (*Solanum nigrum* L.), and ground cherry (*Physalis* spp.), but complete larval development and survival on these hosts are poor (Blickenstaff and Jolley 1982). Available evidence suggests that corn and various species of dry beans (*Phaseolus vulgaris* L., *Phaseolus lunatus* L., *Phaseolus coccineus* L., *Phaseolus acutifolius* Gray, and Vigna angularis (Willd.) Ohwi & Ohashi) are the original and current hosts.

Despite its common name, western bean cutworm does not behave like most other cutworms, e.g., the black cutworm, *Agrotis ipsilon* (Hufnagel). Instead of chewing through and 'cutting' stems and leaf petioles, the western bean cutworm feeds on the reproductive parts of plants (corn tassel, silks, and kernels, or dry bean pods and seeds). Feeding by western bean cutworm causes both yield loss and reduced grain quality by facilitating ear mold infection (Hagen 1962, Catangui and Berg 2006, Seymour et al. 2010, Parker et al. 2017, Smith et al. 2018a). In Ontario, where *Fusarium* spp. are ubiquitous and environmental conditions frequently favor infection, the incidence of injury by western bean cutworm has been shown to increase mycotoxin production in grain corn (Smith et al. 2018a).

Description of Life Stages and Cycle

Adult

Moths are gray-brown and ~2 cm long (Fig. 3). The primary identifying characteristics are found on the forewings of both sexes—a cream-colored stripe along the outer margin of the

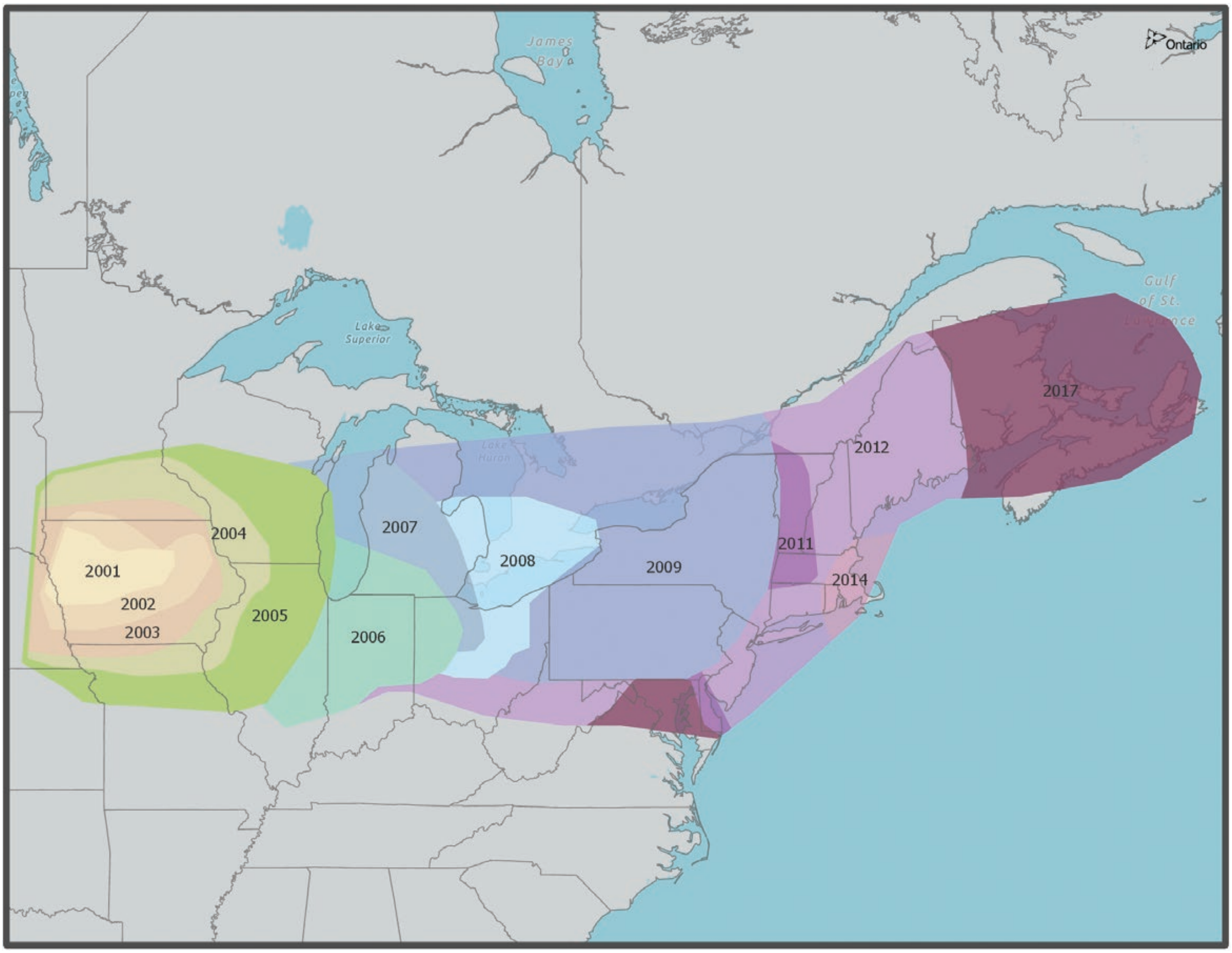

Fig. 2. Detailed expansion of western bean cutworm distribution into the eastern Corn Belt between 2000 and 2017.

Table 1. Eastward range expansion of western bean cutworm—year of first detection

State/Province	Date	Citation/Source
Minnesota	1999	O'Rourke and Hutchison 2000
North Dakota	2002	G. Fauske, NDSU, personal communication
Illinois	2004	Dorhout and Rice 2004
Missouri	2004	Dorhout and Rice 2004
Wisconsin	2004	Cullen 2007
Indiana	2006	Dorhout and Rice 2008
Michigan	2006	DiFonzo and Hammond 2008
Ohio	2006	DiFonzo and Hammond 2008
Ontario	2008	Baute 2009
Pennsylvania	2009	Tooker and Fleischer 2010
New York	2009	Baute 2009
Quebec	2009	Baute 2009
Delaware	2011	Whalen 2012
West Virginia	2012	Lotts and Naberhaus 2012
Maine	2012	Handley 2012
Maryland	2017	P. Coffey, University of Maryland Extension, personal communication (see Supplementary material)
Nova Scotia	2017	G. Murray, Perennia Food and Ag Inc., personal communication
Prince Edward Island	2017	G. Murray, Perennia Food and Ag Inc., personal communication

forewing, a circular spot of similar color approximately halfway along the length of the forewing, and a comma-shaped mark along the same line approximately two-thirds of the way to the wingtip (Fig. 3). Adults may be confused with spotted cutworm (*Xestia dolosa* Franclemont), yellow-striped armyworm (*Spodoptera ornithogalli* (Guene´e)) or dingy cutworm (*Feltia jaculifera* (Guene´e)). All of

Fig. 3. Western bean cutworm moth with key identifying characteristics (cream-colored stripe along front margin, circular spot, and comma) in each forewing. (J. Smith)

Fig. 4. Western bean cutworm egg mass (circled) on an upper leaf of a pre-tassel corn plant. (J. Obermeyer)

these species have distributions that overlap part of the western bean cutworm's expanded range.

