Effect of Within Field Topography on Emergence of Adult Sugarbeet Root Maggot, *Tetanops myopaeformis* (Roder) (Diptera: Otitidae)

Ian MacRae

Dept. of Entomology, University of Minnesota, St. Paul, MN 55108

ABSTRACT

The sugarbeet root maggot, *Tetanops myopaeformis* Roder, is the most important insect pest of sugarbeet in the Red River Valley of Minnesota and North Dakota. It overwinters as a larva 13 to 22.5 cm deep in the soil. In spring, when soil temperatures increase, the larvae move to within 9 cm of the soil surface, pupate and then emerge as adult flies. Both high and low soil moistures can negatively impact pupal development. Many sugarbeet production areas in the Red River Valley suffer overland flooding during the spring when *T. myopaeformis* is pupating and standing water within fields is common. Because field topography heavily influences drainage and soil moisture, it was hypothesized that relative topography within fields can influence the distribution and density of emerging adult *T. myopaeformis*. The influence of within field topography on successful pupation of *T. myopaeformis* was assessed in four commercial fields over two years. Fields were divided into low and high zones, based on the presence of standing water through the period of time when pupation was occurring. A regular grid of emergence traps was used to monitor the adult emergence of *T. myopaeformis* with additional traps specifically located in standing water zones to supplement the catch data of the grid-placed traps. Resulting trap catches were assessed for spatial autocorrelation using semi-variograms and the geographic information system, ArcView© was used to construct interpolated surfaces estimating the distribution and density of emerging adult *T. myo-*

***paeformis*. The emergence data from the traps were compared using a Mann-Whitney U test. Significantly fewer adult *T. myopaeformis* were recovered from traps located in areas within fields that had standing water throughout the pupal development period than from traps located in higher areas of the field. The implications of this work on monitoring efforts are discussed.**

ADDITIONAL KEY WORDS: Geographic Information Systems, GIS, site specific management, within field distribution, soil moisture.

The sugarbeet root maggot, *Tetanops myopaeformis* Roder, was first reported in the Red River Valley of Minnesota and North Dakota in 1947 and has since become the most important insect pest of sugarbeet in the region (McBride et al. 1990). Root yield losses from *T. myopaeformis* injury can range from 0.5 to 2.8 metric tons/ha (Campbell et al. 1998). The average root yield loss has been estimated at 1.3 metric tons/ha in the absence of control measures. Larvae overwinter in the soil at a depth of 13 to 22.5 cm. They become more active in the spring when soil temperatures increase, moving to within 2.5 to 9 cm of the surface in late March or early April (Bechinski et al. 1989 & 1990). Temperatures must rise above 8.6 C for larvae to develop into adults (Whitfield 1984). Larvae then pupate near the soil surface and become adults, emerging from mid-May to late June. Adult *T. myopaeformis* emerge into previous year's beet fields, in which they spend 3 to 10 days before flying into sugarbeet fields to mate, locate suitable host plants and oviposit. Mating and oviposition occur until mid-July with larvae hatching in early June when they start feeding on the maturing sugarbeet root. Larvae cease feeding in September and initiate diapause (Whitfield & Grace 1985).

The importance of sugarbeet root maggot in the Red River Valley has led to a coordinated, annual effort to monitor its population and assess the need for control. This is partially conducted with the use of sticky stake traps to monitor adults leaving last year's sugarbeet fields. Initiation of monitoring is determined annually using predictive emergence models based on temperature accumulation. An emergence model based on air temperature degree-days (Bechinski et al. 1990) predicts peak fly emergence when the maximum air temperature exceeds 26.7 C following the accumulation of 200 degree-days above a base temperature of 8.6 C after 1 March. Emergence predictions of *T. myopaeformis* in the Red River Valley are currently calculated with a modification of this model partially based on soil temperatures using the same base temperature (R. Carlson, pers com). These predictions are made available to growers via the World Wide Web (http://www.ext.nodak.edu/weather/idd/). Although they may be active and moving towards the soil surface, larvae will not develop until soil temperatures reach 8.6 C (Whitfield 1984). In the study area, the soil temperatures at 2.5 to 9 cm under bare soil reach 8.6 C by approximately 1 May (Jensen 1998).

