Within-Field Distribution of the Sunflower Midge (Diptera: Cecidomyiidae)

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ABSTRACT The sunflower midge, *Contarinia schulzi* Gagné (Diptera: Cecidomyiidae), is a pest of cultivated sunflower (*Helianthus annuus* L.). Larval feeding can cause damage and yield loss to the sunflower head. Adult emergence is extended and larvae are well protected in the sunflower receptacle, making chemical control methods difficult and expensive. Sunflower midge enter sunflower fields at the edges but fieldwide distributions occur, although the dynamics are not fully understood. Two commercial fields in 1999 and one field in 2000 were systematically sampled by dividing each field into fixed sample points. Mean egg and larval densities from each sample point were used to describe sunflower midge populations. The sunflower heads at each sample point were also assessed for damage. Maps of sunflower midge population density, cumulative density, and sunflower head damage ratings were estimated with kriging interpolation. Maps were estimated several times during first generation sunflower midge infestation. Field edges that were initially populated continued to be areas of infestation throughout the sampling period. Damage ratings were related to population densities when infestations were high. In 2000, we tested the larval hatching rate from different-sized egg masses with regression to determine an estimation technique for combining numbers of eggs and larvae.

KEY WORDS sunflower midge, spatial distribution, site-specific pest management

THE SUNFLOWER MIDGE, *Contarinia schulzi* Gagné (Diptera: Cecidomyiidae), is a serious threat to the growth and production of cultivated sunflower (*Helianthus annuus* L.) in the Red River Valley of North Dakota, Minnesota, and Manitoba (Charlet 2000). Larval infestations are difficult to predict because sunflower midge adults emerge in erratic cycles, and conditions favorable for heavy infestations are unclear. Although their economic importance has been restricted to the northern Great Plains, sunflower midge can occur from Texas to Manitoba (Rogers et al. 1979). Sunflowers are an important crop in North Dakota, comprising 43% (665,695 ha) of sunflowers harvested annually in the United States (United States Department of Agriculture 1999). In 2000, 72.5% of fields sampled in North Dakota had detectable sunflower midge populations (Lamey et al. 2001).

The sunflower midge life cycle requires 31–35 d (Samuelson 1976). Overwintering larvae pupate in early spring, and adult emergence in late June and July is dependent on temperature and soil moisture (Samuelson 1976). Females have long ovipositors and insert individual eggs between sunflower bracts (Schulz 1973) usually in the R2-R4 stages (mid to late bud stages) (Schneiter and Miller 1981), but may deposit eggs on other tissues and during other plant stages (Hodgson 2001). Eggs hatch in 2–5 d, and larvae move to the bases of the bracts or between the floral tissues of the receptacle to begin feeding. Larvae develop through three instars, drop to the ground, and enter the soil in early to mid-August (Glogoza et al. 1997). A second generation is possible, but in general, only the first generation causes economic damage (Bracken 1990, Glogoza et al. 1997).

Plant damage is variable depending on the density of larvae within the sunflower head and time of year (Bracken 1990). Estimating larval populations and sunflower head damage is difficult because eggs and larvae can both be present over a 2- to 3-wk period (Hodgson et al. 2000, 2001). Initial damage symptoms to reproductive tissue include necrotic spots on sunflower bracts, distorted or absent ray petals, and receptacle thickening (Schulz 1973). Light infestations can result in cosmetic damage with slightly decreased seed production, loss of ray petals, and bract discoloration. Moderate infestations cause considerable seed loss, abnormal head cupping, or a seedless area in the center of the head. Heavy sunflower midge populations can produce complete seed loss and severe deformities. A damage rating scale (Bracken 1990) is currently used to rate sunflower heads for seed loss and head abnormalities.

Damage caused by small populations of sunflower midge is usually restricted to field margins (McBride

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et al. 1994, Charlet and Brewer 1997), but fieldwide damage occurs when populations are high (Glogoza et al. 1997). A field-edge effect is usually more apparent when larval populations are low (McBride et al. 1994). Despite being susceptible to insecticides (Charlet and Brewer 1998), control of sunflower midge populations has been ineffective because of poor application timing. A long oviposition period, movement of larvae between tissues of the receptacle and away from insecticide-treated tissues, growth of new untreated tissues, and rapid insecticide breakdown all contribute to poor insecticide efficacy (Brewer 2002). Consequently, many sunflower producers do not use insecticide treatments to manage sunflower midge populations, and applications are not recommended (Glogoza et al. 1997).

