Journal of Integrated Pest Management
OPEN ACCESS
RECOMMENDATIONS

Managing Colorado Potato Beetle Insecticide Resistance: New Tools and Strategies for the Next Decade of Pest Control in Potato

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J. Integ. Pest Mngmt. 5(4): 2014; DOI: http://dx.doi.org/10.1603/IPM14009

ABSTRACT. Neonicotinoid insecticides have been the most common management tool for Colorado potato beetle, *Leptinotarsa decemlineata* (Say), infestations in cultivated potato for nearly 20 yr. The relative ease of applying neonicotinoids at planting coupled with inexpensive, generic neonicotinoid formulations has reduced the incentive for potato growers to transition from these products to other mode of action (MoA) groups for early-season *L. decemlineata* control. Continuous use of neonicotinoids has resulted in resistant *L. decemlineata* populations in some production areas of the eastern United States. Continued reliance on neonicotinoids will accelerate *L. decemlineata* resistance development and result in additional insecticide inputs to manage these populations. Resistance management recommendations for *L. decemlineata* have focused on rotation of insecticides within the growing season. Growers using at-plant neonicotinoids for early-season *L. decemlineata* control are encouraged to rotate MoAs for later generations to delay resistance development. Although this short-term insecticide rotation has likely prolonged the utility of neonicotinoid insecticides, reducing reliance on a single MoA soil application at planting will improve the longevity of newer, more reduced-risk alternatives. The objectives of this article are twofold: 1) to provide a review of the current status of *L. decemlineata* neonicotinoid resistance, and 2) to propose long-term resistance management strategies that arrange reduced-risk MoA groups into several, multiyear sequences that will maximize *L. decemlineata* control and reduce the probability for resistance development. This recommendation maintains practical and economical approaches for *L. decemlineata* control, but limits reliance on any single MoA group to minimize selection pressure for resistance development.

Key Words: *Leptinotarsa decemlineata*, *Solanum tuberosum*, insecticide resistance management, reduced-risk insecticides, integrated pest management

For almost two decades, neonicotinoid insecticides have been the cornerstone of insect pest management in cultivated potato, *Solanum tuberosum* L. With the registration of imidacloprid in 1995, potato growers had access to a new group of water-soluble, systemic insecticides that provided excellent control of leaf-feeding pests like the Colorado potato beetle, *Leptinotarsa decemlineata* Say (Fig. 1A and B), piercing–sucking pests (e.g., green peach aphid, *Myzus persicae* Sulzer; potato aphid, *Macrosiphum euphorbiae* Thomas; potato psyllid, *Bactericera cockerelli* Šulc; and potato leafhopper, *Empoasca fabae* Harris), and below ground pests (e.g., wireworms and various Coleoptera: Elateridae species; Elbert et al. 2008, Jeschke et al. 2010). Since the initial registration of imidacloprid, new neonicotinoid insecticides (i.e., clothianidin, dinotefuran, and thiamethoxam) and several formulations of those active ingredients have been registered for at-plant use in potato (Nauen et al. 1999, 2012; Agrian Inc. 2013). Benefits of the neonicotinoid mode of action (MoA) group (Insecticide Resistance Action Committee MoA 4A, http://www.irac-online.org/) include versatile application methods (e.g., at-plant, seed-treatment, foliar, chemigation, drip, and side-dress), long residual control of pests when applied in the soil during planting, and limited nontarget impacts (Nauen et al. 1999, 2012; Sheets 2001, 2002). The U.S. Environmental Protection Agency (USEPA) has designated several neonicotinoids as either "reduced-risk" (RR) or as "organophosphate alternatives" during the registration process. The RR program expedites the review and regulatory decision-making process of conventional pesticides that meet one or more of the following criteria: limits impacts on nontarget organisms, reduces acute and chronic exposure to farm workers, and decreases additional pesticide use (Tomizawa and Casida 2005, Elbert et al. 2008, USEPA 2013).

Although the adoption of soil-applied neonicotinoid insecticides has been largely beneficial to the potato industry by reducing use of broad-spectrum foliar insecticides (e.g., carbamates, pyrethroids, and organophosphates), emergence of insecticide resistance and other possible nontarget impacts (e.g., toxicity to pollinators and groundwater contamination) threaten the long-term sustainability of these compounds (Grafius 1997, Szendrei et al. 2012, Goulson 2013, Huseth and Groves 2014). Increasing concern about neonicotinoid resistance in *L. decemlineata* and unknown environmental risks posed by this MoA group have elevated the importance of proactive pest management programs that integrate nonneonicotinoid insecticides (Insecticide Resistance Action Committee [IRAC] 2013). Transitioning from a continuous at-plant neonicotinoid pest management program to one that incorporates newer, RR insecticides will be a challenge for growers who are accustomed to uniform, broad-spectrum pest control provided by these systemic insecticides. Many of the alternative tools for *L. decemlineata* control belong to different MoA groups (e.g., benzoylureas, diamides, and spinosyns), but have limited efficacy against other key potato pests. Moreover, benzoylureas and spinosyns are not systemically mobile in the potato plant, a property of at-plant neonicotinoid insecticides that growers value. Successful incorporation of these newer RR compounds into more diverse insecticide rotations will benefit neonicotinoid resistance management of *L. decemlineata*, but also increase the importance of scouting for other common pests, such as potato leafhopper and colonizing aphid species. This article