Tetanops myopaeformis development can be influenced by soil moisture; a minimum developmental threshold exists below which larval development is impaired (Anderson et al. 1991, McBride et al. 1990, MacRae & Armstrong 2000). A maximum soil moisture threshold also exists, above which pupation fails (MacRae & Armstrong 2000). Increased pupal mortality occurs within 10 days when soil moistures exceed 45% soil moisture by weight. Water standing in a field for 10 days should elevate the soil moisture in the top 9 cm to this level of saturation. Commercial sugarbeet fields in the Red River Valley frequently contain standing water for this time period during spring. The Red River Valley is the bottom of the ancient glacial Lake Aggasiz and is an extremely flat region with an average rise of only 0.25 to 0.5 m / km for the first 17 to 25 km from the river. The Red River itself has a gradient of only about 7 cm / km (Schwert 2001). Consequently, production sugarbeet fields in the Red River Valley often experience overland flooding in the spring. Many production fields, especially those in sugarbeet rotation, have been topographically mapped and ditched for optimum drainage. Despite this management tactic, the low slope of the river's watershed can still result in slow drainage of fields, resulting in areas of standing water.

Soil moisture has been implicated as a factor influencing the regional distribution of *T. myopaeformis* (MacRae et al. 1999). Because soil moisture in a field is strongly influenced by within field topography (Miller et al. 1983, Prax 1991), it was hypothesized that within field topography could be used to refine monitoring efforts for emerging *T. myopaeformis* adults.

Field investigations were initiated to evaluate the effect of within field topography on the emergence of adult *T. myopaeformis*. The distribution and density of emerging adult *T. myopaeformis* in commercial fields that had been planted into sugarbeet the previous year was monitored and compared.

MATERIALS AND METHODS

Two commercial fields were selected in each of 1999 and 2000. All fields had been planted into sugarbeet the year prior to their study. One field in each year was located on the University of Minnesota's Northwest Research & Outreach Center (designated NWROC99 & NWROC2k) in Crookston, MN and two were located near Eldred, MN (designated WAG99 and ELDRED2k). Fields were selected based on variation in topography leading to the presence of standing water during the pupation period for *T. myopaeformis*. The exception was NWROC2k, which had little variation in topography and did not contain standing water. Data was collected from this field despite its failure to fit the selection criteria of standing water to provide a contrast to the other three study fields. Because drainage ditches bordered all fields, which might lead to decreased populations not representative of the entire field, sections away from field borders were selected for study. The study areas were: NWROC99, 25 ha; WAG99, 26 ha; ELDRED2k, 16 ha; and NWROC2k, 25.5 ha.

Complete topographic surfaces were prepared for all fields using data from a laser topography system with a resolution of about 1-m. Laser topographic systems create point maps of relative elevations within a field. The raw topographic data were obtained from the cooperators and the geographic information system (GIS) ArcView© V.3.2 (Environmental Software Research Institute, Redlands, CA) was used to create a distribution map of all of the laser topographic points. This point map was interpolated using the Inverse Distance Weighting (IDW) technique in ArcView Spatial Analyst, using a 1-m cell size. The resulting interpolation estimated the within field topography between measured points. Before interpolating, the point data were evaluated for spatial autocorrelation by creating semi-variograms (variograms) in GS+© V.5.1 (Gamma Design Software, Plainwell MI). A variogram plot is a summary of the variance between datapoint values and the distance between those points. Consequently, it reflects the similarity or dissimilarity of datapoint values over distance. The relationship of nearer datapoints being more similar in value than datapoints further away is referred to as spatial autocorrelation and is an underlying assumption of spatial statistical procedures such as interpolation (Isaaks & Srivastava 1989, Armstrong 1998). As recommended by several authors, variograms were constructed for data values over half of the distance of the sample areas (Isaaks & Srivastava 1989, Liebhold et al. 1993).