Spatial maps of insect pests can be useful strategic and tactical tools. Interpolation methods, such as kriging, provide linear model estimates of values at unsampled locations based on the values of surrounding sampled locations (Myers 1991, Liebhold et al. 1993). Predictable distributions of pests can facilitate targeted applications of insecticide, referred to as site-specific pest management (Weisz et al. 1995, Midgarden et al. 1997). Site-specific pest management offers the advantage of directing controls to areas of need, providing higher yields and improving cropping economics, while reducing chemical exposure to producer and consumer (Weisz et al. 1995, Lefko et al. 1998). In addition, site-specific pest management preserves refuges for natural enemies and parasitoids in the untreated field areas (Weisz et al. 1996).

We sampled commercial sunflower fields over 2 yr and used Global Positioning Systems (GPS) and Geographic Information Systems (GIS) to define the within-field spatial and temporal distribution of sunflower midge in an effort to develop a site-specific pest management program for this pest. Accurate predictions of adult sunflower midge infestation may aid in prescribing the proper insecticidal treatments along crop borders. One well-timed application may reduce the spring colonizing adults on vegetative sunflower. In addition, population estimates of sunflower midge were related to sunflower midge damage ratings. We also assessed the larval hatch rate in the laboratory to refine population estimates from the field.

Methods and Materials

Sunflower midge eggs and larvae were sampled from three commercial sunflower fields in North Dakota and Minnesota, two in 1999 and one in 2000. The within-field larval densities and spatial distributions were digitally mapped for each sample to evaluate initial colonization and patterns of infestation spread. Plant damage was also mapped and related to larval density and cumulative density.

Field Design 1999. Two sunflower fields were sampled using a systematic, uniform design (Figs. 1 and 2). In both fields, an equally spaced grid pattern of 60 cells, with samples taken at the center of each cell, was used to determine sample points. The most exterior samples were 18.3–22.9 m from the field edge and, consequently, field margins were not directly sampled. Commercial fields in 1999 were labeled field 1 and field 2.