Western bean cutworm is univoltine, with only one generation per year in the western (Hantsbarger 1969, Blickenstaff 1979) and eastern (Smith et al. 2018b) parts of its range. Moth flight begins as early as the first week of June, peaks in mid- to late-July, and can linger into early September (Dorhout and Rice 2008, Smith et al. 2018b), although variation in adult emergence and flight time can occur depending on climate and location. Adults are mostly nocturnal and rest on corn plants during the day, usually in leaf axils. Moths are polyandrous, with females mating on average three times during their lifespan (Konopka and McNeil 2015). The life span of female moths is slightly longer than that of males, averaging nine days compared to seven for males (Blickenstaff 1979). Females become sexually mature 4–6 d post-emergence (Konopka 2013) and mating and oviposition occur mainly in July and August. An individual female can lay over 600 eggs in total, with averages ranging from 321 (Douglass et al. 1957) to 407 (Blickenstaff and Jolley 1982) eggs per female. Oviposition occurs in a variety of cultivated and wild plants, although dry beans and field corn are the most commonly reported oviposition sites (Blickenstaff and Jolley 1982).

Eggs

In corn, eggs are laid in masses on the upper surfaces of new, vertically oriented whorl leaves (Fig. 4; Seymour et al. 2010). However, in corn that has already reached the silking stage (R1), egg masses may be laid on leaves closer to the ear or directly on the husk. In dry beans, egg masses are laid on the underside of the leaves, deep within the crop canopy (Hoerner 1948, Blickenstaff 1983). Egg masses on corn may contain 2 to 345 eggs (Paula-Moraes et al. 2013) with an average number per mass reported as 57 in Michigan (DiFonzo et al. 2015) and 85 in Nebraska (Paula-Moraes et al. 2013). Eggs are white when first deposited (Fig. 5) and become tan as they develop (Fig. 6). Within a week after eggs are deposited, they are purple in color, indicating that hatch is imminent within 24–48 h (Fig. 7). Total development time from oviposition to egg hatch in the field is estimated as ranging from 5 to 7 d (Douglass et al. 1957, Seymour et al. 2010). Under laboratory conditions, egg masses hatched in 12, 7, and 6 d at 16, 25, and 30°C, respectively (Paula-Moraes et al. 2013).

Larvae

After eclosion, first instars (Fig. 8) consume their egg shells, making post-hatch scouting for empty egg masses difficult. Newly eclosed larvae are purple with black heads. Their color lightens to tan with subtle longitudinal stripes as they mature (Fig. 9), somewhat resembling true armyworm, *Mythimna unipuncta* (Haworth, 1809). After the fourth instar, larvae are readily identified by two black rectangles or stripes behind the head, and generally smooth skin lacking stripes, visible tubercles, warts, or bumps (Fig. 9). In a cage study, Douglass et al. (1957) reported that larvae developed through the fifth instar in 22 d. Antonelli (1974) reported that under field conditions on dry beans, larvae developed through the sixth instar in 43–70 d, with an average of 55.9 d. He also reported a seventh instar on rare occasions (Antonelli 1974). Dyer et al. (2013) observed six instars within 28 d when larvae were reared on artificial diet in a laboratory setting. Similarly, in a Michigan field study, one-third of a population infested on corn reached the sixth instar by 28 d after egg hatch (DiFonzo 2019).

Fig. 5. A freshly laid western bean cutworm egg mass in a corn leaf axil. (C. DiFonzo)

Larval feeding behavior depends on host plant growth stage and species. In pre-tassel corn, prior to full tassel emergence (VT stage), most neonates crawl upward to feed on moist tassel tissue and developing anthers enclosed by the uppermost leaves (Paula-Moraes et al. 2012) (Fig. 10). Larval weight and survival are higher when feeding on tassel tissue compared to other tissues, and tassel-feeding is likely necessary to complete development on corn; larvae fed leaf tissue alone experience nearly 100% mortality (Paula-Moraes et al. 2012). After tassel emergence, small larvae may be found in central leaf axils feeding on fallen anthers or pollen (Fig. 11), or in silks if available. As pollen shed ends and tassels dry, larvae move downward and concentrate in the ear zone, feeding at the ear tip on fresh silks, then on cob tissue or developing kernels (Fig. 12). As larvae mature, some move between and outside the husks and enter the side of the ear (Fig. 13) to feed on kernels. Several larvae may be present in a single ear (Fig. 14). In addition to within-plant movement, larvae move down and across rows to neighboring plants (Hagen 1962, Pannuti et al. 2016).

On dry beans, newly eclosed larvae feed on leaf tissue (Fig. 15), then chew into flowers and small developing pods (Fig. 16). Unlike on corn, third instars in dry bean fields begin to spend time on the ground in soil cracks or under residue. As they mature, they transition to the ground almost exclusively during the day (DiFonzo et al. 2015). During the night, or on cloudy days, they move up the plant to feed in developing pods (Fig. 17), returning to the ground after a few hours (DiFonzo et al. 2015).

Fig. 6. A developing western bean cutworm egg mass. Note the tan ring indicating fertilization. (C. DiFonzo)

Fig. 7. Purpling of a western bean cutworm egg mass signals imminent egg hatch. (J. Obermeyer)

Prepupae and Pupation

In late summer and early fall, sixth instars leave plants and burrow into the soil where they construct earthen chambers using salivary gland secretions (Fig. 18). Burrowing depth was reported as 12–25 cm, with an average of 21.6 cm (Douglass et al. 1957, Seymour et al. 2010, Smith et al. 2018b). However, larvae have been found as deep as 40 cm in sandy loam soil (Smith et al. 2018b). Insects remain in a quiescent prepupal state throughout the winter. The super-cooling point of prepupae has been estimated as −12.6°C (Hanson et al. 2013). Soils with higher sand content (common around the Great Lakes and in parts of the western United States) may allow for deeper overwintering, providing greater protection from cold temperatures and tillage equipment. However, there are few studies following overwintering survival through pupation and moth emergence in the summer. When larvae were caged on different soil types in Colorado, Hoerner (1948) reported that fewer moths

Fig. 8. Newly eclosed western bean cutworm larvae consuming their egg shells. (T. Baute)

Fig. 9. Early-instar western bean cutworms (left) lack the identifying black rectangles behind the head that develop on older instars (right, indicated by arrows). (J. Obermeyer)