Temperatures under bare soil were obtained for study areas in each year from either the North Dakota Agricultural Weather Network (NDAWN) or from the permanent weather station at the UMN-NWROC. All fields were observed in the spring when soil temperatures had risen above 8.6 C. The coordinates of standing water were established using an Ashtech BR2G differentially corrected Global Positioning System (GPS). Because of the nature of within field topography, less well-drained areas of a field can hold standing water that eventually evaporates. These regions may not have sufficient soil moisture to impair *T. myopaeformis* pupation. For this reason, only the coordinates of water that had been standing in excess of 10 days were recorded and the average relative elevation of these coordinates obtained from the interpolated topographic map. Areas in a field below this elevation were considered standing water zones. For display, the interpolated maps estimating within field topography were divided into four different classes; the first class represents the standing water zone within a field and the remaining field is divided approximately evenly into three topographic classes (e.g. Figure 1a).

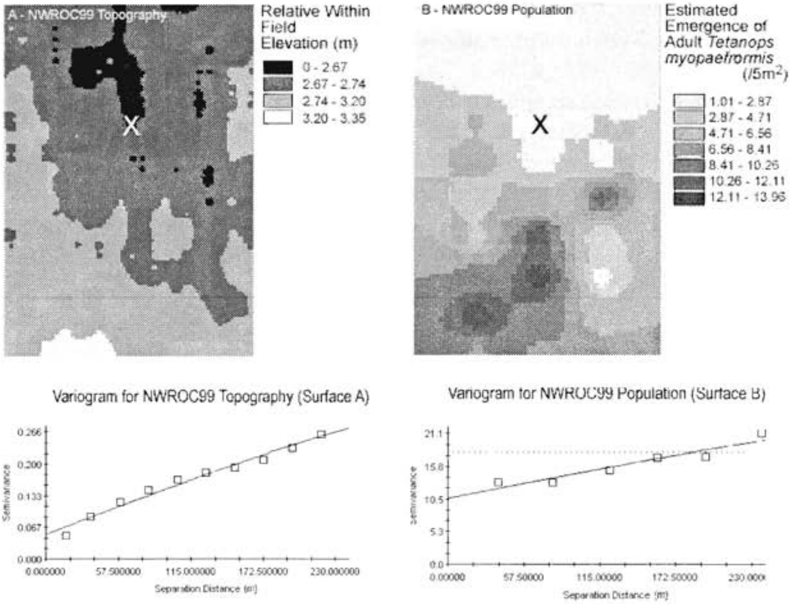

Figure 1. Interpolated surfaces estimating the within field topography and emergence of adult *Tetanops myopaeformis* in fields NWROC99. Locations marked by "X" represent the same spot in the two corresponding surfaces. A) Within field topography. B) Emerging adult *T. myopaeformis* / 5 m^2. Topographic surfaces are interpolated with a cell size of $1m^2$ while *T. myopaeformis* emergence surfaces are interpolated with a cell size of $5m^2$. Variograms below the interpolated maps present the level of spatial autocorrelation in the respective data sets. Each variogram point represents the mean semivariance of > 1000 pair comparisons on the topography variogram and at least 50 pair comparisons on the *T. myopaeformis* population variograms. Positive slopes of the fitted lines indicates data values are positively spatially autocorrelated. Flat fitted lines indicate there is no spatial relationship in the data. Interpolated maps prepared in ArcInfo 3.2 (ESRI, Redlands, CA) and variograms prepared in GS+ 5.1 (Gamma Design Software, Plainwell, MI).