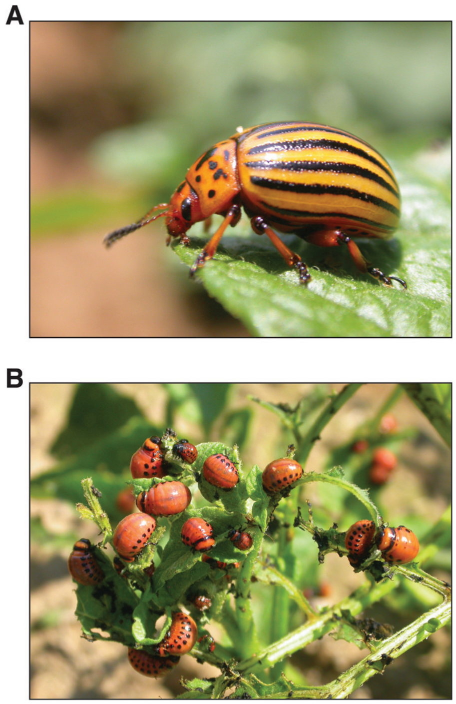

Fig. 1. Adult *L. decemlineata* (A) and larvae feeding on potato (B). Photo by T.P.K.

provides a brief review of the current status of neonicotinoid insecticide resistance in *L. decemlineata* and some recommendations for season-long resistance management plans that incorporate newer conventional insecticides to reduce reliance on at-plant neonicotinoids. Furthermore, using a common estimate of the nontarget effects of insecticides (environmental impact quotient [EIQ]), this recommendation qualifies the reduced-risk attributes of insecticides registered for *L. decemlineata* control since 1970. This estimate of temporal toxicity reduction highlights the value of current insecticides when compared with older, more broad-spectrum materials historically used in potato production. Accounting for the value-added characteristics (e.g., reduced environmental impacts) of individual insecticides will be critical to increase grower adoption of contemporary resistance management programs that use a diverse RR insecticide toolbox to slow selection for resistant *L. decemlineata* populations.

Insecticide Resistance and *L. decemlineata*

Adaptation of insect pests to management strategies (e.g., biological, cultural, chemical control, or host plant resistance) is not a new problem. Pest population adaptation to management strategies is often most obvious when insecticides cannot control insect infestations in the field (i.e., resistance). Functionally, insecticide resistance can be defined as a genetic change in a pest population that results in repeated failure of an insecticide product when applied in a manner consistent with label recommendations (IRAC 2013). However, this definition illustrates a population condition (i.e., genetic shifts in target insects) that results in repeated failures of specifically labeled formulated products. At this failure point, growers will either accept economic damage or reapply with alternative MoA groups, which, in turn, increases the total insecticide input, reduces grower profit, and decreases the sustainability of the production system. A more rigorous definition, field-evolved resistance, quantifies change in alleles related to resistance traits through subsequent generations as an estimate of insecticide insensitivity (Tabashnik et al. 2013). This definition involves an analytical approach that documents resistance gene frequencies of insect populations and how they change over time. With the advent of more inexpensive genomic tools, researchers now have the ability to accurately document these population-scale genetic changes and deploy proactive resistance management strategies in near real time to prevent total product failures (Tabashnik et al. 2013). Although these definitions of insecticide resistance have clear differences, both strive to reduce the probability of insecticide failure that may result in further economic, environmental, and societal costs.

L. decemlineata has a long history of resistance development and has documented insensitivity to 54 different active ingredients in nearly all insecticide MoA groups (Alyokhin et al. 2008a, Whalon et al. 2013). *L. decemlineata* resistance to individual insecticides varies between both local populations and geographic regions (Grafius 1997, Chen et al. 2014), but uniformity of *L. decemlineata* management practices across large geographic extents increases the likelihood of specific patterns of resistance to develop (Huseth and Groves 2013, Huseth et al. 2014). Patterns of population-level insensitivity to specific compounds are likely driven by interactions among a combination of factors including genetic predisposition for resistance, farm-level insecticide use practices, and frequency of potato production in the agroecosystem (Grafius 1997, Szendrei et al. 2012, Huseth and Groves 2013, Piiroinen et al. 2013, Chen et al. 2014). Moreover, repeated failure to control *L. decemlineata* with industry standard products can result in additional insecticide applications, yield reduction, greater nontarget impacts, and economic losses for potato growers across entire production regions (Grafius 1997).