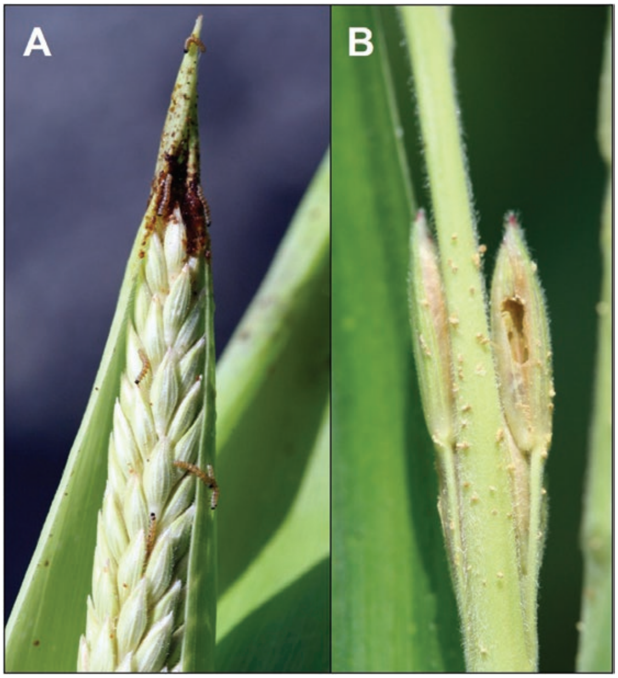

Fig. 10. Feeding on A) a developing tassel and B) an individual anther by early-instar western bean cutworms. (C. DiFonzo)

emerged from clay soil versus sandy soil. In cage studies in Nebraska, Hein and Seymour (2000) found that in sandier soils, a greater proportion of larvae overwintered at deeper depths. However, overall winter survival in their study was only 4%. In recent bucket and cage studies in Ontario, overwintering success was higher, estimated at <40% (Smith et al. 2018b).

Natural Enemies

Lady beetles (Coccinellidae), minute pirate bugs (*Orius* spp.), lacewing larvae (Chrysopidae) (Fig. 19), and predacious ground beetles consume eggs and early-instar western bean cutworms (Seymour et al. 2010, Chludzinski 2013). The parasitoid *Trichogramma* sp. has been recovered from western bean cutworm egg masses collected in Michigan and Ontario cornfields (Chludzinski 2013, Smith 2017). These natural enemies contribute to background mortality, but when egg mass infestations are high in a given field, they will not reliably prevent populations from reaching pest status. Western bean cutworm is also prone to infection by a microsporidium, *Nosema* spp. (Seymour et al. 2010). Research into this pathogen as a significant source of mortality in the field is lacking. Late instars and prepupae are vulnerable to predation by birds and ground-dwelling vertebrates such as raccoons and skunks (Krupke et al. 2009), although these animals can themselves cause significant damage to the crop by opening the ear (Fig. 20) or breaking stalks as they search for larvae.

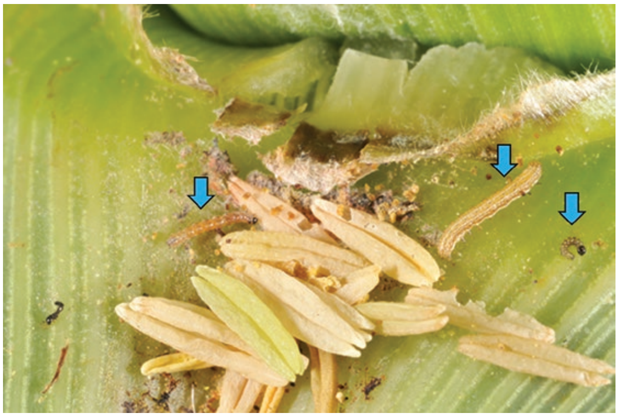

Fig. 11. Three western bean cutworm larvae of various sizes in a leaf axil. (J. Obermeyer)

Fig. 12. A late-instar western bean cutworm feeding in an ear tip. (J. Obermeyer)

Injury, Scouting, and Management Options in Corn

Injury in Corn

Oviposition and subsequent injury are often patchy from field to field, and even within a field, primarily because of variation in crop stages across the landscape. Although up to 10 larvae have been observed on a single ear (Seymour et al. 2010), there is considerable plant-to-plant movement within and across rows early in development (Pannuti et al. 2016), which results in infestation of neighboring plants. Pannuti et al. (2016) reported that the majority of larvae were recovered within 1.7 m of an infested plant, but that the maximum distance moved was nearly 7 m.

Most feeding is concentrated on the ear (Fig. 21A). Larvae feed on the silks, moist cob tissue, and developing kernels at the ear tip (Fig. 21B). Older larvae may chew through the husk, consuming or 'scraping' kernels along the side of the ear (Fig. 21C). They also move within and across rows, damaging multiple ears (Fig. 22). During the field season, infestation may not be readily apparent. Signs include clipped silks, feeding injury or powdery frass in the ear tip, and holes chewed through husks. As husks dry down before harvest, frass, feeding injury, and larvae are more noticeable in the ear tip. Late-season damage may be confused with that of corn earworm, so identification of larvae is necessary to confirm which pest is present. Under heavy infestations, yield losses may be significant. In one of the first efficacy trials in corn, Hagen (1962) reported that up to 40% of kernels were destroyed in untreated plots, and that yield was 32% higher where insecticide was applied. Yield studies conducted in Nebraska showed that an average of one larva per plant caused yield loss of 3.7 to 15.1 bushels per acre (Appel et al. 1993, Seymour et al. 2010, Paula-Moraes et al. 2013).

In some regions, the more serious problem with western bean cutworm is not yield loss, but loss of grain quality due to increased ear mold infection and mycotoxin contamination (Fig. 23). In the Great Lakes region, environmental conditions are often favorable for infection of corn by mycotoxigenic fungi such as *Fusarium graminearum* (Schwabe), which frequently infects corn ears through the silk channel in the absence of insect injury (Vigier et al. 1997, Hooker and Schaafsma 2005). This fungus produces the mycotoxin deoxynivalenol (DON) which causes detrimental health effects to livestock, particularly swine (Miller 2008). This is of particular concern where field corn is used as livestock feed, either directly in the form of grain or indirectly in the form of dried distiller's grain (DDGs), a byproduct of ethanol production (Schaafsma et al. 2010, Bowers and Munkvold 2014). Even small amounts of feeding injury by western bean cutworm can increase ear rot severity and

Fig. 13. Western bean cutworm larvae entering side of ear by chewing through husk. (J. Smith, R. Hammond)

DON accumulation by providing additional entry points for spores (Parker et al. 2017, Smith et al. 2018a). Management of this pest complex requires a combined approach, including hybrid tolerance to *Fusarium* spp. infections, reduction of western bean cutworm injury using transgenic corn hybrids or insecticides, and timely application of fungicides labeled for control of the pathogen. Application of an insecticide/fungicide tank mix at the R1 stage (silking) is recommended to achieve maximum western bean cutworm mortality and protection from fungal infection (Smith et al. 2018a).

