Abundance and Distribution of Western and Northern Corn Rootworm (*Diabrotica* spp.) and Prevalence of Rotation Resistance in Eastern Iowa

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Abundance and Distribution of Western and Northern Corn Rootworm (*Diabrotica* spp.) and Prevalence of Rotation Resistance in Eastern Iowa

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ABSTRACT The western corn rootworm *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae) and the northern corn rootworm *Diabrotica barberi* Smith & Lawrence (Coleoptera: Chrysomelidae) are major pests of corn (*Zea mays* L.). Historically, crop rotation has been an effective management strategy, but both species have adapted to crop rotation in the Midwest. For both species in eastern Iowa, we measured abundance and prevalence of rotation resistance using sticky traps and emergence cages in fields of corn and soybean (*Glycine max* L.). Based on currently available data, we calculated the economic thresholds for these pests at two *Diabrotica* spp. per trap per day in cornfields and 1.5 *D. v. virgifera* per trap per day in soybean fields. The economic injury level of rotation-resistant *D. barberi* was determined to be 3.5 adult insects per emergence cage per year. Peak abundance of rootworm adults in cornfields was below economic thresholds in the majority of fields sampled, suggesting that management of rootworm larvae in continuous cornfields may not always be necessary. Rotation-resistant *D. barberi* was found throughout eastern Iowa using emergence cages in first-year cornfields, however, the abundance was below levels expected to impose economic injury in 14 of 17 fields evaluated. The presence of rotation-resistant *D. v. virgifera*, as measured by the occurrence of this insect in soybean fields, occurred only in northeastern Iowa and was also below the economic threshold. These data suggests that crop rotation remains a viable pest management strategy in eastern Iowa.

KEY WORDS *Diabrotica barberi*, *Diabrotica virgifera virgifera*, economic injury level, integrated pest management (IPM), geographic information systems

Diabrotica virgifera virgifera LeConte (Coleoptera: Chrysomelidae), the western corn rootworm, and *Diabrotica barberi* Smith & Lawrence (Coleoptera: Chrysomelidae), the northern corn rootworm, are important pests of corn (*Zea mays* L.) in North America. For both species corn is the primary host throughout the lifecycle (Chiang 1973). Larval feeding injury to roots reduces uptake of nutrients and water, which can reduce yield. Additionally, larval feeding can cause corn plants to lodge (Spike and Tollefson 1991), which can complicate mechanical harvest (Riedell 1990).

Economic thresholds for *Diabrotica* spp. focus on the adult population size to predict the severity of larval injury to corn the following year. One method uses whole-plant counts, with counts >1.62 and 0.71 adults per plant for continuous cornfields and first-year cornfields, respectively, predicted to cause economic damage (Godfrey and Turpin 1983). Another method uses sticky traps deployed throughout a field to estimate adult abundance. Average captures exceeding six adult *Diabrotica* spp. per sticky trap per day are indicative of economic damage to corn the following year (Hein and Tollefson 1985). However, these economic thresholds may not accurately predict economic injury in current corn production systems because agricultural practices, commodity process, and input cost have changed over time.

Some of the current challenges of managing *Diabrotica* spp. include resistance to some pesticides by adults (Meinke et al. 1998, Zhu et al. 2001). Furthermore, there are no commercial hybrids produced today, other than genetically modified plants, which have sufficient host plant resistance against *Diabrotica* spp. to reliably prevent yield loss (Khishen et al. 2009). Transgenic hybrids expressing rootworm active *Bacillus thuringiensis* (Bt) proteins will kill larvae that feed on corn root tissue (Vaughn et al. 2005), although Bt hybrids have a technology cost that is paid by the grower (Martin and Hyde 2001, Hyde et al. 2003). Additionally, some cases of Bt resistance have been documented for *D. v. virgifera* in the field (Gassmann et al. 2011).

Crop rotation is an inexpensive option for control of both *D. v. virgifera* and *D. barberi.* Larvae that hatch in fields rotated from corn to an alternative crop will

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not survive (Branson and Ortman 1970, 1971). Oviposition by both species primarily occurs in corn, so in the absence of rotation resistance, fields rotated to corn from a noncorn crop have limited risk of larval injury. Crop rotation can further benefit growers as a 2-yr rotation of corn and soybean (*Glycine max* L.) can increase yields by 5–20% compared with corn in continuous production, even when higher rates of pesticide and fertilizer are applied to continuous corn (Bullock 1992). However, *D. v. virgifera* and *D. barberi* have developed resistance to crop rotation within the Corn Belt, and this is associated with injury to first-year corn.

Injury to first-year corn by *D. barberi* was first recorded in the 1920s (Bigger 1932). Eggs of *D. barberi* can survive multiple winters (Chiang 1965), and in some cases, >40% of eggs hatch after the second winter (Krysan et al. 1984, 1986). Eggs hatching after two winters are rotation resistant through the physiological adaptation of extended diapause. Extended diapause has been documented to last up to 4 yr in *D. barberi*, and within a population the percentage of eggs that hatch per year can mimic regional patterns of rotation (Levine et al. 1992). Rotation-resistant *D. barberi* may be found over much of the northern Corn Belt (Foster 1987, Landis et al. 1992, Levine et al. 1992, Krysan 1993), although in some areas extended diapause occurs less frequently (Krysan et al. 1986, Steffey et al. 1992). Mating between rotation-susceptible and rotation-resistant *D. barberi* is essentially random and expression of extended diapause is predicted to increase only in areas where crop rotation is practiced frequently (Krafsur 1995). Historical data on the distribution of rotation-resistant *D. barberi* within Iowa indicate that extended diapause occurs primarily in the northwest (Foster 1987).