When standing waters had receded, a 0.5 ha grid was established within each field and sample locations established at the center of each grid space. In addition, a number of additional traps were placed in standing water zones and other locations in each field as indicated by the topographic interpolation to ensure that adequate data were collected for a statistical comparison of emerging adults from standing water zones and other areas within each field. Because of the different areas of the fields and varying number of additional traps placed into standing water zones within each field, sample numbers varied (NWROC99 = 66, WAG99 = 78, NWROC2K = 74, ELDRED2K = 45). The geographic coordinates of each sample location were obtained with an Ashtech BR2G differentially corrected GPS (Thales Navigation Inc. Santa Clara, CA). Soil samples were collected from each sample location at 2-week intervals throughout each study period. Soil samples were weighed, dried and reweighed to determine soil moisture (Cassel & Nielsen 1986). Linear regression analyses were conducted to assess relationships between soil moisture and adult fly emergence (Neter et al. 1990).

At each sample location, numbers of emerging adult *T. myopaeformis* were monitored with two sticky stake traps. Sticky stake traps are a standard method of monitoring for adult *T. myopaeformis* (Bechinski et al. 1990) and were used because of the relative cost of construction and maintenance compared to a similar number of funnel soil emergence traps. Sticky stake traps were constructed by placing into the fields 1 m lengths of lathing (5 cm x 1.25 cm) onto the north facing side of which was attached a 30.5 cm orange garden stake coated in Tanglefoot© (The Tanglefoot Co., Grand Rapids, MI). Traps were set so that the orange stake was about 9 cm above ground level and were checked at 1 to 2 day intervals for about 6 weeks. The number of adult *T. myopaeformis* were counted and totaled over the sample period. At each sample location in each field, a funnel type soil emergence trap with a basal diameter of 0.25 m was also established and the approximate density of emerging adult flies per m^2 was calculated. The relative trapping area of the sticky stake traps was calculated by comparing the mean total cumulative *T. myopaeformis* adults captured by the two sticky stakes and the trap capture from the emergence traps at each sample location. The mean of all ratios was calculated and used to estimate the area being sampled by the stakes. This value was used to determine the cell size for the population interpolations estimating the distribution and density of emerging adult *T. myopaeformis*.

ArcView© was used to create point maps of the mean total emergence at each point on the grid. Variograms were constructed in GS+ to assess spatial autocorrelation. An interpolated surface estimating the distribution and density of emerging adult *T. myopaeformis* in each field was created in ArcView© using IDW. Because the additional traps were clustered in standing water zones and other locations in the fields, they were not used in either the calculation of variograms or the interpolated surface as both techniques are sensitive to clustered data (Clark & Harper 2000, Krajewski & Gibbs 2001).

The mean total emerging adult *T. myopaeformis* was calculated for all sample locations in each field. Sample locations below the mean relative elevation of standing water in a field were assigned as standing water zone data points. All sample locations above this level were assigned as dry zone data points. Because spatially autocorrelated data violate the assumptions of independence, a Mann-Whitney U ranked sum comparison (Zar 1984) was used to assess the probability that the numbers of emerging adult *T. myopaeformis* recovered from traps in standing water zones were similar to those from traps located in the rest of the field. Unlike the interpolations and variograms, all sample points were used in this comparison.

RESULTS

The interpolated topographic surfaces of NWROC99, WAG99, and ELDRED2k showed distinct standing water zones within the fields compared to the remaining topography within those fields (Figure 1a, 2a, & 3a respectively). Standing water zones in NWROC99 were those areas of the field below 2.67 m relative elevation and the overall topographic difference in NWROC99 (lowest to highest points in the field) was 2.35 m (Figure 1a). Standing water zones in WAG99 were those areas below 2.84 m relative elevation, and the overall topographic difference was 3.96 m (Figure 2a). Standing water zones in ELDRED2k were those areas below 3.02 m relative elevation, and the field had an overall topographic difference of about 3.96 m (Figure 3a). An arbitrary standing water zone of 2.25 m was selected in NWROC2k, and the field had an overall topographic difference of 3.14 m (Figure 4a).