Neonicotinoid Resistance—Perspectives From the Field

Control of *L. decemlineata* populations with neonicotinoid insecticides has been declining nationally since the mid-2000s (Mota-Sanchez et al. 2006, Alyokhin et al. 2008a, Szendrei et al. 2012). Laboratory bioassay estimates have confirmed the suspicion that *L. decemlineata* insensitivity to imidacloprid and thiamethoxam has increased throughout the northeast and upper Midwestern potato production regions of the United States (Alyokhin et al. 2008a, Szendrei et al. 2012, Whalon et al. 2013). Although field-level failures are uncommon, the duration of beetle control within the growing season has declined significantly over time. A survey of pesticide application history in Wisconsin potato fields showed that the time between the at-plant neonicotinoid and first foliar application targeting *L. decemlineata* has declined steadily since 1995 (Fig. 2). Annual planting records from commercial fields were standardized by cumulative growing degree–days (GDD). Cumulative growing degree-days were calculated as summed growing degree-days where GDD = $[(Temp_{max} - Temp_{min})/2] - Temp_{base}$. Year is represented as a continuous variable for graphical presentation. On average, fields lost 35 growing degree–days of control per year since the initial registration of imidacloprid in

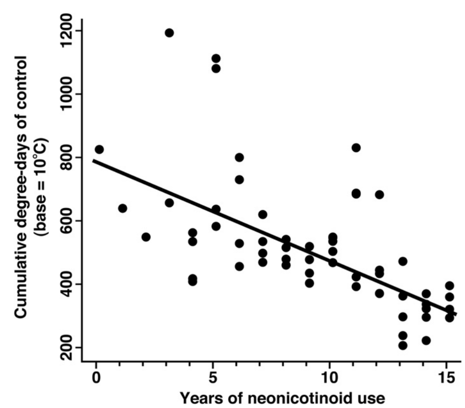

Fig. 2. Duration of *L. decemlineata* control since registration of neonicotinoid insecticides in 1995 (i.e., year 0). Cumulative growing degree–days of control represents the period from at-plant neonicotinoid application until first foliar application for *L. decemlineata*. The black line represents a simple correlation between cumulative growing degree–days of control and years after 1995.

1995 (Huseth and Groves 2013). Growing degree–day losses corresponded to ≈3.3 fewer calendar days of control per year or ≈50 d of lost control since registration of neonicotinoids in 1995 (Huseth and Groves 2013). Erosion of neonicotinoid control in these locations is likely representative of *L. decemlineata* populations across much of the Wisconsin potato production regions. Moreover, similar control losses are likely in other potato production regions where resistance has historically been an issue. Reduced duration control of *L. decemlineata* with systemic neonicotinoids has necessitated the use of extra foliar-applied insecticides in addition to the at-plant application. A greater proportion of growers shifting to this pest management strategy is another indication that insecticide susceptibility has changed at a large spatial scale (Grafius 1997, Huseth and Groves 2013).

Although resistance is an emerging concern in some areas of the United States, several other potato production regions continue to have adequate control of *L. decemlineata* with the at-plant neonicotinoid applications. Furthermore, even in potato production regions where *L. decemlineata* resistance has developed, growers continue to use at-plant neonicotinoids to control the piercing–sucking potato pest complex. While many growers acknowledge that using neonicotinoid insecticides does not benefit long-term resistance management of *L. decemlineata*, the availability of these relatively inexpensive insecticides continues to incentivize at-plant use to control other potato pests (e.g., leafhoppers, aphids, and psyllids). Moreover, growers still value at-plant neonicotinoid treatments for their partial control of early-season *L. decemlineata* populations because the number of subsequent foliar applications of other more expensive products (e.g., benzoylureas, diamides, and spinosyns) applied to the crop may be reduced. Expectation of additive *L. decemlineata* control with a combination of at-plant neonicotinoids and newer MoA groups will increase population-level exposure to multiple toxins with different efficacy, thereby accelerating selection for resistance to both MoAs. Because this combination of multiple insecticides currently has superior control of *L. decemlineata* populations, the impact of this simultaneous insecticide selection factor may not be immediately apparent but will likely result in accelerated resistance to multiple MoAs. Growers at both ends of the resistance continuum will benefit by adopting resistance management strategies that incorporate a more diverse set of insecticides as one approach to maintain or improve the efficacy and longevity of neonicotinoids and newer RR products.

Using the Entire Toolbox—Planning a 3-yr Resistance Management Program

Flexible resistance management strategies that rotate chemistries in time and space are critical to maintain the efficacy of each individual insecticide used in a production sequence (Insecticide Resistance Action Committee, http://www.irac-online.org/). When successful, growers can prolong the longevity (duration of effective control) of useful insecticides, which, in turn, improves profitability and minimizes the need for additional insecticide inputs to manage problematic populations (Grafius 1997). Currently, potato growers have access to many MoA groups, delivery methods, and formulations of insecticides to control *L. decemlineata* (Table 1); but continue to use at-plant neonicotinoids for *L. decemlineata* on the majority of potato cropland (Szendrei et al. 2012, Huseth and Groves 2013). Incorporation of newer MoA groups into a long-term *L. decemlineata* resistance program will reduce selection pressure for resistance to any one of these new RR MoA groups. Moreover, nonchemical strategies should be considered as a component in long-term *L. decemlineata* resistance management (Text box 1).