Injury to first-year corn by *D. v. virgifera* was first observed in 1987 in east–central Illinois (Levine and Oloumi–Sadeghi 1996). Rotation-resistant *D. v. virgifera* have adapted to crop rotation by decreased oviposition fidelity to corn (Levine et al. 2002) and have since spread outward from this epicenter (Onstad et al. 1999). Oviposition by rotation-resistant *D. v. virgifera* is indiscriminate and eggs can be found in many types of crops (Rondon and Gray 2003, 2004, Schroeder et al. 2005). Oviposition in soybean fields occurs frequently because soybean are planted more than other crops rotated with corn in areas affected by rotation-resistant *D. v. virgifera* (Onstad et al. 2003). Areas with a high frequency of rotation-resistant *D. v. virgifera* can have a higher percentage of female *D. v. virgifera* in soybean fields than cornfields (O'Neal et al. 1999). Furthermore, in some cases 27% of the variation in root injury to first-year corn can be explained by the abundance of *D. v. virgifera* in soybean fields (O'Neal et al. 2001). It is important to note that this adaption does not translate to an attraction to soybeans (Spencer et al. 1999, Hibbard et al. 2002) nor are rotation-resistant *D. v. virgifera* able to gain more sustenance from soybeans than rotation-susceptible individuals (Mabry and Spencer 2003, Mabry et al. 2004, Dunbar and Gassmann 2012). Models of the expansion of rotation-resistant *D. v. virgifera* from Illinois into Iowa predict that the rotation-resistant variant would invade eastern Iowa sometime between 2007 and 2011 (Onstad et al. 1999, Levine et al. 2002).

In the current study, which was conducted in eastern Iowa, our objectives were to 1) measure the overall abundance of *D. barberi* and *D. v. virgifera* in cornfields and 2) measure the distribution and prevalence of rotation resistance in these two species. This research may increase the effectiveness of pest management by providing data on the landscape-level distribution of these species and the prevalence of rotation resistance.

Materials and Methods

Estimations of Economic Injury Level. We estimated economic injury level (EIL) using the basic formula of $EIL = C/ (V \times I \times D \times K)$ (Pedigo and Rice 2009), where C is the cost of management, V is the market value of the crop, I is the estimated injury per pest, D is the relationship between yield and root injury, and K is efficacy of the management tactic.

We set C = \$37.07/ ha, which has been used as an estimated cost of a rootworm active Bt toxin hybrid (Crowder et al. 2005) and as an estimated cost of soil insecticide (Mitchell et al. 2004). The value of corn (V) was averaged between the dollar value per metric ton from 2008 and 2009 (USDA, National Agriculture Statistics Service [USDA, NASS] 2011) as \$149.8/MT. Dun et al. (2010) estimated that each node destroyed corresponds to a 17.9% decrease in yield. Assuming an average yield of 9.41 MT/ha (Van Mellor et al. 2006), we set yield loss per node (D) to equal 1.68 MT/ha. K was estimated from Dillen et al. (2009), with the efficacy of rootworm active Bt toxin as 0.96 and soil applied insecticides as 0.93.

To estimate injury (I) in cornfields, we used a value of six *Diabrotica* spp. captured per sticky trap per day from Hein and Tollefson (1985) as the level of pest abundance capable of causing root-injury ratings the following year of 0.5 on the node-injury scale of Oleson et al. (2005). For rotation-resistant *D. v. virgifera* in soybean fields, we estimated I from O'Neal et al. (2001) where 4.7 *D. v. virgifera* captured per sticky trap per day could be capable of producing a 0.5 root-injury rating the following year. Fisher (1985) reported that capture between 20 and 24 *D. barberi* per emergence cage was capable of producing a root injury score of three on the Iowa 1–6 root-damage scale (Hills and Peters 1971), which we equate to 0.5 root-injury ratings on the node-injury scale of Oleson et al. (2005). The emergence cages used by Fisher (1985) covered three plants while cages used here covered one plant and ca. one quarter of each of its neighbors. Based on differences in sizes of emergence cage, we estimate that capturing an average of 11 *D. barberi* for each emergence cage used in this study would cause an average of 0.5 root-injury rating.

Sticky trap data provide an economic threshold (ET) because captures from sticky traps indicate larval injury the following year, and if expected injury is

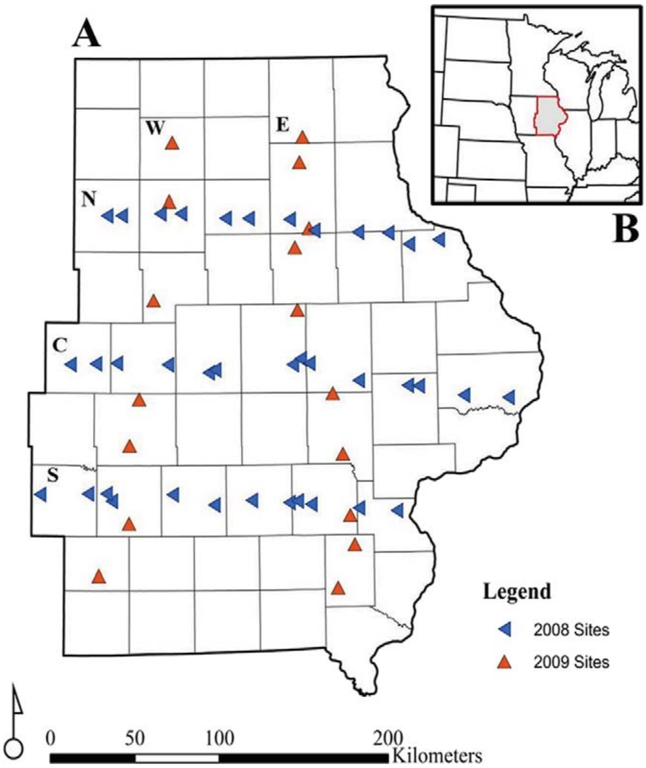

Fig. 1. Map of (A) transects and field sites in 2008 and 2009 and a map of (B) the region sampled within the Midwest. The three transects from 2008 run horizontally with field sites represented by blue triangles pointing west. The two transects from 2009 run vertically with field sites represented by red triangles pointing northward. Transects in 2008 were N (north), C (central), and S (south) and in 2009 were W (west) and E (east), corresponding to their position within the state. Data corresponding to specific transects is provided in Tables 1 and 2.

sufficiently great, may trigger management action. By contrast data on capture of *D. barberi* in emergence cages is a direct proxy for injury that has already occurred in the same season, and is best described as whether or not an EIL was exceeded.

Quantifying Rotation Resistance. *D. v. virgifera* that are susceptible to crop rotation are found almost exclusively in cornfields and oviposit their eggs in cornfields. Rotation-resistant *D. v. virgifera* leave cornfields and oviposit their eggs in noncorn crops including soybeans (Rondon and Gray 2003, 2004; Schroeder et al. 2005). The abundance of rotation-resistant *D. v. virgifera* can be quantified by establishing monitoring traps in soybean fields, as done in this study in 2008 and 2009, and previously by O'Neal et al. (2001).