Fumonisin mycotoxins produced by *F. verticilloides* (Saccardo) (Nirenberg) are typically associated with lepidopteran insect injury to grain corn ears and have been attributed to western bean cutworm injury (Bowers et al. 2013, 2014). Fumonisins are classified as potential carcinogens in humans (Marasas 1995, IARC 2002) and cause numerous health issues in horses and swine (Ahangarkani et al. 2014). In Ontario, fumonisin concentration in grain corn has historically remained below 1.0 μg g^{-1} (Schaafsma et al. 2008). However, since 2012, increasing incidence and concentration of fumonisin in grain corn has been observed in the presence of western bean cutworm injury (A.W. Schaafsma and V. Limay-Rios, University of Guelph, personal communication).

Fig. 14. Three western bean cutworm larvae in a single ear tip; note the copious frass pellets. (J. Smith)

Fig. 15. Feeding by newly eclosed western bean cutworms on a dry bean leaf, near the site of an egg mass. (T. Baute)

Trapping for Adults in Corn

Monitoring for adult moths is recommended to time scouting to coincide with the presence of egg masses and larvae. Methods involve either blacklight or pheromone traps. Blacklight traps were used historically in the western Great Plains states (Hagen 1976, Mahrt et al. 1987). Although reliable for catching western bean cutworm adults, blacklight traps are expensive and bulky, and their operation depends on a power supply (Mahrt et al. 1987). Additionally, they catch many non-target insects, which can make sorting and counting moths difficult. For most applications, pheromone traps are a better option for adult monitoring. A comparison of captures from blacklight traps and two types of pheromone trap showed no significant difference in counts (Mahrt et al. 1987).

Milk jug and bucket pheromone traps have been used to monitor western bean cutworms; there is no significant difference in performance between the two, if milk jug traps are frequently refilled (Mahrt et al. 1987, Dorhout and Rice 2008, Chludzinski 2013). The least expensive trap is a clear plastic, 1-gallon milk jug (Fig. 24A). Openings are cut on all four sides, leaving a 5 cm reservoir to hold a 4:1 ethylene glycol (antifreeze) and water solution, with a few drops of liquid soap added to decrease surface tension. The antifreeze prevents evaporation and helps preserve the moths. A pheromone lure is hung on a paperclip poked through the milk jug cap (Fig. 24B). Despite the low cost, milk jug traps are messy (fluid must be changed at least once a week), prone to spillage or evaporation, and potentially hazardous to children and animals since ethylene glycol is

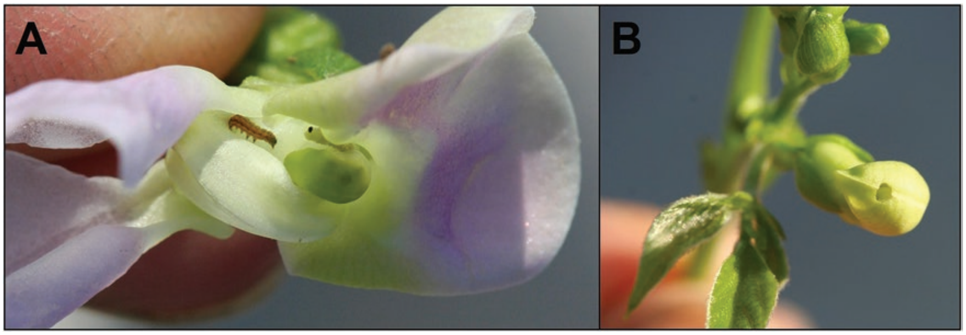

Fig. 16. Early signs of western bean cutworm on dry beans: (A) a second instar feeding in a dry bean flower, (B) a hole chewed into a developing pod. (C. DiFonzo)

Fig. 17. Western bean cutworm pod damage: Holes chewed into the pod (A) are used to access and consume the developing seeds inside (B) (C. DiFonzo)

toxic. Less-toxic propylene glycol is a safer option to reduce evaporation in jug traps. Plastic bucket traps, also known as Universal traps or Uni-traps (Great Lakes IPM, Vestaburg, MI) (Fig. 25A) are the recommended alternative to milk jug traps. This trap consists of a funnel twisted onto a bucket, with a pheromone lure suspended in a basket above the funnel. No liquid is used in this style of trap. Insects are killed using an insecticidal strip placed in the bucket (Fig. 25B). Bucket traps only need to be checked once a week, and although there is an initial cost to purchase, buckets are less messy, safer, and reusable for many seasons.

Milk jug and bucket traps are attached to fence stakes and placed on the edge of the field (Seymour et al. 2010, Smith et al. 2018b). Pheromone lures should be replaced every 3 wk to maintain trap attractiveness, with lures stored in the freezer until their use. One trap per cornfield is recommended. Trap height should be at least 1.2 m (Dorhout and Rice 2008). As in many pheromone-based trapping systems, trap catch is improved by positioning the trap so that prevailing winds can move through the openings and spread the pheromone plume into the field (Mahrt et al. 1987, Dorhout and Rice 2008). In addition, placing traps in a host plant (e.g., corn) environment rather than in a corn–soybean or a more heterogeneous environment may slightly improve effectiveness (Dorhout and Rice 2008). However, consideration must be given to placing the trap in an area that encourages consistent monitoring but is not prone to vandalism or being knocked down by field equipment.

The beginning of moth flight varies depending on location. In historical studies in the western Great Plains, moths were rarely collected before July, whereas moths were collected as early as 19 May 2012 in Michigan, during the week of 31 May 2015 to 6 June 2015 in Ontario (Smith et al. 2018b), and 18 June 2007 in Iowa (Rice 2007). Moth flights taper off by late August or mid-September. Since the majority of moth catch occurs over a 5- to 6-wk period, traps

Fig. 18. A western bean cutworm prepupa, found 23 cm deep in sandy soil in its earthen cell. (J. Obermeyer)

deployed by late June should efficiently catch adults such that peak flight can be observed. Traps should be inspected at least weekly, but during peak flight it may be necessary to check and empty traps more frequently.

Scouting in Corn

While pheromone traps are useful to detect the presence and relative abundance of western bean cutworm moths in a region, they do not predict the incidence of egg laying and subsequent injury in surrounding cornfields. To determine the risk of injury, individual fields must be scouted for western bean cutworm egg masses and larvae after moths are collected with increasing frequency in pheromone traps, usually by the middle of July. The predicted value for 25% moth emergence is sometimes used to initiate scouting (Seymour et al. 2010) if degree days (DD) are available from a local weather station. The original DD model developed in Nebraska (Ahmad 1979), using a base developmental threshold of 10°C, predicted 25, 50, and 75% moth emergence at accumulations of 733, 790, and 853 $DD_{10°C}$ after May 1. A refined model developed by Hanson et al. (2015), using base and maximum developmental thresholds of 3.3 and 23.9°C, respectively, recommended that fields be scouted between 25% and 50% emergence, i.e., 1432 to 1502 $DD_{3.3°C}$. In the Great Lakes region, emergence occurred earlier than predicted by both models (J.L.S., unpublished data). One difference may be that the Nebraska models were based on blacklight captures, whereas moth emergence in the Great Lakes region was monitored using pheromone traps. Additional work is needed to refine an emergence model based on catches in these traps, which are commonly used by crop scouts, agribusinesses and growers.