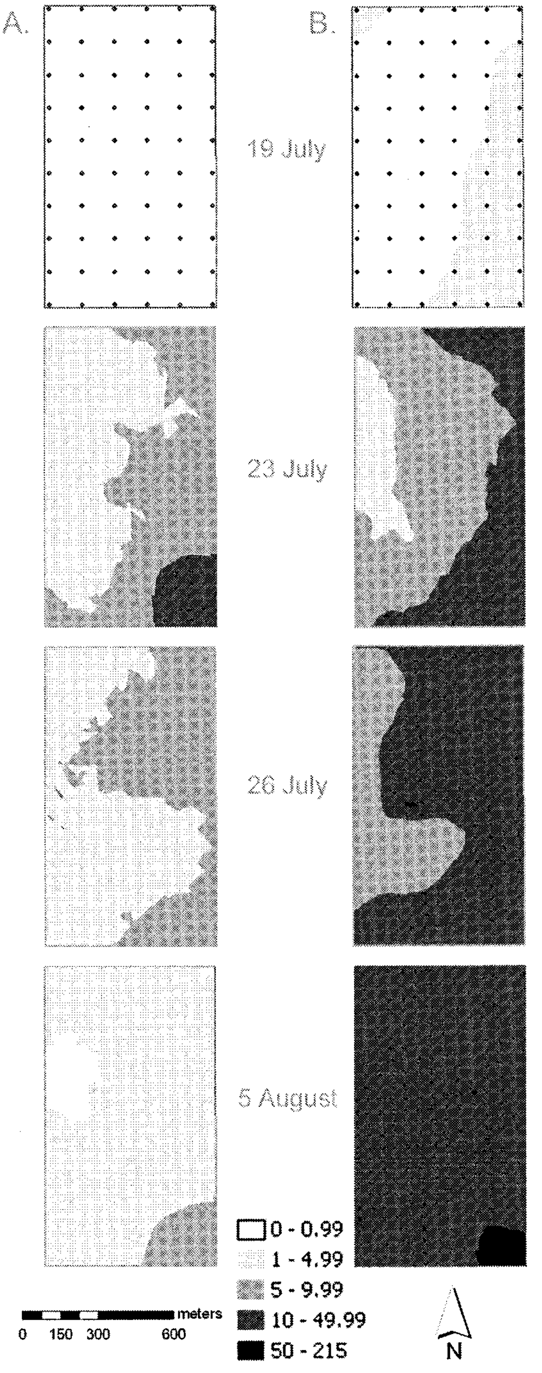

Fig. 1. Interpolated surfaces estimating the density and distribution of larval sunflower midge within field 1, sampled in 1999. The density scale applies to all maps, and 19 July is shown with overlaid sample design. Selected sample dates shown. (A) Estimated larval density for indicated sample period (B) Cumulative midge days up to that date.

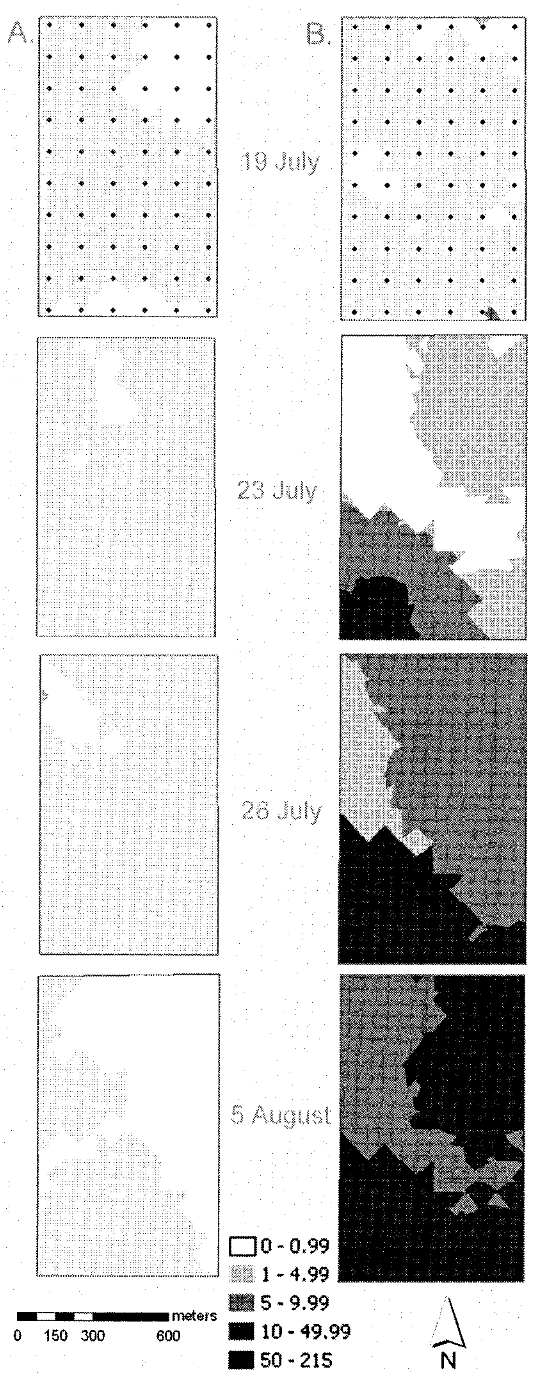

Fig. 2. Interpolated surfaces estimating the density and distribution of larval sunflower midge within field 2, sampled in 1999. The density scale applies to all maps, and 19 July is shown with overlaid sample design. Selected sample dates shown. (A) Estimated larval density for indicated sample period (B) Cumulative midge days up to that date.

Field 1 was 3 km south of Pillsbury in Barnes County, North Dakota, was 32.4 ha in size (≈777.2 × 640.0 m), and was seeded on 11 June. Field 2 was located 16 km east of Shelly in Norman County, Minnesota, was 32.0 ha in size (≈762.0 × 661.4 m), and was seeded on 13 June. The contiguous fields to the south of both fields 1 and 2 were planted with sunflower in 1998 and were the nearest site of overwintering sunflower midge.