When a field is rotated into corn production (i.e., a first-year cornfield) larvae of rotation-susceptible *D. barberi* and *D. v. virgifera* should be absent from the field (Chiang 1973). Collection of adult *D. barberi* and *D. v. virgifera* from first-year cornfields through the use of emergence cages provides evidence that those adults are resistant to crop rotation. Emergence cages in first-year corn were used in this study in 2009.

Data Collection in 2008. Three transects were established in eastern Iowa to measure the distribution and abundance of *D. barberi* and *D. v. virgifera* in cornfields and the distribution of rotation-resistant *D. v. virgifera.* Transects were established parallel to three east-west highways in eastern Iowa and were designated north, central, and south, respective of their position in the state (Fig. 1; Table 1). Field sites used to monitor *Diabrotica* spp. were identified by Iowa State University Regional Agronomists and local cooperators. Two field sites were established within each county intersected by transects. Each field site was composed of a first-year cornfield (i.e., the field had been planted to soybeans during the previous season) to measure total abundance of *D. barberi* and *D. v. virgifera* at the site, and an adjacent soybean field

Table 1. Transect length, no. of field sites, and avg distance between field sites sampled in 2008 and 2009

	North	Central	South
2008			
Transect length	204 km	264 km	217 km
No. field sites	12	14	12
Avg distance between field sites	18 km	19 km	19 km
2009		West	East
Ransect length		238 km	255 km
No. field sites		7	10
Avg distance between field sites		40 km	28 km

Table 2. Field type and sampling methods for transects in 2008 and 2009

	North	Central	South	Trap type	Traps/field	Weeks sampled
2008 transects						
No. first-year cornfields sampled	12	14	12	Sticky traps	12	3
No. soybean fields sampled	12	14	12	Sticky traps	12	5
2009 transects		West	East			
No. continuous cornfields sampled		7	16	Sticky traps	6	3
No. soybean fields sampled		7	10	Sticky traps	6	3
No. first-year cornfields sampled		7	10	Emergence cages	6	7

to measure the abundance of rotation-resistant *D. v. virgifera.* Data were collected from a total of 38 field sites containing 76 individually monitored fields. At each field site cooperators were asked if cornfields were planted to a hybrid expressing a rootworm active Bt toxin during that season.

Unbaited Pherocon AM yellow sticky traps (Trece Inc., Adair, OK) were placed in cornfields and soybean fields following Hein and Tollefson (1985) and O'Neal et al. (2001) (Table 2). Sticky traps were divided between two transects running throughout each field. Transects within a field were separated by at least 100 m and kept a minimum of 50 m from any field edge. Sticky traps within a given transects were separated by a minimum of 50 m. In soybean fields, traps were kept roughly 0.3 m above the canopy while in cornfields traps were attached directly over the corn ear. Traps were placed in cornfields and soybean fields from 28 July to 22 August and changed weekly throughout this period (Table 2).

Data Collection in 2009. Two transects, designated as east and west, were established in eastern Iowa to monitor *D. barberi* and *D. v. virgifera* in cornfields and to monitor for rotation-resistant *D. barberi* and *D. v. virgifera* (Fig. 1; Table 1). Field sites were again identified by Iowa State University Regional Agronomists and local cooperators. Each field site contained 1) a first-year cornfield, planted with corn that did not produce a rootworm active Bt toxin, in which we placed emergence cages to measure the abundance of rotation-resistant *D. barberi* and *D. v. virgifera,* 2) a soybean field, in which we placed unbaited Pherocon AM yellow sticky traps to measure the abundance of rotation-resistant *D. v. virgifera,* and 3) one or two continuous cornfields, in which we placed unbaited Pherocon AM yellow traps to measure the total abundance of *D. barberi* and *D. v. virgifera* (Table 2). Cooperators were asked whether continuous cornfields were planted to a hybrid expressing a rootworm active Bt toxin. The number of sticky traps per field was reduced in 2009 to enable the sampling of more fields per site and to enable the use of emergence cages (Table 2). Fewer traps in a field may increase the variance among samples periods and sites (Hein and Tollefson 1985), however, as few as four traps per field was shown to be as effective as 12 traps at predicting larval injury from *Diabrotica* spp. (O'Neal et al. 2001). Placement of sticky traps throughout soybean fields and continuous cornfields were the same as 2008. No first-year cornfields used in this study were reported to have problems with volunteer corn the previous year when planted to soybean. Continuous cornfields were identified as any field in which corn had been grown for two or more consecutive years. There were a total of 17 field sites containing a total of 57 individually monitored fields. Six of 17 field sites in 2009 contained two continuous cornfields, while the other 11 field sites contained one continuous cornfield. For those sites with two continuous cornfields, data were pooled between fields within each sampling period.

Illinois style emergence cages (38.1 × 76.2 cm) were placed along two transects (three cages per transect) within first-year cornfields. Emergence cages were modified from designs used in Fisher (1980), which cover the ground surrounding the base of a corn plant and captures insects that emerge while allowing the corn plant to survive and grow. Insect collection cups on emergence cages were changed weekly from 26 June through 21 August (Table 2). Soybean fields and continuous cornfields were monitored for 3 wk, 27 July through 21 August, with unbaited Pherocon AM sticky traps that were changed weekly.

Data Analysis. For sticky traps placed in cornfields and soybean fields in 2008 and 2009, the total number of *D. barberi* and *D. v. virgifera* captured by each sticky trap during each of the sampling periods was counted. The capture per trap per sampling period was then averaged among the traps placed within a particular field. This average capture per trap per sampling period was divided by the number of days the sticky traps were in the field to yield the average *D. barberi* and *D. v. virgifera* captured per sticky trap per day for each sampling period.

Data on capture of *D. barberi* and *D. v. virgifera* from sticky traps in cornfields and soybean fields were used to generate several maps in ArcGIS 9.3 (ESRI, Redlands, CA). These data were displayed on maps using graduated symbols.