The variograms indicated that the distribution of emerging *T. myopaeformis* adults was aggregated in NWROC99, WAG99, and ELDRED2k but not in NWROC2k (Figures 1, 2, 3, & 4). There are distinctly positive slopes in the variograms for *T. myopaeformis* population distributions in all three fields (Figures 1, 2, & 3). This indicates the emergence data for these three fields were spatially autocorrelated. The flat slope of the variogram for the population data in NWROC2K indicated the emergence data in this field were not aggregated at any distance (Figure 4), and therefore we cannot say this data is spatially autocorrelated. However, because the interpolated

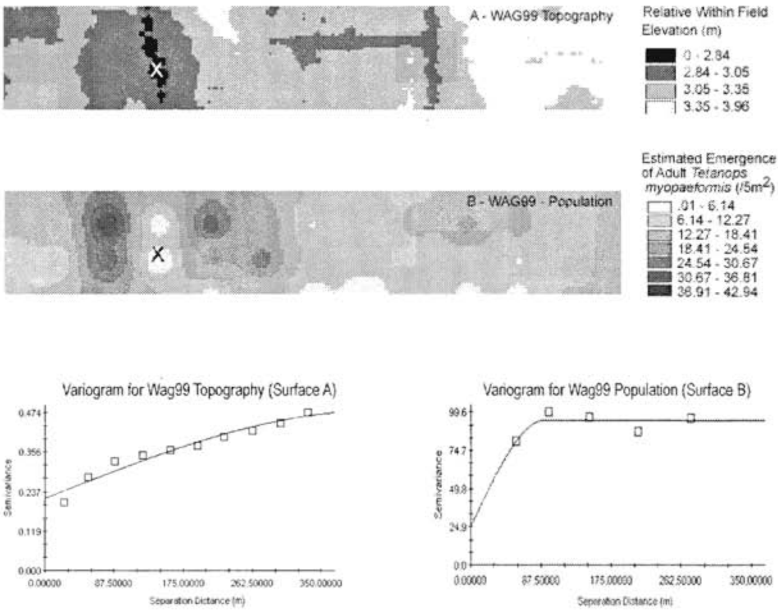

Figure 2. Interpolated surfaces estimating the within field topography and emergence of adult *Tetanops myopaeformis* in fields WAG99. Locations marked by "X" represent the same spot in the two corresponding surfaces. A) Within field topography. B) Emerging adult *T. myopaeformis* / 5 m^2. Topographic surfaces are interpolated with a cell size of $1m^2$ while *T. myopaeformis* emergence surfaces are interpolated with a cell size of $5m^2$. Variograms below the interpolated maps present the level of spatial autocorrelation in the respective data sets. Each point represents the mean semivariance of > 1000 pair comparisons on the topography variogram and at least 50 pair comparisons on the *T. myopaeformis* population variograms. Positive slopes of the fitted lines indicates data values are positively spatially autocorrelated. Flat fitted lines indicate there is no spatial relationship in the data. Interpolated maps prepared in ArcInfo 3.2 (ESRI, Redlands, CA) and variograms prepared in GS+ 5.1 (Gamma Design Software, Plainwell, MI).