Initially, monitoring efforts should focus on pre-tassel cornfields which are preferred by gravid females for oviposition (Blickenstaff 1979, Holtzer 1983). In years with widespread delayed planting or slow crop development, egg laying in whorl-stage corn has been observed. However, larvae do not survive on corn leaf tissue alone, and need reproductive tissues with higher nutrition to complete development (Paula-Moraes et al. 2012). Therefore, insecticide treatment is not recommended unless reproductive tissues (e.g., tassels) are present within a field. A minimum of 20 consecutive plants in five locations in each cornfield should be scouted for egg masses and larvae by examining the upper surfaces of new and not-yet unfolded leaves of plants (usually the top three leaves still vertical in orientation). Scouting is recommended every five days throughout the oviposition period. Egg laying may last for several weeks, especially when uneven plant growth stages in a field result in prolonged attractiveness

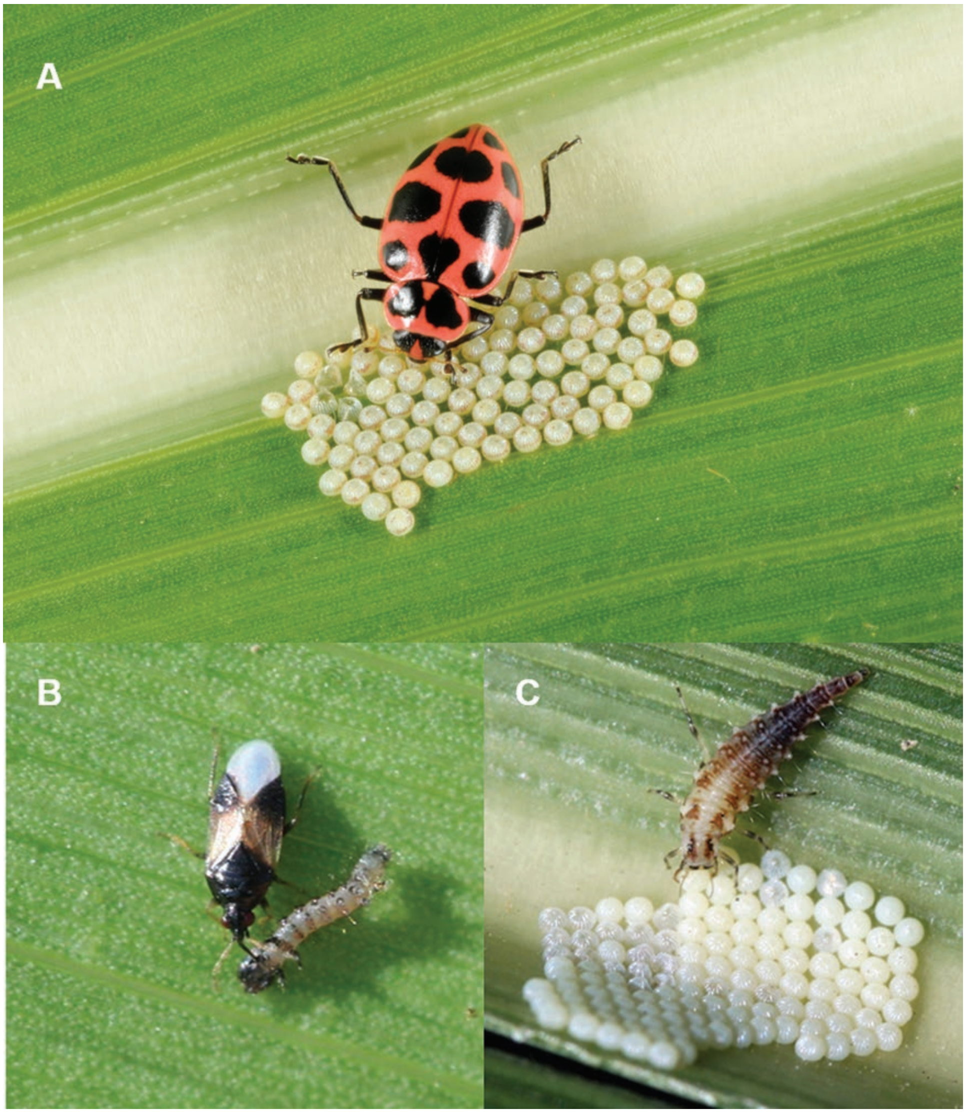

Fig. 19. Biological control of western bean cutworm: A) lady beetle (J. Obermeyer), B) minute pirate bug (C. DiFonzo), C) lacewing larva (C. DiFonzo).

to female moths. Egg masses can often be spotted on sunny days by looking for shadows through leaf surfaces (Fig. 26), but empty masses are difficult to find because newly eclosed larvae consume their egg shells. Upper leaf axils, tassels (before pollen shed), and silks should also be examined for young larvae. As tassels in early-maturing cornfields emerge and dry, female moths typically seek later-developing cornfields or dry beans for oviposition. However, oviposition has been observed in corn beyond this stage in the Great Lakes region, when these options are not available.

Management in Corn: Thresholds and Foliar Insecticides

Managing western bean cutworm in corn is challenging because of their patchy distribution, cryptic nature, and protected feeding behavior. Adult monitoring and early detection of egg masses and larvae are critical for proper timing of insecticide application, because effective control occurs only when larvae encounter insecticide before entering the ear. Appel et al. (1993) recommended an economic threshold of 33 eggs per plant, but counting the number of eggs per mass is impractical in the field. Alternatively, extension entomologists and crop consultants in the western United States used nominal thresholds of ~14% (given as one egg mass per seven plants) (Blickenstaff et al. 1975, Hagen 1979) or 8% (Wright et al. 1994) of plants with egg masses or tiny larvae. If eggs masses had already hatched, spraying was recommended when 95% of the tassels emerged; alternatively, if tassels had emerged, spraying was recommended after most egg masses hatched (Wright et al. 1994). In the 2000s, Rice (2007) suggested reducing the 8% threshold, to account for higher crop prices. The current recommendation in the western range stands at a threshold of 5 to 8% of plants infested with egg masses or small larvae (Seymour et al. 2010).