The highest weekly capture from sticky traps in 2008 first-year cornfields and 2009 continuous cornfields were used to create maps of peak abundance of *D. barberi* and *D. v. virgifera* combined, and peak abundance of each species separately. The highest weekly capture of *D. v. virgifera* in soybean fields was used to map the peak abundance of rotation-resistant *D. v. virgifera.*

The total number of *D. barberi* and *D. v. virgifera* captured from sticky traps in first-year cornfields during 2008 and from sticky traps in continuous cornfields in 2009 was used to calculate the proportion of *D. barberi* versus *D. v. virgifera* at each field site. Field sites were labeled as dominated by *D. v. virgifera* if the proportion of *D. v. virgifera* was ≥ 0.7, and as dominated by *D. barberi* if the proportion of *D. barberi* was ≥ 0.7. Fields were labeled as neutral field if the proportion of *D. barberi* and *D. v. virgifera* was >0.3 and <0.7. These values were used to create a map illustrating the species composition within cornfields throughout eastern Iowa. A G-test of independence was used to test whether the frequency of neutral fields and fields dominated by one species differed from the frequencies expected by chance (Sokal and Rohlf 1981). Based on our definition of neutral fields and fields dominated by a single species, the null hypothesis was that 0.6 of the fields should be dominated by one species (0.3 of the fields dominated by *D. barberi* + 0.3 of the fields dominated by *D. v. virgifera*) and 0.4 of the fields should be classified as neutral. Additionally, the correlation between abundance of *D. barberi* and *D. v. virgifera* was calculated (PROC CORR) (SAS Institute Inc. 2008).

For first-year cornfields sampled in 2009, *D. barberi* and *D. v. virgifera* captured in each emergence cage were totaled over the 7 wk sampling period. Totals per cage were then averaged within field site to yield the average *D. barberi* and *D. v. virgifera* captured per emergence cage per field. A map was created with these data to show distribution of rotation-resistant *D. barberi* emerging from first-year cornfields.

Results

Calculations of *Diabrotica* spp. ET in cornfields using the efficacies of Bt and soil insecticides (K) yielded 1.85 and 1.91 *Diabrotica* spp. per sticky trap per day, respectively. For interpretation of our survey data, we chose to round this ET to two *Diabrotica* spp. per sticky trap per day to make our maps more conservative and to simplify the interpretation of the maps. Economic threshold estimations for *D. v. virgifera* in soybean fields were 1.44 and 1.49 *D. v. virgifera* per sticky trap per day using efficacies (K) of Bt and soil insecticides, respectively, which we rounded to 1.5 *D. v. virgifera* per sticky trap per day. We calculated an EIL of 3.38 *D. barberi* per emergence cage during a single summer and rounded this estimate to 3.5 *D. barberi* adults per cage.

Peak abundance of *Diabrotica* spp. (both *D. v. virgifera* and *D. barberi*) in 2008 cornfields occurred along the north and central transects (Table 3; Fig. 2). In 2008 there were eight cornfields with peak populations above our calculated ET, seven of which were found on the northern and central transects. The southern transect generally had peak populations of <1 *Diabrotica* spp. per sticky trap per day, although one field site did exceed the ET. Peak abundances of *D. v. virgifera* in 2008 cornfields were higher in the eastern portion of the sampling area (Table 3; Fig. 3). Two field sites had peak abundances of *D. v. virgifera* above the ET, while most field sites recorded peak abundances below 0.5 captured per sticky trap per day. Peak abundances of *D. barberi* in 2008 cornfields were greater in the northern and central transects than the southern transect (Table 3; Fig. 4). Five field sites recorded peak *D. barberi* abundance above the calculated ET, the northern and central transect each having two field sites exceeding this value and the southern only one. Of the 38 rotated cornfields monitored 2008 only 16 were planted to a hybrid expressing rootworm active Bt (Table 3).

Table 3. Peak abundance of *D. v. virgifera* and *D. barberi* captured from sticky traps (*Diabrotica* spp./sticky trap/d) in first-year cornfields and soybean fields in 2008

Field site[a]	Bt cornfield	Cornfield peak abundance		Soybean field peak abundance
		D. v. v.	*D. b.*	*D. v. v.*
N1	No	1.95	0.31	0.05
N2	No	0.06	1.71	0.05
N3	Yes	0.01	2.33	0.00
N4	Yes	0.06	1.64	0.03
N5	Yes	0.03	0.08	0.01
N6	Yes	0.16	0.99	0.11
N7	No	0.08	0.13	0.11
N8	No	0.14	0.08	0.05
N9	No	0.08	0.01	0.13
N10	Yes	16.32	3.68	1.04
N11	No	0.92	0.07	0.44
N12	No	1.15	0.04	0.13
C1	Yes	0.00	0.01	0.00
C2	No	0.27	0.12	0.02
C3	No	0.07	2.40	0.01
C4	No	1.62	1.83	0.01
C5	No	0.01	0.30	0.02
C6	No	0.00	0.48	0.00
C7	No	0.08	1.09	0.00
C8	Yes	0.01	2.83	0.00
C9	Yes	0.02	1.88	0.02
C10	No	0.01	0.14	0.00
C11	No	0.65	0.17	0.10
C12	Yes	3.89	1.24	0.24
C13	No	0.71	0.07	0.15
C14	No	1.12	0.15	0.30
S1	Yes	0.01	0.11	0.01
S2	Yes	0.01	0.02	0.02
S3	Yes	0.01	0.35	0.06
S4	Yes	0.03	0.04	0.02
S5	No	0.18	2.87	0.01
S6	No	0.01	0.56	0.01
S7	Yes	0.00	0.05	0.00
S8	No	0.01	0.14	0.03
S9	Yes	0.03	0.36	0.00
S10	Yes	0.04	0.90	0.01
S11	No	0.17	0.73	0.02
S12	No	0.06	0.18	0.02

[a] Field sites are listed from west to east along the north (N), central (C), and southern (S) transects.

In 2009, peak abundance of *Diabrotica* spp. in continuous cornfields was generally very low (Table 4; Fig. 2) and only two field sites out 17 exceeded the ET. Peak abundance of *D. v. virgifera* was lower in 2009 than 2008 (Table 4; Fig. 3), one field site out of 17 was found above the ET and only three had >0.5 *D. v. virgifera* per sticky trap per day. *D. barberi* were more commonly found on the eastern transect then the western (Table 4; Fig. 4), though there was only one field site with peak abundance of *D. barberi* above the ET.