Field Design 2000. Although two commercial sunflower fields were initially selected for sampling, one field was lost because of flooding. The remaining field (field 3) was 3 km north of Starkweather in Ramsey County, North Dakota; it had 64 sample points, was 89.03 ha in size (≈914.4 × 713.2 m), and was seeded on 20 May. A shelterbelt bordered the western field edge, and sunflower was last planted in the field in 1996. The field directly to the west of field 3 had been planted with sunflower in 1999 and was heavily damaged by sunflower midge. Field 3 was systematically sampled using a nested stratified-regular pattern (Fig. 3). In contrast to 1999, sample points were stratified near the exterior of the field, in addition to the regular grid of sample points in the field interior. The exterior sampling points added in 2000 were designed to improve sample resolution along the field margin. Around the exterior of the field, samples were taken 1, 3, and 10 m from the edge, with the remaining samples taken at regular 183-m intervals through the interior of the field.

Sampling. The 1999 design had sample points in an evenly spaced grid with a constant distance between sample points. Fixed sample points were located at the center of each cell and were evenly spaced throughout the field. This allowed the assignment of X, Y coordinates to sample points rather than real earth coordinates (i.e., latitude and longitude). The X, Y grid was then used as the reference for subsequent map construction. In 2000, an Ashtech BR2G, a differentially corrected GPS accurate to 1 m, was used to construct the point maps.

Four randomly selected sunflower heads were removed near each designated sample point: twice per week from 15 July to 5 August in 1999 (seven sample dates) and three times per week from 17 July to 14 August in 2000 (13 sample dates). Collection started at the R2 stage (early budding) and ended at the R7 stage (flowering complete) (Schneiter and Miller 1981). Each head was separately bagged, labeled, and later dissected in the laboratory. Individual bracts were removed, and the number of eggs and larvae was recorded. In 1999, egg masses were recorded as either small (≤10 eggs) or large (>10 eggs); in 2000, actual numbers of eggs per egg mass were recorded. Actual larval numbers were recorded for each field in 1999 and 2000.

Cumulative "midge days" (the cumulative number of sunflower midge larvae on a plant over time) were calculated for sunflower midge larval populations at each fixed sample point for every sample date at all three fields using the equation:

$$y = \sum_{i=1}^{n} [((P_t + P_{t+1})/2)/D],$$

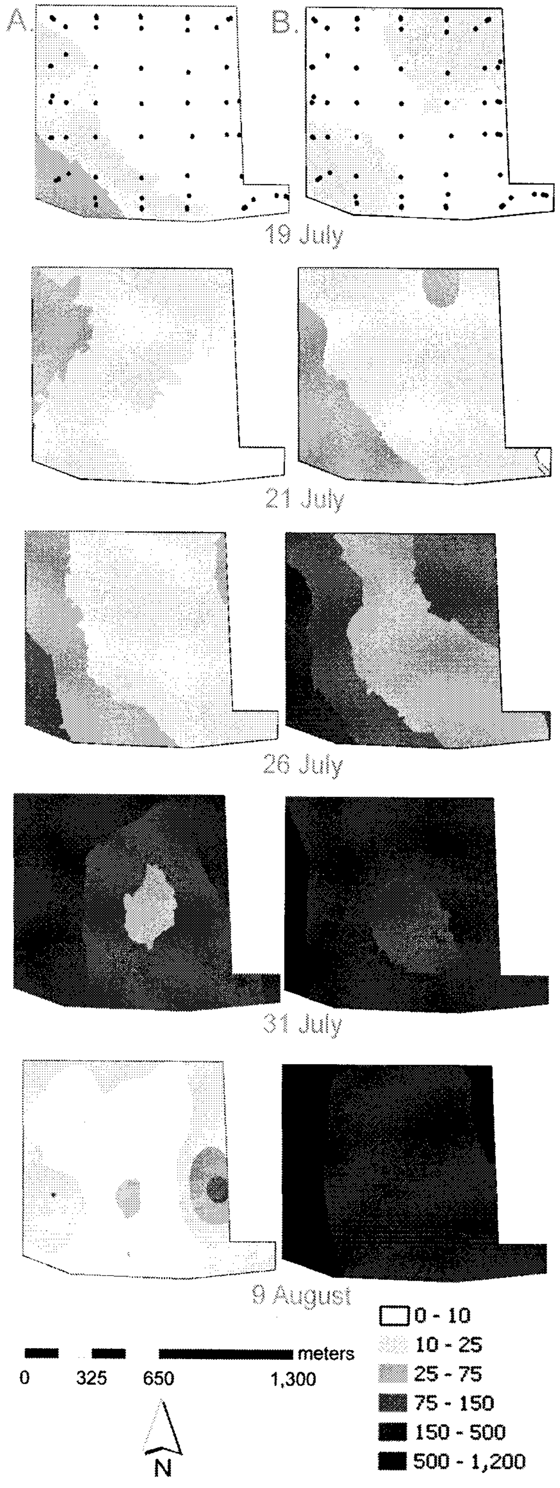

Fig. 3. Interpolated surfaces estimating the density and distribution of larval sunflower midge within field 3, sampled in 2000. The density scale applies to all maps, and 19 July is shown with overlaid sample design. Selected sample dates shown. (A) Estimated larval density for indicated sample period (B) Cumulative midge days up to that date.

where y = the cumulative number of sunflower midge for each sample date, P_t = the larval density at each fixed point for a sample date, P_{t+1} = the larval density at each fixed point on the next sample date, and D = the time in days between samples.

Larval Hatch Study. Eggs and larvae were concurrently present in some samples from all three fields. Because larvae are the damaging stage, we converted egg numbers to predicted number of larvae. Predicted numbers of larvae and actual numbers of larvae present were combined to estimate the population in each field.

In 2000, 1,000 egg masses, oviposited on bracts, were collected from field 3. The numbers of eggs per mass were counted, and the initial egg color was noted (clear, yellow, light orange, orange, and dark orange) using a dissecting microscope. The undisturbed egg masses were left on the sunflower bracts, placed on number 3 filter paper, and stored in 9-cm petri dishes sealed with parafilm. The filter paper was moistened daily, as needed. All petri dishes were stored in a rearing room at 29°C in constant light. Eggs were examined daily for 4 d for color changes and larval hatch. By day 4, all eggs had hatched or were dead. Hatching rate per egg, per color class, and per egg mass category was determined. In 2000, egg masses were separated into three categories: small (1–10 eggs), medium (11–50 eggs), and large (51^+ eggs).

Because egg clusters were categorized as small or large in the 1999 field studies, egg masses from that year's sampling study were converted to a predicted number of larvae by multiplying the small and large egg masses by the mean number of larvae produced per similar sized egg masses in the 2000 larval hatch study. In 2000, eggs per sample in field 3 were multiplied by the computed ratio of larvae per egg, as determined by regression (SAS Institute 2000). For both years, predicted numbers of larvae were used to calculate population densities. Predicted larvae were estimated as the sum of larvae expected to hatch from eggs and the actual number of larvae counted per sample. Analysis of variance (ANOVA) (SAS Institute 2000) was used to compare hatching rates of eggs of differing initial egg mass color and size.

Plant Damage. Sunflower midge damage ratings were obtained at the end of each growing season by averaging the damage ratings of four randomly selected sunflower heads near each sample point. Ratings of each mature sunflower head were recorded on the scale proposed by Bracken (1990): 0, no visible damage; 1, light bract damage; 2, bract damage evident; 3, heavy bract damage and seedless area in center of head; 4, extreme damage and seedless area; and 5, complete seed loss. Linear correlations of damage ratings with numbers of larvae and cumulative larval density for each sample date were calculated, and the significance of the lines was tested using a t test (SAS Institute 2000).

Spatial Data Analysis. The GIS ArcMap 8.2 (Environmental Systems Research Institute 1999) was used to create point maps of predicted larval densities from each sample date, cumulative midge days, and plant

Table 1. Sunflower midge larval emergence over four days from egg masses collected in the field in 2000

Egg mass category (no. eggs)	n	Mean no. eggs per mass (± SEM)	Hatching rate per egg (± SEM)
Small (1–10)	399	6.51 ± 0.15	0.35 ± 0.03a
Medium (11–50)	513	23.70 ± 0.44	0.18 ± 0.01b
Large (51+)	88	81.30 ± 3.08	0.21 ± 0.03b

Different lowercase letters denote statistical significance (F = 21.88; df = 2, 997; $P < 0.001$) in column values.

damage from sunflower midge in each field. These point maps were used to create interpolated maps of density, cumulative density, and damage to plants. Interpolative techniques rely on data having spatial autocorrelation. Spatial autocorrelation was assessed using variogram analysis in GS^+ (Gamma Delta Software, Plainwell MI). More detailed information about variogram interpretation is provided by Krajewski and Gibbs (2001) and Hohn et al. (1993).