In the Great Lakes region, the risk of ear mold infection (Fig. 23) and mycotoxin contamination outweighs yield loss considerations (Smith et al. 2018a). Entomologists in this region now recommend a nominal threshold at the lowest end of the western range—5% of plants with egg masses—with an added specification that it is cumulative. In other words, egg mass counts are accumulated over several weeks of scouting, when a field is attractive to egg-laying females, until the action threshold has been reached. Furthermore, to manage the increased risk of mycotoxin accumulation in the presence of western bean cutworm, an insecticide–fungicide tank mix is recommended at the R1 stage (silking), rather than 95% tassel emergence, to optimize fungicide protection from silk infection and still achieve mortality of western bean cutworm larvae before they enter the ear.

Pyrethroids are the most widely used insecticide group for control of western bean cutworm in corn in the United States (Archibald et al. 2017). Diamide and spinosyn insecticides are also labeled for western bean cutworm control and are commonly used in Ontario, Canada (OMAFRA 2018). Regardless of insecticide choice, rotation and mixing of insecticide classes is strongly recommended to prevent insecticide resistance development. Scouting for live larvae in the field in August or September is recommended to evaluate insecticide performance after spraying. Although field-level resistance to pyrethroids has not yet been documented for this pest, 41% of agricultural professionals in a recent Nebraska survey said that insecticides were providing less control (Archibald et al. 2017). In follow-up bioassays, larvae collected in Nebraska (where pyrethroids have a longer history of use) were less susceptible to bifenthrin than larvae collected in Ontario (where pyrethroids are used less and for a shorter period) (Peterson et al. 2018). Besides resistance development, an additional concern associated with pyrethroid use in corn against western bean cutworm is the disruption of natural enemies attacking cutworms and other pest species. This can increase the risk of secondary pest outbreaks, including two-spotted spider mite (*Tetranychus urticae* Koch).

Fig. 20. Injury to corn ear caused by birds feeding on western bean cutworm larvae. (J. Smith)

Management in Corn: Transgenic Corn

There are limited options for control of western bean cutworm with transgenic corn containing *Bacillus thuringiensis* (Bt) proteins, since few Bt toxins target the pest. Only the Vip3A Bt protein (event MIR162, Syngenta Seeds Inc., Research Triangle Park, NC) currently provides control of western bean cutworm (Bowers et al. 2013, Farhan et al. 2017, Smith et al. 2018b). Cry1A, Cry1Ab, and Cry2Ab Bt proteins, which protect against European corn borer, have no activity against western bean cutworm (Eichenseer et al. 2008, Dyer et al. 2013). The Cry1F protein (Event TC1507, co-developed by the registrants Dow AgroSciences LLC, Indianapolis, IN and Pioneer Hi-Bred International, Johnston, IA) was originally registered for European corn borer control (US EPA 2001) and commercialized in the United States and Canada in 2003. After western bean cutworm began to move eastward, the Cry1F label was amended in August 2003 to include control of this pest as well (US EPA 2003). Cry1F was eventually pyramided into numerous Bt trait packages, including Herculex, most AcreMax and Agrisure hybrids, and SmartStax products. Initial field studies of Cry1F against western bean cutworm were promising. For example, across multiple field trials in South Dakota (Catangui and Berg 2006), Cry1F hybrids had no or extremely low ear injury from western bean cutworm, compared with 7.5–57.5% of ears injured in Cry1Ab-expressing hybrids.

However, as the range of western bean cutworm expanded, additional studies suggested that Cry1F may not provide complete

Fig. 21. Western bean cutworm larval damage to the ear: (A) range in severity of injury (J. Obermeyer), (B) tip feeding (J. Smith), (C) injury caused by 'scraping' of kernel pericarp. (J. Smith)

Fig. 22. The damage path of one western bean cutworm larva moving along a row, feeding on multiple, consecutive plants. (C. DiFonzo)

Fig. 23. Mold growth associated with western bean cutworm feeding injury. (J. Smith)

control (Eichenseer et al. 2008). In laboratory bioassays, Dyer et al. (2013) found that despite a delay in growth and development on artificial diet containing Cry1F, larval tolerance to the toxin was high, even in neonates, compared to other species such as European corn borer. Ostrem et al. (2016) reported a fivefold increase in the median lethal concentration of Cry1F required to kill 50% of populations tested in 2013/2014, compared to populations assessed a decade before. Field and laboratory studies in Ontario between 2011 and 2016 showed rapid development of field-evolved resistance (Smith et al. 2017, 2018b). By 2016, Cry1F hybrids across the Great Lakes region routinely suffered extensive infestation, feeding, and grain quality issues in the field (Fig. 27; DiFonzo 2016, Krupke and Obermeyer 2016, Michel et al. 2016, Unglesbee 2016). The registrants of the trait removed a rating of western bean cutworm control from Cry1F in 2017 (Unglesbee 2017). Recognizing that Cry1F hybrids offer no reliable control of this pest, entomologists now

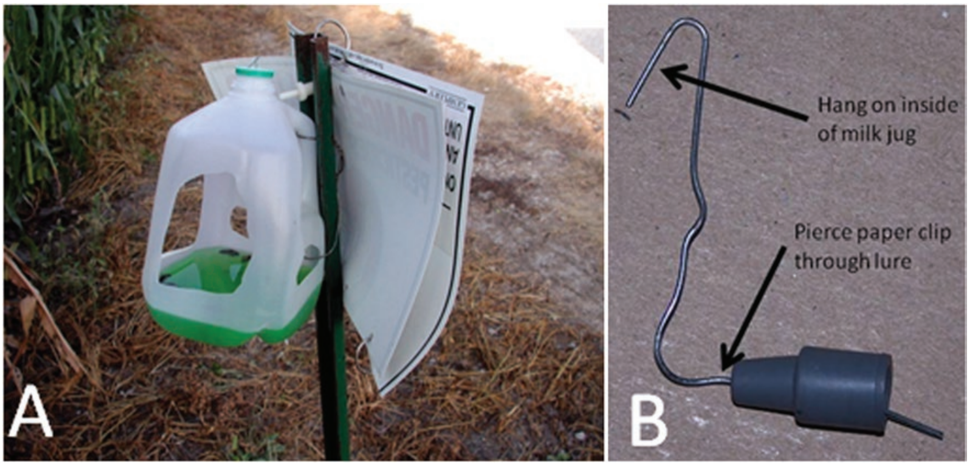

Fig. 24. (A) Milk jug pheromone trap for western bean cutworm (M. Rice); (B) Lure and paper clip for placement in milk jug. (A. Michel)

Fig. 25. (A) Plastic bucket pheromone trap for western bean cutworm; (B) insecticidal strip placed in the bottom of bucket to kill moths. (J. Smith)

recommend that these hybrids be scouted and sprayed at thresholds in the same manner as non-Bt hybrids (DiFonzo 2016).