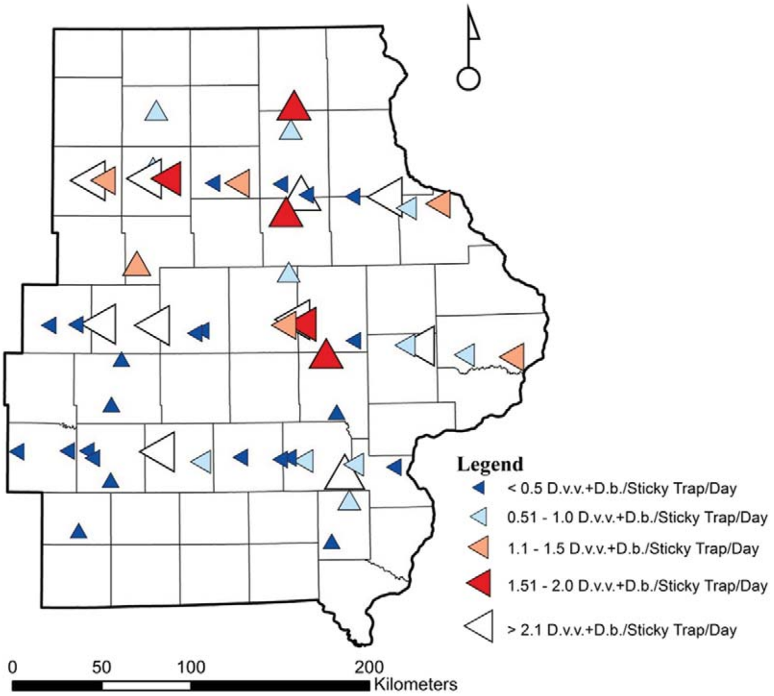

Fig. 2. Map of combined peak abundance of both *D. v. virgifera* and *D. barberi* in cornfields. 2008 field sites are represented by triangles pointing west, and 2009 field sites are represented by triangles pointing north. White triangles indicate populations above economic threshold.

Of the 23 continuous cornfields sampled in 2009, 21 were planted to a hybrid expressing rootworm active Bt. The two continuous cornfields with peak abundances above the ET were both planted to a hybrid expressing rootworm active Bt. One had peak abundance of *D. v. virgifera* above the ET (2.05 *D. v. virgifera* captured per trap per day, and 2.48 *Diabrotica* spp. per trap per day) while the other contained *D. barberi* that were above economic threshold (2.67 *D. barberi* captured per trap per day, and 2.81 *Diabrotica* spp. per trap per day) (Table 4). In 2009 we only selected first-year cornfields for monitoring that were planted to a hybrid that did not produce rootworm active Bt toxin.

The majority of cornfields sampled in 2008 and 2009 were dominated by a single *Diabrotica* spp. The map of species composition within cornfields showed large areas dominated by either *D. barberi* or *D. v. virgifera* (Fig. 5). Cornfields dominated by *D. v. virgifera* were more commonly found in the east while *D. barberi* dominated fields occurred throughout the south and northwest of the sampling area. If the occurrence of dominated fields and neutral fields was determined by chance alone, the null hypothesis would be that 22 of the 55 fields would be neutral (40%) and 33 of the fields would be dominated by one species or another (60%). However, only seven cornfields were classified as neutral with the remaining 48 dominated by either *D. barberi* or *D. v. virgifera.* This null hypothesis was rejected based on a G-test of independence ($G = 10.94$; df = 1; $P < 0.0001$). Results from correlation analysis revealed a positive correlation between the abundance of *D. barberi* and *D. v. virgifera* ($r = 0.55$; df = 53; $P < 0.0001$). Thus, even though fields were often dominated by one species or the other, the total population size of both species tended to display a positive association across fields, with some fields supporting large populations of both species while others contained smaller populations.

The map *D. v. virgifera* abundance in soybean fields from both 2008 and 2009 showed that the majority of field sites monitored in eastern Iowa had very low abundance of rotation-resistant *D. v. virgifera* (Tables 3 and 4; Fig. 6). Over much of the map, the abundance of rotation-resistant *D. v. virgifera* was <0.1 adults per sticky trap per day. The highest peak abundances occurred in 2008 along Iowa's eastern border, however, the majority of these higher abundance field sites still recorded <1 *D. v. virgifera* per sticky trap per day. No soybean field in 2008 or 2009 exceeded the estimated ET of 1.5 *D. v. virgifera* per sticky trap day.

Emergence of rotation-resistant *D. barberi* from first-year cornfields occurred at 16 of the 17 field sites monitored in 2009 (Table 5). The map of average total capture per emergence cage illustrated higher abundances of rotation-resistant *D. barberi* along the western transect (Fig. 7). Three field sites recorded *D. barberi* emerging from first-year cornfields above our calculated EIL of 3.5 *D. barberi* per cage, and those were found along the western transect. Nine of 17 field sites recorded fewer than one *D. barberi* emerging per cage. Assuming corn population per hectare is

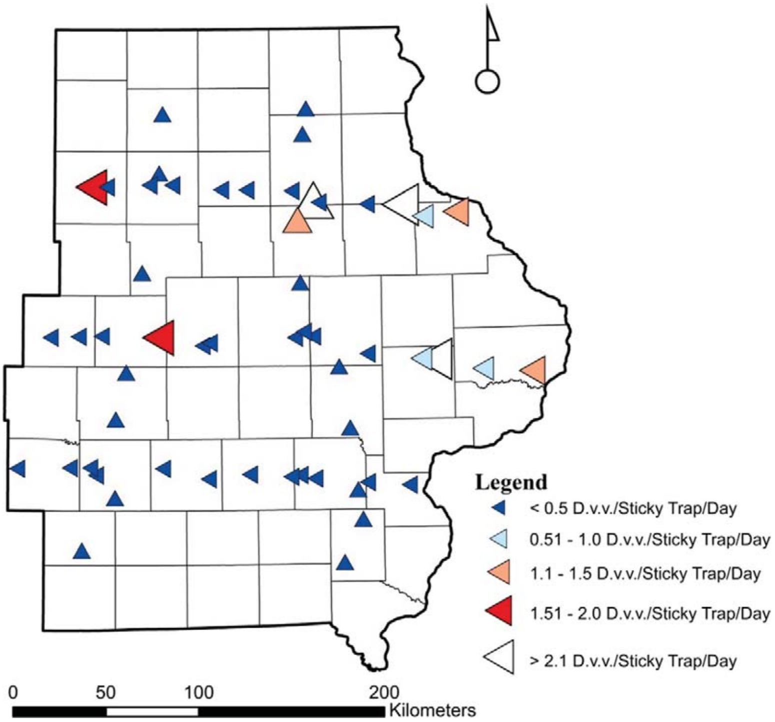

Fig. 3. Map of peak abundance of *D. v. virgifera* in cornfields. 2008 field sites are represented by triangles pointing west, and 2009 field sites are represented by triangles pointing north. White triangles indicate populations above economic threshold.