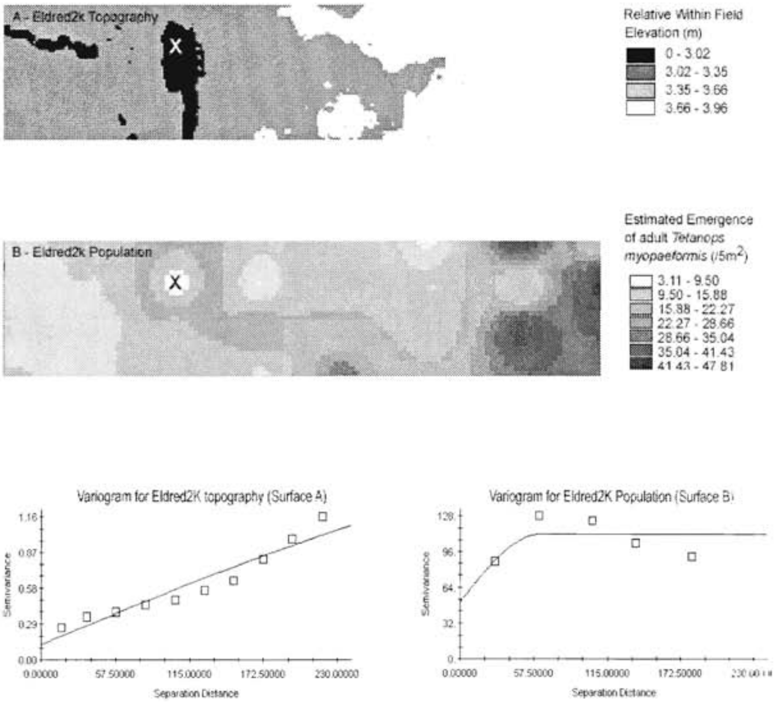

Figure 3. Interpolated surfaces estimating the within field topography and emergence of adult *Tetanops myopaeformis* in fields ELDRED2K. Locations marked by "X" represent the same spot in the two corresponding surfaces. A) Within field topography. B) Emerging adult *T. myopaeformis* / 5 m^2. Topographic surfaces are interpolated with a cell size of $1m^2$ while T. myopaeformis emergence surfaces are interpolated with a cell size of $5m^2$. Variograms below the interpolated maps present the level of spatial autocorrelation in the respective data sets. Each point represents the mean semivariance of > 1000 pair comparisons on the topography variogram and at least 50 pair comparisons on the *T. myopaeformis* population variograms. Positive slopes of the fitted lines indicates data values are positively spatially autocorrelated. Flat fitted lines indicate there is no spatial relationship in the data. Interpolated maps prepared in ArcInfo 3.2 (ESRI, Redlands, CA) and variograms prepared in GS+ 5.1 (Gamma Design Software, Plainwell, MI).

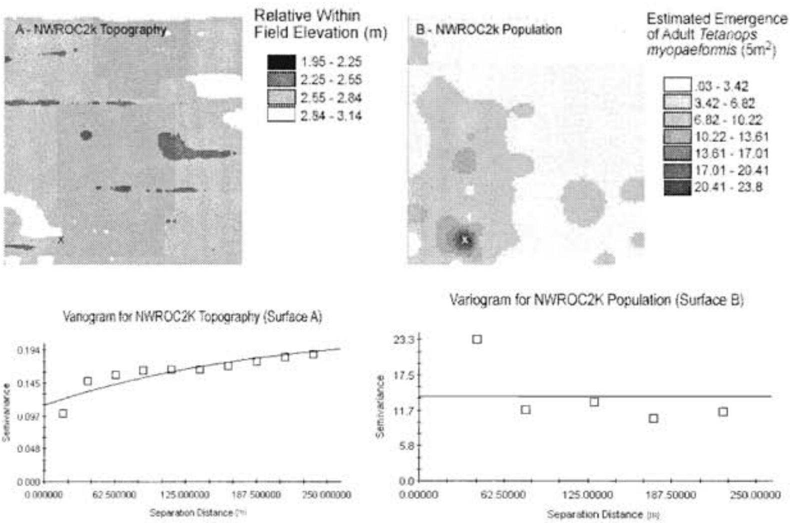

Figure 4. Interpolated surfaces estimating the within field topography and emergence of adult *Tetanops myopaeformis* in fields NWROC2K. Locations marked by "X" represent the same spot in the two corresponding surfaces. A) Within field topography. B) Emerging adult *T. myopaeformis* / 5 m^2. Topographic surfaces are interpolated with a cell size of $1m^2$ while *T. myopaeformis* emergence surfaces are interpolated with a cell size of $5m^2$. Variograms below the interpolated maps present the level of spatial autocorrelation in the respective data sets. Each point represents the mean semivariance of > 1000 pair comparisons on the topography variogram and at least 50 pair comparisons on the *T. myopaeformis* population variograms. Positive slopes of the fitted lines indicates data values are positively spatially autocorrelated. Flat fitted lines indicate there is no spatial relationship in the data. Interpolated maps prepared in ArcInfo 3.2 (ESRI, Redlands, CA) and variograms prepared in GS+ 5.1 (Gamma Design Software, Plainwell, MI).

surfaces were primarily for visual comparison and other statistical comparisons were conducted, a surface estimating emergence of adult flies for NWROC2k was interpolated as well.