The following suggestions assume a two-generation, *L. decemlineata* lifecycle common to many potato production regions of the temperate eastern United States (Fig. 3). The growing season has been subdivided into three specific treatment windows, early generation, late generation, and spring trap crop (i.e., reducing populations of colonizing adults). These treatment windows provide a general reference that specifies when individual MoA groups should be used to target larval generations during the growing season (Table 2). In regions where only a single generation occurs each year, growers may only need to use one MoA group applied early in the season for adequate control of larvae. In regions where either sporadic infestations (western United States) or three functional generations (southeast United States) occur, these MoA rotation suggestions may not apply. All compounds included have the greatest activity on small larvae (first and second instars). However, one compound (i.e., novaluron, IRAC group 15—benzoylureas) has effects on several life stages including molting disruption in small larvae, reduced female *L. decemlineata* fertility, and reduced viability of eggs that have not hatched (Cutler et al. 2005; Alyokhin et al. 2008b, 2009). Growers will achieve the greatest control using novaluron during the early

Table 1. Average grams active ingredient (means ± SD) per hectare labeled for *L. decemlineata* in potato in 2014

IRAC MoA group	Delivery[a]	*N* insecticide formulations[b]	Avg grams active ingredient per hectare	Min.	Max
Single MoA					
Avermectins	F	16	28.4 ± 22.1	5.0	84.1
Benzoylureas	F	1	87.2		
Carbamates	F	11	2,343.7 ± 785.1	1,122.4	4,483.3
	IF	3	1,486.7 ± 633.7	1,120.8	2,218.4
Cyclodiene organochlorines	F	3	1,145.2 ± 44.7	1,118.0	1,196.8
Cyromazine	F	1	279.5		
Diamides	F	1	73.1		
	IF	1	197.4		
METI	F	1	229.9		
Neonicotinoids	F	31	84.2 ± 72.3	44.6	350.3
	IF	27	325.7 ± 64.4	52.5	368.8
	ST	27	261.8 ± 56.5	112.9	350.4
Organophosphates	F	2	734.1 ± 404.2	448.3	1,020.0
	IF	3	3,967.7 ± 0.0	3,967.7	3,967.7
Pyrethroids	F	44	75.5 ± 72.4	3.5	224.2
Spinosyns	F	4	105.7 ± 38.8	70.1	157.6
Two MoA (prepack)[c]					
Avermectins + pyrethroids	F	1	127.9		
Neonicotinoid + diamides	F	1	110.7		
Neonicotinoids + pyrethroids	F	7	96.2 ± 32.9	60.4	155.7

[a] Labeled application methods: Foliar (F), in-furrow (IF), and seed treatment (ST).
[b] Composition of inert ingredients in formulated products were unknown. Each registered trade name was considered an individual formulation.
[c] Average grams active ingredient calculated from the sum of total insecticidal active ingredients in formulated product (i.e., grams of first active ingredient + grams of second active ingredient = grams total active ingredient in formulated product).

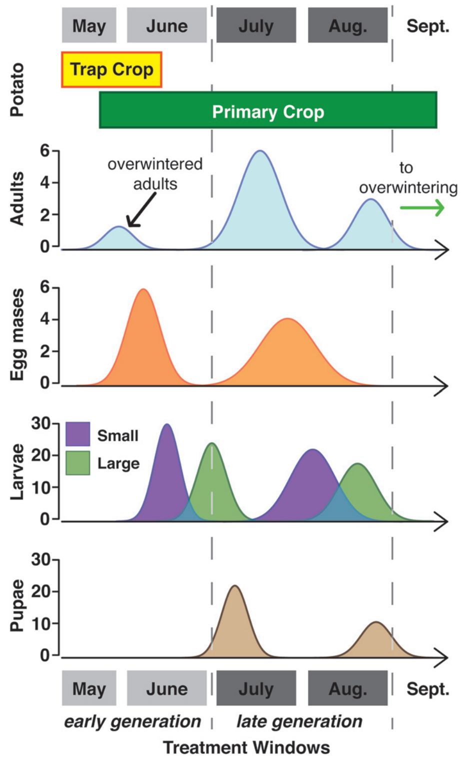

Fig. 3. Insecticide application treatment windows for *L. decemlineata*. Demographic curves represent a hypothetical pattern of life stages in potato. Vertical axes show an average *L. decemlineata* life stage count per 10 plants. The light gray treatment window represents early *L. decemlineata* generations, dark gray is the late generation window, and yellow is the spring trap crop window (Text box 1).

generation window when synchronous egg deposition occurs and larval life stages are the most uniform in the crop. The current label for novaluron permits a series of three applications each season. Growers can take advantage of its activity on multiple *L. decemlineata* life stages by splitting the full-season rate over three sprays beginning at 50% egg deposition and continuing the second and third applications at 7-d intervals during the early generation treatment window.

Multiple-season *L. decemlineata* management plans are designed to limit exposure to MoA groups over consecutive generations. Here, populations are exposed to a given MoA group once every three to six generations (Fig. 4). Decisions on specific programs should be based on a reasonable estimate of neonicotinoid insensitivity observed or measured in commercial fields. Presented are several different scenarios that are adapted to potato maturity, choice of application approach, and the degree of field-level neonicotinoid insensitivity (Fig. 4; Table 3). For long-maturing cultivars, program options A–D and E–G are listed in descending order of neonicotinoid insensitivity. Options A and F would be selected for a population that is becoming less controllable with neonicotinoids, whereas Options D and G would be chosen for a population in which neonicotinoids are still very effective. For short-maturity cultivars, Option H would only need to target the early generation each year. Option H would also be very suitable for regions with only a single *L. decemlineata* generation per year, although timing of applications should be adjusted to coincide with presence of small larvae in the crop.