Individual point maps were interpolated using ordinary kriging in ArcMap 8.2. Interpolated maps were created for every sample date at all three fields. For the interpolations, the cell size was set at 2 m, which approximated the sampling area in which we collected sunflower heads. Maps were constructed by categorizing density (five categories in 1999 and six in 2000) and plant damage (five categories). The number of sunflower midge categories was determined by breaking up the total range into five or six distinguishable grayscale categories. Maps were visually compared to evaluate the movement of sunflower midge over time and investigate the potential for targeted insecticide applications.

Results and Discussion

Larval Hatch Study. Of the 1,000 egg masses collected, 399 were small, 513 medium, and 88 large (Table 1). Small egg masses (≤10 eggs per mass) produced significantly more larvae per egg than medium (11–50 eggs per mass) or large egg masses (51^+ eggs per mass) ($F = 21.88$; df = 2, 997; $P < 0.001$). The regression analysis between the number of eggs per egg mass and the larval hatching rate was also significant ($F = 195$; df = 2, 997; $P < 0.001$; $R^2 = 0.16$). The number of eggs per egg mass cannot fully explain the variation of larval hatching rates in 2000. The model equation for estimating the number of larvae hatching per each egg mass in field 3 was 1.052 + (0.142) (number of eggs), and the number of larvae hatching per egg mass for fields 1 and 2 was (number of small egg masses) (0.35) (6.5) + (number of large egg masses) (0.18) (52.5) (Table 1). The hatching rate for large egg masses was determined by calculating the mean of medium and large egg masses (Table 1). The hatching rate of different colored egg masses also varied. The hatching rate from light orange, orange, and dark orange egg masses was similar (0.13–0.17 larvae per egg) and significantly less than those produced from clear and yellow egg masses (0.37–0.45 larvae per egg) ($F = 17.32$; df = 4, 830; $P < 0.001$).

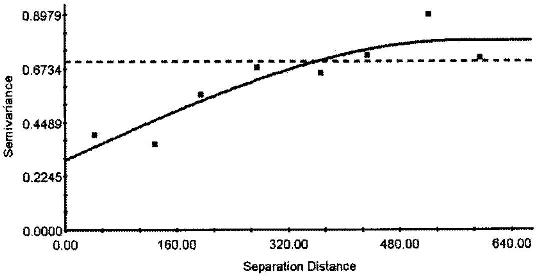

Fig. 4. Representative variogram analysis (from larval densities of field 3, 31 July 2000) with equation: spherical model (R^2 = 0.833; Nugget = 0.2920; Sill = 0.788; Range = 565). Semivariance is the average squared difference between samples, and the separation distance between samples is in meters. The solid represents the best fit for the spherical model, and the dashed line represents the distance (in meters) at which meaningful differences between samples can no longer be observed.

Field Sampling. Variogram analyses showed counts of midge larvae were spatially correlated. A variogram for field 3 is presented as an example (Fig. 4). A spherical model (Environmental Systems Research Institute 1999) was selected as having the best fit for all predicted larval densities and for cumulative midge days.

Few sunflower midge were detected in field 1 on the first collection dates of 15 and 19 July (Fig. 1A). By 23 July, larvae were located throughout the field, and the population peaked at 200 larvae per head, but with a mean of only 5.94 ± 3.34 (mean ± SE) larvae per head (Fig. 1A). The southeastern corner was the most densely populated, but this infestation is considered relatively low. On 26 July, the sunflower midge population began to decline with the most dense population along the eastern field edge. The last sample was collected 5 August, and the population was highest in the southeast corner (Fig. 1A).

Cumulative midge day values for field 1 were mapped and visually compared with the predicted larval values. By 23 July, interpolations estimating the cumulative sunflower midge density indicated midge were distributed throughout the field (Fig. 1B). The cumulative density began to plateau on 26 July, with the eastern field edge reaching 10–49.99 larvae per head. The peak cumulative sunflower midge density was in the southeast corner (5 August), but at no location in the field did the cumulative population exceed 215 larvae per head.