The loss of Cry1F as a control for western bean cutworm leaves Vip3A as the only currently available Bt toxin with efficacy against this species. Vip3A Bt hybrids suitable for Canada and the northern United States were not widely available in corn hybrids marketed in the region over the last decade, so field exposure of western bean cutworm larvae (and therefore opportunities for resistance development) to the Vip3A toxin has thus far been low. In laboratory bioassays, first instars were readily killed by Vip3A overlaid on artificial diet (Farhan et al. 2017). Based on estimates of tissue consumption by neonates and the amount of Vip3A expressed by transgenic plants (Farhan et al. 2019), it is assumed that young larvae on Vip3A Bt corn experience similar levels of mortality. However, there is evidence that the level of Vip3A expressed in plants may not be high enough to kill older larvae (Farhan et al. 2019). Given that older instars move from plant to plant, and that most Bt hybrids are sold with an integrated 5% non-Bt 'refuge in the bag' (RIB), there is a substantial risk of sub-lethal exposure for larvae which initially develop on a non-Bt refuge plant and later move to a neighboring Bt plant. Sub-lethal exposures are a key mechanism driving the development of resistance. In Bt cropping systems. While government regulators in the United States and Canada are currently exploring resistance management plans for Vip3A and western bean cutworm, some extension entomologists have recommended proactive practices such as scouting of Vip3A fields to assess efficacy, and insecticide applications to Vip3A hybrids when they exceed the action threshold in order to maintain the durability of this management approach as long as possible.

Management: Cultural Methods

Cultural control options for western bean cutworm are limited and unreliable (Seymour et al. 2004). Because the period of adult emergence and oviposition is long and environmental factors are variable, adjusting planting dates as a way to avoid crop injury is not effective (Douglass et al. 1957). Deep soil disturbance through tillage may cause mortality of overwintering prepupae (Blickenstaff 1979), but no studies have directly tested this. Since western bean cutworms overwinter at different depths in different soil types (Smith et al. 2018b), mortality due to tillage would likely differ from field to field. Nevertheless, the increased prevalence of reduced tillage is often noted as one of the factors in the range expansion of western bean cutworm (Hutchison et al. 2011). However, a return to conventional tillage is both unlikely and unadvisable given the agronomic benefits of reduced tillage and soil conservation. Furthermore, conventional tillage would have to be implemented across a broad area to reduce cutworm numbers, since moths emerging from no-till fields could simply move in the landscape and oviposit in tilled fields.

Fig. 26. Western bean cutworm egg masses appear as shadows on corn leaves backlit by the sun. (C. DiFonzo)

Injury, Scouting, and Management Options in Dry Beans

Injury in Dry Beans

Oviposition and damage are often patchy in dry bean fields. Dispersal of larvae from one egg mass can be as much as twice the distance typically reported in corn, but movement still tends to be greater within rows than across rows (Blickenstaff 1983). Injury begins as leaf (Fig. 15) and flower (Fig. 16) feeding, which does not reach economic levels. By the third instar, most larvae spend most or all their daytime hours on the ground (Hoerner 1948, DiFonzo et al. 2015). Larvae move up on the plant at night (after 2100 hours in Michigan), chew into pods to feed directly on developing beans (Fig. 17), and return to the soil surface by sunrise (DiFonzo et al. 2015). This daily movement results in each larva damaging multiple pods during development (Fig. 28). Direct feeding on beans may cause yield loss by reducing pounds harvested. In Michigan, an artificial infestation of one egg mass per 1.5 m row resulted in 20% of pods and 2% of beans damaged; infesting with as few as two larvae per 30 cm resulted in significantly more pod feeding and bean damage than in non-infested plots (DiFonzo et al. 2015).

Yield loss is usually less concerning in dry beans than quality loss. Pod damage allows for the introduction of fungi or bacteria, and exposes seed to oxygen, which results in discoloration of some bean types (Figs. 29 and 30). Beans from damaged pods may be partially eaten, shriveled, or moldy (Fig. 30). Extra labor, time, and money must be spent to separate out damaged and off-color beans using a gravity table or optical sorter, to avoid contamination of finished canned or dried products (Fig. 31). As few as 2% culls (termed 'pick') can result in downgrading of beans (Blickenstaff 1979, Antonelli and O'Keeffe 1981) and heavy damage can result in entire loads being rejected. Because dry beans are harvested early in the fall, larvae may still be present when plants are pulled, wind-rowed, or direct-harvested. Larvae sometimes are found in trucks, cleaning facilities, and storage facilities, but do not survive or overwinter in grain bins.

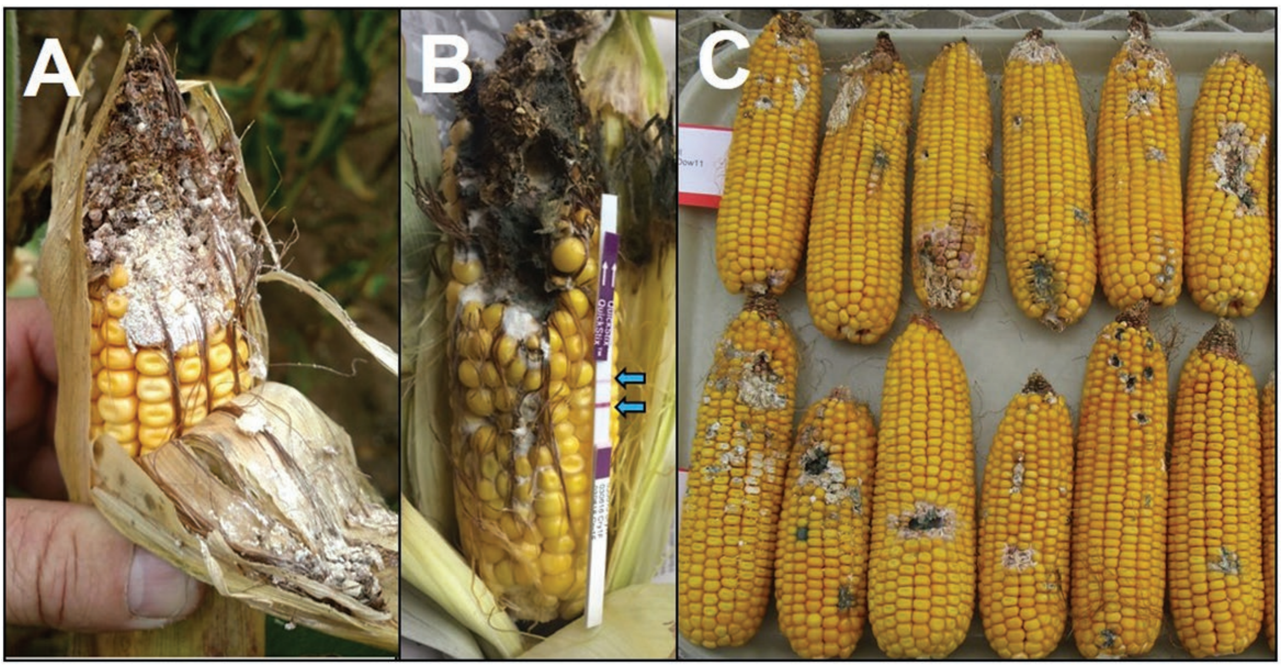

Fig. 27. Western bean cutworm damage to Cry1F Bt corn in 2016: (A) Michigan, tip feeding with copious frass (B. MacKellar), (B) Ohio, ear mold and associated feeding—note the test strip with two lines indicating that ear tissue was producing Cry1F toxin (A.P. Michel), (C) Ontario, similar levels of feeding on non-Bt (top row) and Cry1F (bottom row) ears harvested from a field trial (J. Smith).