All foliar-applied compounds should be applied as a series of two, successive applications spaced 7–10 d apart to improve control of staggered life stages (e.g., eggs in development that will eclose over an interval of several days). Moreover, several RR compounds require specific spray tank conditions (e.g., pH of water source), companion adjuvants, and timing with vulnerable early stage life stages (e.g., first and second instar). Moreover, several of these compounds (e.g., diamides or spinosyns) may have less activity on other key potato pests (e.g., potato leafhopper and colonizing aphids); scouting and economic thresholds for secondary pests will remain a critical component of weekly field management activities. Although neonicotinoids have been the most common tactic to manage early-season piercing–sucking pests, a diversity of other MoA groups can be used to control these pests in potato. These alternate MoA groups should be incorporated as a replacement for at-plant neonicotinoids to minimize further selection for *L. decemlineata* neonicotinoid resistance through incidental exposure. The decision to apply any insecticide (except prophylactic, at-plant applications) should be completed for each field based on scouting results and established economic damage observed in that individual management unit. Reference individual product label specific for reentry and preharvest intervals. Insecticides included represent formulations that are commonly available. Other active ingredient formulations may be labeled for these uses, and it is appropriate to consult individual state recommendations for a comprehensive list of

Table 2. Registered products to manage *L. decemlineata* small larvae

Treatment window	Active ingredient	IRAC MoA group	Delivery[a]	Common trade names
Early generation	Abamectin	6	F	Agri-Mek, generics
	Chlorantraniliprole	28	F	Coragen
	Cyantraniliprole	28	F, IF	Exirel, Verimark
	Imidacloprid	4A	IF, ST	Admire Pro, generics
	Novaluron	15	F	Rimon
	Spinetoram	5	F	Radiant
	Spinosad	5	F	Blackhawk, Entrust
	Thiamethoxam	4A	IF, ST	Platinum, Cruiser Maxx Potato
Late generation	Abamectin	6	F	Agri-Mek, generics
	Chlorantraniliprole	28	F	Coragen, Voliam Xpress[b]
	Cyantraniliprole	28	F	Exirel
	Imidacloprid	4A	F	Admire Pro, generics
	Indoxacarb	22A	F	Avaunt
	Spinetoram	5	F	Radiant
	Spinosad	5	F	Blackhawk, Entrust
	Thiamethoxam	4A	F	Actara, Endigo ZC[c]
	Tolfenpyrad	21B	F	Torac
Trap crop	Indoxacarb	22A	F	Avaunt

[a] F, foliar; IF, in-furrow; ST, seed treatment.
[b] Contains lambda-cyhalothrin, use when *E. fabae* and *L. decemlineata* at threshold.
[c] Contains cyfluthrin, use when *E. fabae* and *L. decemlineata* at threshold.

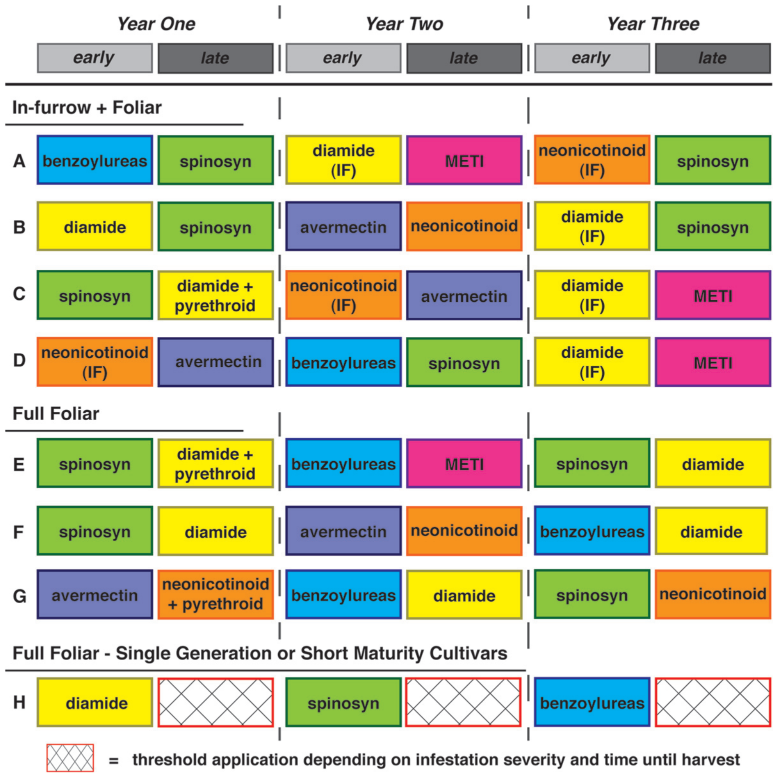

Fig. 4. Product rotation suggestions to manage *L. decemlineata* larvae. Programs A–G alternate IRAC MoA groups across early and late generation treatment windows in each season (see Table 3 for program descriptions). In-furrow, at-plant insecticides are designated with IF. Prepack insecticides containing two MoAs (e.g., neonicotinoid + pyrethroid) should be only used in the presence of two target pests at economic threshold. Programs A–G were designed for long-maturity potato cultivars that require protection from several *L. decemlineata* generations. Program H was developed for short maturity cultivars (e.g., red and heirloom cultivars) or single generation populations that may not require application of another MoA for later generation *L. decemlineata* control.