Few sunflower midge were found on the first collection date (15 July) in field 2. By 19 July, several isolated areas of increased sunflower midge density were located throughout the field (Fig. 2A). Larvae occurred throughout the field and with little spatial variation by 23 July (Fig. 2A). Densities peaked on the southern field margin on 26 July at 41 larvae per head, although the mean number of larvae per sunflower head was 5.80 ± 0.91. By 29 July, the population density was decreasing throughout the field. On the last collection dates of 2 and 5 August, few larvae were collected. Throughout the season, overall the sunflower midge population remained low in field 2.

For field 2, cumulative midge day patterns were more variable compared with the predicted larval densities in Fig. 1 (Fig. 2). By 26 July, cumulative midge days indicated that sunflower midge larvae were concentrated in the southern half of the field. This area continued to have high populations until the last sample on 5 August, and reached a plateau of 20 larvae per head along the southern and northeast field margins.

In 2000, field 3 had considerably higher sunflower midge populations than either field sampled in 1999. On 19 July, sunflower midge density was greatest along the southwestern edge at 8.25 ± 0.19 larvae per head, and field-wide densities already surpassed maximum mean densities of either field sampled in 1999 (Fig. 3A). Sunflower midge density increased along the western and northern field edge by 28 and 31 July (Fig. 3A). The peak field-average density was on 28 July with 537 larvae per head. The peak mean number of larvae on 31 July was 124.59 ± 11.89 larvae per head. A large population decline began in August, and larval populations were near zero by the last sample on 14 August.

Cumulative midge day density maps for field 3 show elevated levels of sunflower midge populations throughout the field, with increased cumulative density along the western edge (Fig. 3B). This area remained the region of highest cumulative density throughout the entire sampling season. By 31 July, a cumulative density of 500-1200 larvae per head was recorded along the western edge (Fig. 3B). Cumulative densities plateaued on 9 August, with some areas near 1,200 larvae per head. On 9 August, the average cumulative density was 538.95 ± 41.11 per head. The western field edge and northeast corner had the largest cumulative midge day values and the center of the field remained the least populated (Fig. 3B).

In sunflower fields 1 and 3, sunflower midge populations were first detected along the edge proximal to the previous years' sunflower field. Adult sunflower midge most likely emerged from the overwintering sites (fields infested the previous season) and moved to the current season's sunflower fields, where females began ovipositing near the field edge. Areas of initial infestation had the highest number of larvae throughout the sampling period for all three fields, and this pattern was emphasized during 2000 when the larval populations were elevated. These data suggest that adjacent areas within a field are likely to have similar damage levels when larval populations are relatively high.

Plant Damage. Sunflower midge damage ratings from all fields sampled in 1999 and 2000 were recorded and mapped. Visual inspection of interpolated maps estimating sunflower midge populations indicates that sunflower midge damage, as measured by the Bracken (1990) scale, may be related to population density. Bracken indicated that damage ratings were correlated with yield. Light bract damage occurred along all four edges of field 1, but the field interior had no visible damage (Fig. 5A). Bract damage was apparent along the portions of the eastern, northern, and western edges of field 2 (Fig. 5B). Light head cupping and head creasing were also evident along the eastern field edge. However, the field interior had no visible damage. Field 3 had complete seed loss along the entire western edge, and all other field edges had heavy sunflower head creasing and abnormal seed production (Fig. 5C). Although plant damage was less in the middle of the field, there were considerable bract damage and head creasing.