generally between 69,00 and 79,000 plants (Farnham 2001) and each emergence cage covers roughly 1.5 plants, then *D. barberi* adults emerging per hectare would range between 52,000 and 59,000. Emergence from first-year corn by *D. v. virgifera* in 2009 was rare, *D. v. virgifera* emerged from only three field sites and were extremely low in abundance (>1 adult per cage per site) (Table 5), and were therefore not mapped.

Discussion

Crop rotation is an important component of integrated pest management (IPM) for *Diabrotica* spp. The benefits of crop rotation extend beyond pest management and include increased yields (Bullock 1992). Both *D. barberi* and *D. v. virgifera* have evolved resistance to this management practice (Krysan et al. 1984, Levine et al. 1992), reducing the benefits of crop rotation in some areas. In addition to crop rotation, farmers can scout cornfields for adults to determine whether management of larval *D. barberi* and *D. v. virgifera* will be necessary the following season (Godfrey and Turpin 1983, Hein and Tollefson 1985). In this 2-yr study we measured the abundance of *D. barberi* and *D. v. virgifera,* the prevalence of rotation resistance in these species, and then mapped these measurements using ArcGIS. These data illustrate that the abundance of *D. barberi* and *D. v. virgifera* was often below EIL for cornfields throughout eastern Iowa (Figs. 2–4). Thus, scouting during the previous season may enable farmers to forego the input costs associated with management of larval *D. barberi* and *D. v. virgifera.* These maps also suggest that crop rotation remains a viable option for managing *D. barberi* and *D. v. virgifera* in eastern Iowa, because the presence of rotation resistance in both of these species was rarely above the calculated ET or EIL (Figs. 6 and 7).

Diabrotica spp. abundance can be affected by many abiotic and landscape level factors. For example, *D. barberi* and *D. v. virgifera* were both found in greater abundance on loam and silty clay loam soil textures (Beckler et al. 2004, French et al. 2004) and at elevations that are between the highest and lowest points within the landscape (Beckler et al. 2005). Populations of *Diabrotica* spp. can be negatively affected by abiotic factors too, in particular wet soil conditions when larvae hatch (Hoback et al. 2002). In general we found that populations were larger in 2008 than 2009 (Figs. 2–4) even though spring soils were cool and wet in both years (USDA, NASS 2008, 2009), suggesting that in neither spring was soil moisture great enough to substantially diminish larval establishment.

Another factor affecting *Diabrotica* spp. populations is the wide spread adoption of Bt corn, with 69 and 71% of Iowa corn growers planting a hybrid with a Bt trait in 2008 and 2009, respectively (USDA, NASS 2009). All fields monitored in 2008 were first-year

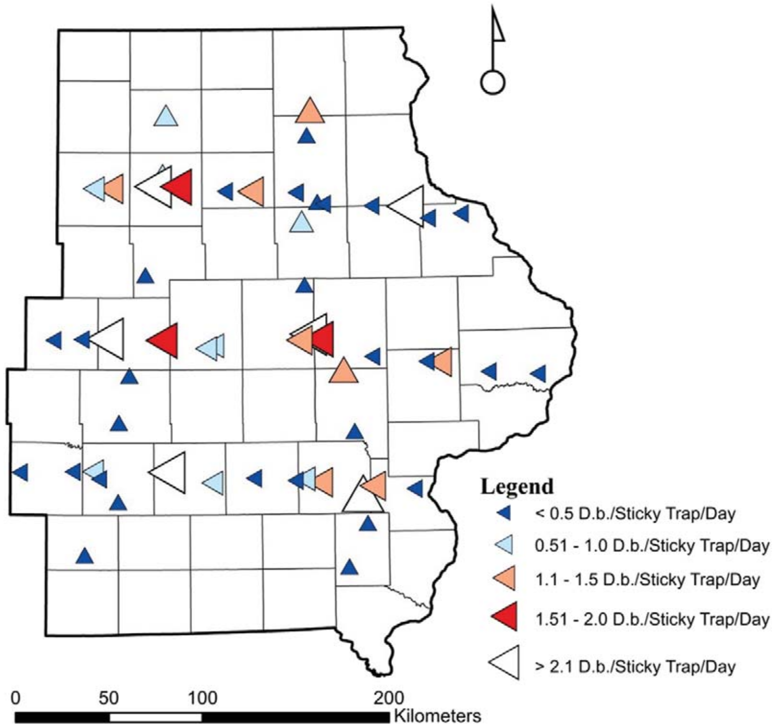

Fig. 4. Map of peak abundance of *D. barberi* in cornfields. 2008 field sites are represented by triangles pointing west, and 2009 field sites are represented by triangles pointing north. White triangles indicate populations above economic threshold.

cornfields, and thus were at a lower risk for injury from larval *Diabrotica* spp., yet 16 of 38 fields contained a rootworm active Bt trait (Table 3). For continuous cornfields monitored in 2009, 21 of 23 were planted with a rootworm active Bt train (Table 4). Among all Bt fields in both years, six had peak abundances of *Diabrotica* spp. above the calculated ET, however, four were first-year cornfields and these populations

Table 4. Peak abundance of *D. v. virgifera* and *D. barberi* captured from sticky traps (*Diabrotica* spp./sticky trap/d) in continuous cornfields and soybean fields in 2009