Table 3. Three-year *L. decemlineata* resistance management programs

Program	Description
In-furrow + Foliar management programs	A. Neonicotinoid (F, IF, or ST)[a] used with very limited success. Management plan rotates away from the neonicotinoid group over four consecutive treatment windows. B. Neonicotinoid (F, IF, or ST) was used in prior year with limited success. Early season colonization has been historically high at specific field location. Prepack neonicotinoid + pyrethroid could be used in year 2 if potato leafhopper numbers are high. C. Populations easily controlled with at-plant neonicotinoids. Tolfenpyrad (IRAC group Mitochondrial complex 1 Electron Transport Inhibitor [METI]) was placed behind in-furrow diamide to manage any larvae that persist through in-furrow diamide. D. Use only if neonicotinoid (F, IF, or ST) was not used in year zero and populations are still susceptible. Years 2 and 3 can be switched depending on in-furrow diamide availability.
Foliar management programs	E. Full foliar program if *L. decemlineata* resistance is suspected in a group of fields. If fields are relatively close (<1, 500 m), use the same MoA rotation scheme uniformly to avoid selection over less than four generations. F. Full foliar program if neonicotinoids have limited efficacy. G. Neonicotinoids maintain satisfactory efficacy annually. Prepack neonicotinoid can be switched with foliar neonicotinoid if *E. fabae* (potato leafhopper) numbers are low in year 2.
Short maturity-single generation program	H. Full foliar program for short maturing cultivars and regions with only a single *L. decemlineata* generation each year. In areas where colonization pressure is low, early season applications in the first treatment window may be satisfactory to manage beetles until harvest. Follow up applications of another mode of action group (cross-hatched box) should be completed only if an economic damage is likely to be reached. Companion groups could be foliar neonicotinoid, prepack neonicotinoid, or abamectin. A foliar diamide should only be used in the late season treatment window of year 3.

Programs are sequentially ordered by observed neonicotinoid efficacy in the field (low to high control). All descriptions correspond to Figure 4.
[a] Labeled application methods: F, foliar; IF, in-furrow; ST, seed treatment.

registrations. These recommendations are not designed for management of persistent or nonpersistently transmitted pathogens (e.g., potato leafroll virus, potato virus Y, and zebra chip), so please consult the proper literature for specific programs to manage insect vectors in potato (Ragsdale et al. 2001, Goolsby et al. 2007, Boiteau et al. 2009, Frost et al. 2013, Prager et al. 2013, Workneh et al. 2013).

Specific information about insecticide formulation is a critical component of resistance management. The diversity of formulations for individual MoA groups and blends of MoA groups presents a challenge for resistance management (Table 1); therefore, the product label should always be consulted for specific information on resistance management and active ingredients in the formulation. For more information about *L. decemlineata* generation number in specific geographic regions, scouting procedures, application rates, reapplication intervals, preharvest intervals, and other recommendations consult respective state management guidelines.

Insecticide Stewardship Reduces the Environmental Footprint of Potato Production

For potato growers, neonicotinoid insecticides are a component in a broader group of RR insecticides that control *L. decemlineata* and limit nontarget impacts of pest management activities. More recent registrations (USEPA Federal Insecticide, Fungicide, and Rodenticide Act—Section 3 national registrations) in the current potato insecticide toolbox are a considerable improvement over older, broad-spectrum insecticides that have greater impacts on the environment and direct consequences for human health (Pimentel et al. 1992). Although the importance of resistance management has been widely discussed (Grafius 1997, Alyokhin et al. 2008a, Szendrei et al. 2012), few studies have examined major transitions in *L. decemlineata* pest management technology over time (i.e., adoption of new RR MoA groups) and the significance of those events for the broader sustainability of potato production. As neonicotinoids continue to lose efficacy throughout the United States, an estimation of the environmental value of these RR insecticide technologies for *L. decemlineata* will be one important step to incentivize more proactive resistance management using newer MoA groups (Grafius 1997, Osteen and Fernandez-Cornejo 2013).