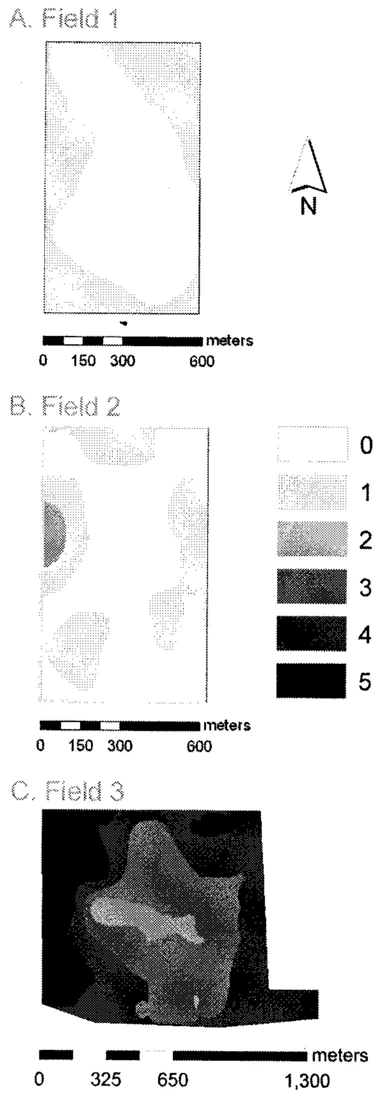

Fig. 5. Estimated sunflower damage ratings using Bracken's (1990) damage rating scale: 0, no visible damage; 1, light bract damage; 2, bract damage evident; 3, heavy bract damage and seedless area in center of head; 4, extreme damage and seedless area; and 5, complete seed loss.

The averaged plant damage rating at each sample point was correlated with predicted larval density and cumulative midge days for each sample date. For fields 1 and 2, the linear correlations for predicted larval density and cumulative midge days were not related to plant damage. The slope was not significantly different than one for field 1 (predicted: $t = -0.080$, df = 6, $P = 0.938$, and cumulative: $t = 1.576$, df = 6, $P = 1.66$), or for field 2 (predicted: $t = -1173$, df = 6, $P = 0.285$, and cumulative: $t = 0.844$, df = 6, $P = 0.431$). A relationship between the correlation coefficient and date was evident for cumulative midge days in field 3 ($R^2 = 0.7892$). At high densities, cumulative midge day density was correlated with damage beginning in late July. The slope of the cumulative midge days regression was significantly different than one (predicted: $t = -200.964$, df = 12, $P = 0.0$, and cumulative: $t = -394.904$, df = 12, $P = <0.0001$).

The lack of a significant relationship between sunflower midge population and damage in fields 1 and 2 was probably because of low sunflower midge density, and because of the inability of the damage rating scale to detect minor damage. The plant damage rating scale is based on the outward appearance of the sunflower head, and this could indicate damage ratings from visual inspection are more useful at higher infestation levels. A low sunflower midge population may not produce noticeable damage symptoms and may go undetected. However, low populations can still impact yield by reducing the maximum potential for seed production and affecting the quality of protein and oil produced within the seed (G.J.B., unpublished data).

Cumulative midge days began a plateau at the end of July in 1999 and 2000. This is approximately the beginning of flowering in North Dakota. At this temporal point, females have stopped ovipositing and larvae are no longer accumulating in the heads. So, it may be unnecessary and inefficient to continue sampling and estimating cumulative midge days during the reproductive stages.

Conclusions

Relating cumulative midge days to sunflower head damage may be a useful technique when larval populations are high. Counting egg masses and larvae per plant based on a single scouting event may result in inaccurate estimations of resulting plant damage. The extended ovipositing period during late June and July often complicates sampling effort during the vegetative stages. By early August, late-instar larvae begin to drop to the ground to overwinter. Larval populations gradually decrease, and estimations of resulting damage from larval density will also not be accurate during plant flowering. Therefore, taking repeated samples of vegetative plants until early August and calculating cumulative midge days may result in more accurate predictions of harvest yield.

Calculating the predicted larval density based on egg and larval populations is a novel approach for estimating sunflower midge populations in sunflower. Population density and cumulative population maps were effective in showing visual patterns of sunflower midge distribution in commercial sunflower. Cumulative population density is a better predictor of damage than density estimates at single points in time.

Based on this study and previous work (McBride et al. 1994, Charlet and Brewer 1997, Glogoza et al. 1997), a site-specific pest management program does not appear to be feasible for reducing sunflower midge populations in sunflower. Because adults have a prolonged emergence throughout July (Figs. 1–3), multiple pesticide applications would have to be used to treat sunflower. The temporal window for potential immigration into sunflower is long, and the population can disperse across the field relatively evenly. Consequently, targeted applications of insecticides (i.e., one well-timed border treatment to suppress immigrating females) cannot be expected to control sunflower midge adults.

Although most sunflower midge damage is concentrated around the exterior of the field at low and high densities, populations can expand through the field interior and can cause significant economic loss (Fig. 5). Currently, the use of tolerant hybrids and crop rotation continues to be the best strategy for reducing sunflower midge outbreaks in commercial sunflower fields (Charlet and Brewer 1997). Growers should consider not planting sunflower directly next to fields previously planted to sunflower during severe outbreaks.

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