Trapping Adults in Dry Beans

Pheromone traps associated with dry bean fields or a mixed landscape of dry beans and corn catch more moths than traps associated only with corn (Chludzinski 2013). Thus, it is important for dry bean producers to trap in dry bean production areas separately from cornfields. The milk jug and bucket pheromone traps described previously for corn can be used in dry beans, but two traps should be positioned on opposite ends of each field. Trap height is the same as for corn (at least 1.2 m), with placement of the trap in dense vegetation such as beans, alfalfa, or low-lying weeds along the field edge.

Fig. 28. Western bean cutworms climb into the dry bean canopy at night to feed, resulting in injury to multiple pods by each larva. (C. DiFonzo)

Scouting in Dry Beans

Scouting for egg masses in dry beans is labor-intensive and ineffective because masses are typically laid on the undersides of leaves, deep in the canopy. Scouting for egg masses in adjacent cornfields is a better indicator of local risk to dry beans. If the western bean cutworm population in a cornfield reaches a threshold level of egg masses, dry bean fields immediately adjacent to the cornfield are likely at risk, particularly after corn becomes less attractive to egg-laying females. Larval scouting in dry beans is also difficult since larvae hide on the ground during the day and climb up into the canopy only in late evening or on cloudy days to feed (DiFonzo et al. 2015). A more practical alternative to egg and larval counts is to scout dry bean fields for pod feeding after peak moth flight, at multiple locations in a field. This may still underestimate the damage being done since spotting early pod feeding can be difficult while leaves are still on the plants.

Management in Dry Beans: Thresholds and Foliar Insecticides

A nominal spray threshold used in the western United States is one larva per foot of row (or two larvae per foot of row in irrigated fields) (Seymour et al. 2010). Field studies in Michigan similarly found that two larvae per foot resulted in significantly more pod and bean damage compared to non-infested controls (DiFonzo et al. 2015). However, scouting for larvae is impractical in most situations. Another commonly

Fig. 29. Discoloration of cranberry beans at the site of western bean cutworm feeding injury on a pod. (J. Smith)

Fig. 30. Whole cranberry beans (right) compared to damaged culls (left) which were screened out of a dry bean load from a western bean cutworm-infested field. (C. DiFonzo)

Fig. 31. Cannellini beans partially fed on by western bean cutworm, found in canned product by one of the authors. (C. DiFonzo)

used threshold in the western United States uses cumulative pheromone trap catch before peak moth flight to rate the damage risk in nearby bean fields. A cumulative catch averaging fewer than 700 moths per trap is 'low' risk, while averages of 700–1,000 or more than 1,000 per trap indicate 'moderate' or 'high' risk, respectively. Scouting is recommended for both moderate and high-risk fields to determine the level of feeding and larval infestation. If pod feeding is observed, chemical control is recommended (Mahrt et al. 1987, Seymour et al. 2010). These trap levels have generally been too high for the Great Lakes region. Fields with cumulative trap catch of fewer than 120 moths before peak flight had up to 5% culls at harvest in central Michigan (G. Varner, Research Director, MI Dry Bean Research Board, personal communication). Regardless, trapping to monitor moth flight is still important to determine which fields, and when, to scout for pod damage. Based on infestation trials in Michigan, a strong positive correlation was found between pod damage and pick (DiFonzo et al. 2015). To keep pick from western bean cutworm damage under 1%, a nominal threshold of 12% of pods fed on is recommended (DiFonzo et al. 2015).

Insecticide application prior to pod development is premature, but once pod damage is detected in dry beans, pyrethroid insecticide sprays have been effective. A single well-timed application of a long-lasting product made up to 2 wk after infestation killed larvae already present and moving around the canopy, as well as larvae hatching from new egg masses (DiFonzo et al. 2015). Insecticides applied at planting for nematode control (aldicarb), or as seed treatment for leafhopper control (thiamethoxam), provided no reduction in cutworm infestations later in the season (DiFonzo et al. 2015). Dimethoate, commonly used as a foliar application for leafhopper control in Canada, does not provide control of western bean cutworm (Goudis et al. 2016). Some dry bean varieties were reported as resistant to western bean cutworm (Antonelli and O'Keeffe 1981, Seymour et al. 2010), but these were not well-suited for commercial production. In a variety trial in Michigan in 2009, under natural infestation of western bean cutworm, the percentage of pick varied among varieties, but all had some level of injury (G. Varner, Research Director, MI Dry Bean Research Board, personal communication). A trend of higher pick in large-seed varieties in Ontario, Canada has been observed (T.S.B., unpublished data). This could be the result of a greater proportion of damaged seeds from large-seeded varieties making it through the combine into the harvested beans although this has not been tested in the field.

Conclusion

Before 1999, western bean cutworm was a sporadic pest in dry bean and corn production in the western Great Plains. At that time, it was arguably of secondary or no concern to the vast majority of farmers in the United States and Canada. Over the last two decades, for reasons that remain unclear, it rapidly expanded its range all the way to the Atlantic coast, placing most U.S. and Canadian corn and dry bean production areas at risk for infestation. In the last 20 yr, especially in the last decade, there has been a considerable increase in research on western bean cutworm biology and management in both crops, not only in the western states but in the Great Lakes region. In its expanded range, management recommendations have been altered to address the unique risks of the region, such as the association of injury with mycotoxigenic fungal infections. A great deal of effort has also focused on education of crop scouts and pest managers. Scouting and trapping recommendations have been improved and have become much more routine in high-risk areas. Growers and crop consultants in the current range are well aware of this pest, either through direct experience with damage in their fields or through outreach efforts by extension educators and agribusinesses. In some regions, especially around the Great Lakes, western bean cutworm is now the primary above-ground pest of corn because of the impact of larval damage on grain quality and because millions of additional corn acres are at risk of infestation after the failure of Cry1F Bt toxin.

Although western bean cutworm life history and management is now better understood, many questions still remain compared to other key Lepidopteran pests in corn, such as European corn borer and corn earworm. For example, many aspects of its biology, such as flight capability, mating behavior, type and impact of mortality factors, and baseline susceptibility to insecticides have not been explored in detail. This information is necessary to refine and improve IPM recommendations and to validate or modify thresholds in both dry bean and corn. Critically, this information is needed to develop and implement future resistance management strategies for foliar insecticides, Vip3A (currently the only effective Bt toxin against this pest), or future transgenic events targeting western bean cutworm.

Supplementary Data

Supplementary data are available at *Journal of Integrated Pest Management* online.

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