Conventional insecticide use remains the cornerstone of *L. decemlineata* management for most potato growers. As a result of this widespread chemical dependency, sustainability assessments for pest management in potato are likely to see some of the greatest improvements where broad spectrum products can be replaced by newer, more environmentally friendly tools over large spatial extents (i.e., entire growing regions). As a first step, the long-term improvement of *L. decemlineata* insecticide tools can be estimated over time. Documenting this trend in declining toxicity of registered potato insecticides over time shows an unmeasured value-added attribute of newer RR tools that have replaced older, broader spectrum insecticides. Insecticides registered by the USEPA as a national label (Section 3) for *L. decemlineata* control were selected to estimate progress in tools available for pest management in potato. Application rates for *L. decemlineata* were determined using historical insecticide screening records generated by vegetable entomologists at the University of Wisconsin, Madison, WI, from 1970 to 2010 and should reflect similar studies screening insecticides for this pest in eastern North America. These individual formulations and rates were then used to calculate individual field use EIQs (Kovach et al. 1992). Briefly, the EIQ uses several measures of environmental and toxicological risk that are provided to the USEPA during the pesticide registration process. These risk estimates are then combined into a single metric that can be used to compare the nontarget impact of different agrochemical active ingredients, field use rates, and formulations (Kovach et al. 1992, New York State Integrated Pest Management Program [NY IPM] 2013, http://www.nysipm.cornell.edu/publications/eiq/equationasp). To estimate the improvement in the tools registered to control *L. decemlineata*, the field use EIQ was calculated for each active ingredient evaluated by vegetable entomologists at the University of Wisconsin. Active ingredients were often tested with several different delivery methods and rates over several years. In the current study, we present only the first observation of each active ingredient in the Wisconsin Annual Reports from 1970 to 2010. If more than a single rate was tested in the first year, the lowest insecticide rate was included as the most conservative estimate of impact. We considered year as a continuous variable to measure the trend in toxicity (field use EIQ) for available products for *L. decemlineata* management.

Since 1970, the state of Wisconsin has authorized 69 different formulations of 46 individual active ingredients among 10 MoA groups for *L. decemlineata* control (Wisconsin Annual Reports 1970–2010). During this 40-yr period, registered insecticides have increased target pest specificity and improved formulation technology, which, in turn, reduced the amount and toxicity of active ingredients to manage *L. decemlineata*. In 1970, the average field EIQ of insecticides tested for *L. decemlineata* control was 20.2 ± 15.2 (mean ± SD, minimum 5.5, maximum 61.1). In comparison, insecticides tested in 2010 had a far smaller average EIQ of 1.5 ± 1.1 (mean ± SD, minimum 0.7, maximum 2.2). When considered as a continuous variable scaled to years since the first available annual report (1970 equals year 0), a significant main effect of year existed (simple linear regression, $F = 14.47$; df = 1,42; $P < 0.001$). On average, field use EIQ decreased by 0.45 U per year since 1970, or ≈18 U since 1970 (Fig. 5). This considerable reduction in toxicity of individual insecticides registered for *L. decemlineata* control represents important progress in the environmental impact of registered insecticides to control this pest. Currently, nontarget impacts are underrepresented components in resistance management recommendations for *L. decemlineata.* Furthermore, over reliance on a single MoA group (e.g., neonicotinoids, diamides) may result in additional insecticide applications and reduced sustainability of potato production.

One new pest management tool, IPM PRiME, improves the ability of growers and pest management practitioners to assess the environmental impacts of pest management programs for individual fields (IPM PRiME, https://ipmprime.org/pesticides/). IPM PRiME is a free online tool developed through a collaboration of several public institutions that gives growers an additional method to assess environmental risks related to seasonal inputs for several specialty crops (e.g., potato). For multiyear *L. decemlineata* resistance management plans,

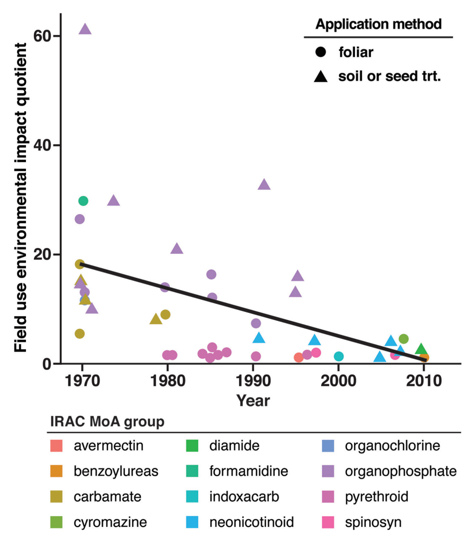

Fig. 5. Estimated field use EIQ per acre for insecticides registered to control *L. decemlineata* since 1970 (Kovach et al. 1992). Individual points represent the first screening event conducted by vegetable entomologists at the University of Wisconsin at the Hancock Agricultural Experiment Station, Hancock, WI.

this tool could be used to estimate the environmental footprint of sequences of insecticides over time. Specifically, individual potato field locations can be mapped through a geographic information system interface and pesticide inputs cataloged (e.g., fungicides, herbicides, insecticides, and fumigants) for an entire growing season. Furthermore, environmental risk assessments also incorporate several other parameters defined by the user including type of application equipment used on the farm (e.g., ground or aerial spray, application nozzle type, and spray boom height), insecticide rates and application timing in the season, soil characteristics, proximity to sensitive areas (e.g., schools, houses, and riparian areas), and abiotic factors specific to geographic location (Jepson et al. 2014, IPM PRiME 2014). Outputs identify nontarget organisms that are at particular risk to one or many pest management practices (e.g., fish or pollinators), adjusting specific inputs can mitigate risk scores to balance trade-offs between environmental risk and adequate management of the potato crop. Moreover, growers could use this insecticide resistance recommendation to optimize annual MoA rotations for their individual fields, but also generate a site-specific environmental risk assessment for each insecticide program based on specific production and location conditions (IPM PRiME 2014). Tools like IPM PRiME improve the ability of growers to comprehensively evaluate the environmental impacts of individual insecticides and insecticide programs to make more educated decisions about insecticide use at the field- and farm-scale. Insect resistance management programs will need to encourage adoption of technology like IPM PRiME to record context-based management records (geospatial production histories) and also increase the accessibility of large amounts of information to improve stewardship of useful pesticides. Moreover, outcomes of well-planned resistance management strategies will minimize the inherent risks high-input production systems may pose to humans, nontarget organisms, and the environment.