Field site[a]	Bt cornfield	Cornfield peak abundance		Soybean field peak abundance
		D. v. v.	*D. b.*	*D. v. v.*
W1	Yes	0.24	0.55	0.00
W2	Yes	0.05	0.62	0.03
W3	Yes	1.00	0.21	0.00
W4	Yes	0.12	0.31	0.00
W5	Yes	0.12	0.17	0.02
W6	Yes	0.02	0.24	0.00
W7	Yes	0.02	0.05	0.00
E1	No	0.36	1.50	0.02
E2[b]	Yes/yes	0.50	0.29	0.00
E3	Yes	2.05	0.43	0.02
E4	Yes	1.31	0.60	0.10
E5	Yes	0.31	0.24	0.00
E6[b]	Yes/yes	0.43	1.31	0.00
E7[b]	Yes/no	0.24	0.26	0.00
E8[b]	Yes/yes	0.14	2.67	0.00
E9[b]	Yes/yes	0.14	0.40	0.02
E10[b]	Yes/yes	0.14	0.05	0.00

[a] Field sites are listed from north to south along the west (W) and east (E) transect.

[b] Field site contained more than one continuous cornfield. Peak abundance values for these field sites were an avg from the two continuous cornfields sampled.

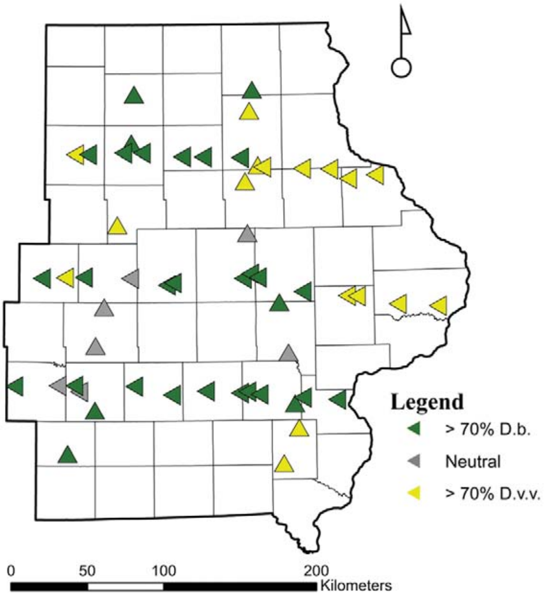

Fig. 5. Map of *D. v. virgifera* and *D. barberi* species composition within cornfields. 2008 field sites are represented by triangles pointing west, and 2009 field sites are represented by triangles pointing north.

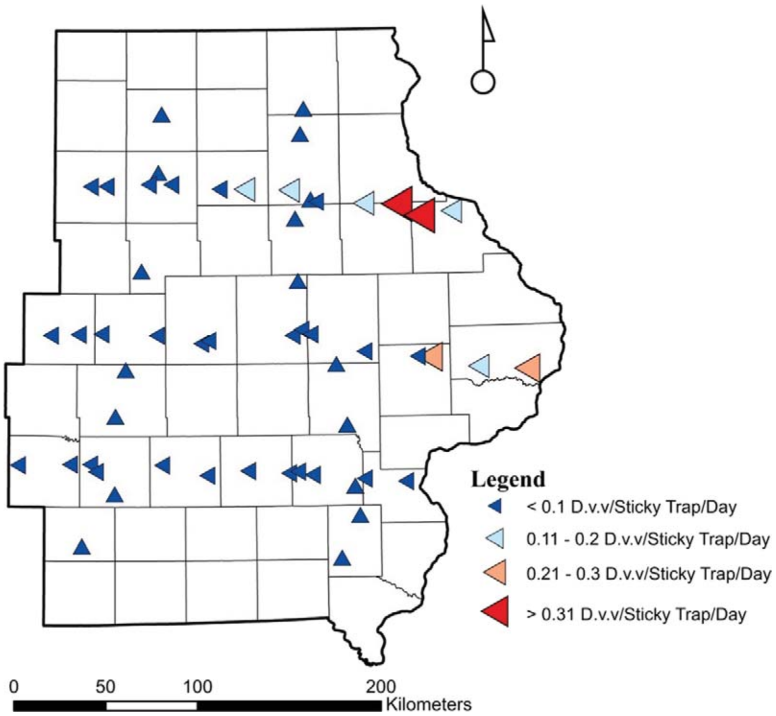

Fig. 6. Map of peak abundance of *D. v. virgifera* in soybean fields. 2008 field sites are represented by triangles pointing west, and 2009 field sites are represented by triangles pointing north.

most likely emigrated from surrounding fields. There were two continuous cornfields in 2009 above the ET planted to rootworm active Bt corn. Often, peak abundance of *Diabrotica* spp. was <1 adult captured per trap per day in cornfields, and only 10 of 55 field sites (including both Bt and non-Bt cornfields) exceeded our calculations of an ET. These data indicate that scouting could be used as part of an IPM program, and in many instances, a grower's most profitable option would be to leave the field untreated for corn rootworm.

Table 5. Average total emergence of *D. v. virgifera* and *D. barberi* from first-year cornfields (*Diabrotica* spp./emergence cage) in 2009

Field site[a]	Bt cornfield	First-year cornfield average total emergence	
		D. v. v.	*D. b.*
W1	No	0.00	5.50
W2	No	0.00	3.83
W3	No	0.00	1.50
W4	No	0.00	0.50
W5	No	0.00	0.33
W6	No	0.00	1.00
W7	No	0.00	4.00
E1	No	0.17	1.67
E2	No	0.17	0.17
E3	No	0.00	0.00
E4	No	0.17	1.83
E5	No	0.00	0.17
E6	No	0.00	2.00
E7	No	0.00	0.50
E8	No	0.00	0.67
E9	No	0.00	1.17
E10	No	0.00	0.17

[a] Field sites are listed from north to south along the west (W) and east (E) transects.

Computer models used to estimate the spread of rotation-resistant *D. v. virgifera* predicted that the rotation-resistant variant would enter eastern Iowa in ≈2010 (Onstad et al. 1999, Levine et al. 2002). Our data indicate that rotation resistance is not present in eastern Iowa or is present at only a very low frequency (Tables 3 and 4; Fig. 6). Before rotation resistance was present in Illinois the maximum capture of *D. v. virgifera* from 100 sweeps using a sweep net in soybean fields was between 10 and 16 adults (Levine 1995). The value of 10 *D. v. virgifera* captured in soybean fields per 100 sweeps was used as the minimum number needed to indicate the presence of rotation resistance (Onstad et al. 1999) and later this value was converted in to an average capture per sticky trap per day of 1.34 adults (Onstad et al. 2003). Only one field site had greater than one *D. v. virgifera* captured per sticky trap per day in soybean fields, but it did not exceed the value of 1.34 adults and suggests that we were unable to detect the presence of rotation resistance in eastern Iowa.