In conclusion, with the decline of carbamate, organophosphate, and pyrethroid efficacy in the late 1980s, potato growers were left with few options to manage *L. decemlineata* (Ioannidis et al. 1991, Wyman et al. 1994, Grafius 1997). To produce a viable crop, growers became reliant on numerous insecticides and repeated applications with limited success (Grafius 1997). With the registration of imidacloprid on potato in 1995, growers regained season-long control of resistant populations with a single at-plant application (Huseth and Groves 2013). Popularity of neonicotinoids spread quickly among growers, a trend that resulted in widespread adoption of neonicotinoids on nearly all potato acres in the United States for the past two decades. When compared with *L. decemlineata* control programs in the late 1980s, this shift to neonicotinoids reduced the environmental impact of potato pest management; but recurring use of neonicotinoids has eroded efficacy and has resulted in more inputs for control (Huseth and Groves 2013). For newer MoA groups (e.g., diamides) and locations where neonicotinoids remain effective, proactive resistance management recommendations will be critical to prolong the longevity of these valuable RR insecticides.

Text box 1. Cultural control of resistant *L. decemlineata*

Crop Rotation. Separation of potato crops in space and time remains the most widely practiced nonchemical strategy to reduce infestation of *L. decemlineata* annually. Although crop rotation is not often thought of as a resistance management strategy for this insect, any reduction in the number of resistant *L. decemlineata* infesting a field could be considered a net improvement over a field that was not rotated. Estimates of the distance required to rotate potato for *L. decemlineata* control vary considerably, ranging from 400 to 1,500 m in distance from previous potato fields (Sexson and Wyman 2005; Weisz et al. 1994, 1996; Boiteau et al. 2008). Although these distance estimates differ, the general consensus among researchers is that maximizing interannual potato separation will reduce the number of postdiapause adults infesting the crop (Huseth et al. 2012), thereby reducing the number of resistant *L. decemlineata* that can reproduce on the crop and limiting exposure of offspring to insecticides. Though potato rotation has been an effective management tool for many large-scale potato growers, those who lack sufficient acreage (e.g., small-scale growers, fresh-market growers, community-supported agriculture farms) to adequately rotate their potato crop are often challenged by increasing populations of *L. decemlineata* over time. In situations where cropland for rotation is limited, growers can use alternative population and resistance management strategies (e.g., trap crops) to control *L. decemlineata.*

Spring Trap Crops. Trap crops are small plantings of potato that are more attractive to *L. decemlineata* than the main crop and are often used to aggregate the pest in time and space. *L. decemlineata* infesting trap crops can be controlled mechanically or with pesticides. Insecticides with activity against adult *L. decemlineata* are presented as an optional resistance management strategy occurring at the beginning of the season when adults are colonizing the potato crop in the spring. Trap crops can be used annually to reduce overwintering beetle populations (Fig. 3). Trap crops are typically located in lightly cultivated, field perimeter areas between the main crop and the nearest previous potato field. Trap crops should be planted early enough in the spring to have a full canopy before the primary crop emerges to enhance their attractiveness to colonizing *L. decemlineata* (Wyman et al. 1994). Spring trap crops may work best when coupled with short to medium maturity cultivars that are typically planted later, ensuring the trap crop emerges long before the main crop. Trap crops should be planted in a large enough area to be attractive to aggregate colonizing beetles. Insecticides with excellent activity on adult *L. decemlineata* should be used when infestations are high (e.g., indoxacarb; Table 2). Adults can also be killed mechanically with a flail or stalk chopper, vacuum unit, or propane flamer (Wyman et al. 1994). Spring trap crops should be destroyed before risk of foliar pathogens occurs during the growing season (e.g., potato late blight fungus, *Phytophthora infestans* (Montagne) de Bary).

Acknowledgments

We thank cooperating growers for generously providing insecticide application records and allowing us to conduct research on their farms. We also thank the research programs of Jeffrey A. Wyman and R. Keith Chapman for generating *L. decemlineata* screening data used to determine sustainability improvements of insecticide tools in Wisconsin. We thank the Wisconsin Potato and Vegetable Growers Association (WPVGA) and the New York Empire State Potato Growers Association for continued support of our research efforts. Funding was provided by Wisconsin Potato Industry Board, Distinguished Graduate Student Fellowship 2009 & 2011, R. Keith Chapman and Jeffrey A. Wyman—Wisconsin Distinguished Graduate Fellowship in Vegetable Entomology 2010, and National Potato Council—State Cooperative Potato Research Program FY09-13.

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Received 20 May 2014; accepted 12 August 2014.