Abundance of *D. v. virgifera* in soybean fields was very low throughout eastern Iowa, with the exception of northeastern Iowa where abundance was higher relative to the rest of the area sampled. The map of *D. v. virgifera* in cornfields also shows a high abundance

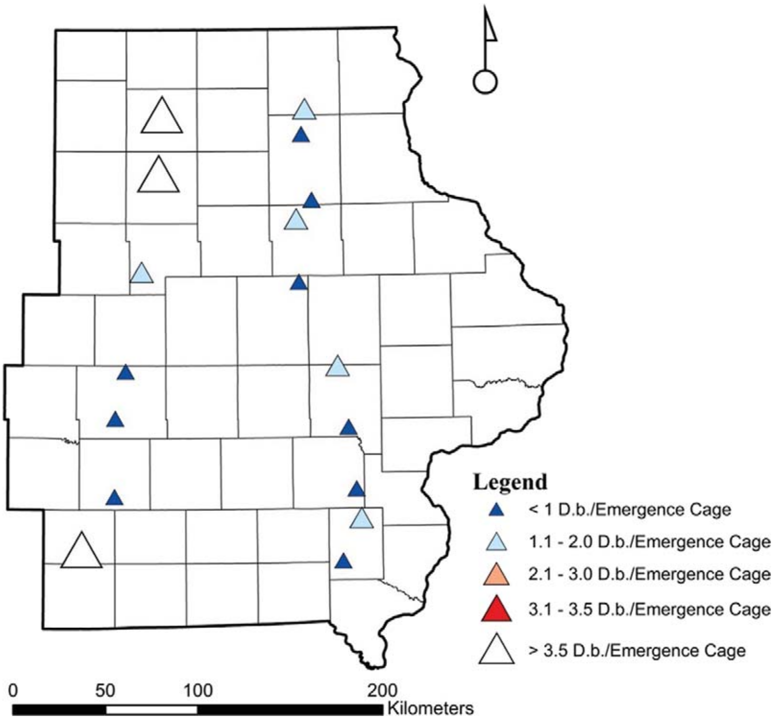

Fig. 7. Map of the average total capture of *D. barberi* from first-year cornfields in 2009. White triangles indicate populations above the EIL.

in cornfields in northeastern Iowa (Fig. 3). By contrast, a high abundance of *D. v. virgifera* in cornfields also was recorded in central Iowa on the northern and central transect (Fig. 3), however, the map of *D. v. virgifera* in soybean fields in that same area showed very low abundance of adults (Fig. 6). These contrasting results between the abundance of *D. v. virgifera* in cornfields and soybean fields suggests that our observation of *D. v. virgifera* in soybean fields was not entirely caused by high abundance in cornfields, and may have been because of a low frequency of rotation-resistant genotypes in northeastern Iowa. Previous research, conducted in 2005, also reported *D. v. virgifera* in soybean fields in eastern Iowa (Prasifka et al. 2006), which suggests little if any expansion of this trait over the last 5 yr.

Rotation-resistant *D. barberi* have been reported over much of the Midwest (Landis et al. 1992, Levine et al. 1992, Krysan 1993), although the frequency and duration of extended diapause varies (Steffey et al. 1992). Historically, injury to first-year corn by rotation-resistant *D. barberi* in Iowa occurred primarily in the northwestern portion of the state, and injured first-year corn occurred in a minority of rotated cornfields (Foster 1987). Our data indicate the presence of pockets of rotation resistance in north–central and south–central Iowa (Fig. 7), which is similar to the injury to first-year corn reported by Foster (1987). Foster (1987) did not report any injury to first-year corn in eastern Iowa but this could be because frequency of extended diapause in eastern Iowa was relatively low and produced little if any noticeable injury, which is congruent to the map of emergence of *D. barberi* from first-year corn (Fig. 7). We estimated an EIL of 3.5 adult *D. barberi* per emergence cage. Average total capture of *D. barberi* emerging from first-year cornfields in 2009 exceeded this estimate in only three of 17 field sites, two of which were within the range for rotation resistance proposed by Foster (1987). Taken together these data suggest that there has been very little change in the distribution and abundance of rotation-resistant *D. barberi* in eastern Iowa over the last 20 yr and that crop rotation is still an effective tool for managing *D. barberi* in most eastern Iowa fields.

Displacement in insect communities may be caused by many factors including competition, and may occur between closely related species if they occupy the same ecological niche (Reitz and Trumble 2002). The competitive exclusion principle states that species that occupy the same niche cannot do so indefinitely (Hardin 1960), although competing species can coexist in the presence of continual disturbance, with extinction and colonization leading to periods of species overlap. The map of *D. barberi* and *D. v. virgifera* composition in cornfields shows large areas dominated by one species (Fig. 5). Furthermore, a test of independence showed that there were significantly more fields dominated by either species than if relative frequencies were independent (see Results). These data are consistent with other studies that have found areas dominated by one species or the other. Hill and Mayo

(1980) observed *D. v. virgifera* displacing *D. barberi* in areas of Nebraska where continuous planting of corn was more commonly practiced, while in areas where crop rotation was more prevalent *D. barberi* were found more frequently. This pattern also was observed in South Dakota, where abundance of a *D. v. virgifera* but not *D. barberi* was positively correlated with proximity of continuous cornfields (Beckler et al. 2004, French et al. 2004).

Crop rotation is valuable to corn producers because it increases corn yields and helps manage injury from *D. barberi* and *D. v. virgifera.* Our data suggest that *D. barberi* and *D. v. virgifera* can be effectively controlled by crop rotation in much of eastern Iowa. Furthermore, for many cornfields in eastern Iowa, populations of *D. barberi* and *D. v. virgifera* were below economic thresholds suggesting that growers cultivating corn need not treat for corn rootworm larvae in all cases, provided scouting is conducted during the previous season.

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