Ratios of emergence trap estimates of *T. myopaeformis* population densities to sticky stake captures were variable field to field but sticky stakes always trapped more insects than did emergence traps (NWROC 15.9 in sticky stake traps : 1 in emergence traps, WAG99 9.89:1, NWROC2K 4.3:1, ELDRED2K 16.2:1). The emergence traps in WAG99 suffered some disturbance in a wind event and had to be reset. This likely resulted in a decreased cumulative catch for those traps. Although trap catch for sticky stakes may have been decreased because of individuals not flying during this event, no sticky stakes were disturbed and catch data was collected for that period. Because of the disturbance of emergence traps in WAG99, and because a larger cell size results in a more conservative interpolated estimate, it was decided to use a ratio of 20:1 in estimating the relative areas trapped by sticky stakes compared to the emergence traps ($5m^2$). This value was subsequently used as the cell size for the population interpolations. The legends of the interpolated surfaces report population numbers for this area (i.e. n / $5m^2$). The interpolated surfaces estimating the distribution and densities of emerging adult *T. myopaeformis* illustrate that in NWROC99, WAG99 and ELDRED2k distinct patterns in the emergence of adults were observed (Figure 1b, 2b, and 3b). In NWROC99, the interpolated surfaces estimated emergence within the field to vary from 1.01 to 13.96 flies / $5m^2$ (Figure 1b). In WAG99, the interpolated surfaces estimated between 0.01 to 42.94 flies / 5 m^2 (Figure 2b). In ELDRED2k, the interpolated surfaces estimate emergence of adult flies vary between 3.11 and 47.81 adults per 5 m^2 (Figure 3b) while in NWROC2k, the estimated emergence of adults ranges from 0.03 to 23.8 flies / 5 m^2 (Figure 4b).

In two fields, a distinct trend in the interpolated estimate of adult emergence was observed. In NWROC99, the number of emerging adult *T. myopaeformis* decreased from the southern to the northern end of the study field, which corresponded with decreasing relative elevation of the field (Figure 1a & 1b). A similar pattern was seen in ELDRED2k; higher numbers of emerging adult flies were recovered in the eastern end of the field than in the western end (Figure 3a & 3b). This too corresponded to the topographic trend in that field, which was graded to drain to the west. Although the pattern was less distinct in the WAG99 field, areas with low numbers of emerging adult flies corresponded with standing water zones within the field (Figure 2a & 2b). However, previous research indicated no direct relationship between within field topography and adult *T. myopaeformis* emergence (MacRae et al. 1999). In NWROC99, WAG99, and ELDRED2k (Figure 1a & 1b, 2a & 2b, and 3a & 3b) some locations had considerable emergence of adult flies but these points were not the highest locations in the fields. Regression analyses indicated no linear relationships between soil moisture at individual sample locations and adult fly emergence in any of the fields (Table 1).

Little if any pattern was observed in the emergence of adult flies in NWROC2k. The topography of this field was quite uniform (Figure 4a). This was expected, as no areas within this field had water

Table 1. Regression statistics for soil moisture and mean cumulative *T. myopaeformis* capture per trap location.

Location	F-Ratio	R^2	P	N
NWROC99	0.219	0.003	0.641	66
WAG99	0.438	0.006	0.510	78
NWROC2K	0.480	0.007	0.491	74
ELDRED2K	0.221	0.005	0.640	45

standing for longer than 7 days. Consequently the numbers of emerging adult *T. myopaeformis* were relatively uniform across the field.

In all three fields, fewer adults were recovered from traps in standing water zones than from traps in other areas of the fields (Table 2). The Mann-Whitney U comparisons indicated that significantly fewer *T. myopaeformis* adults were recovered from traps in standing water zones than from traps in the rest of the field (NWROC99 P = 0.035, WAG99 P = 0.011, ELDRED2K P = 0.044). The numbers of adults emerging from standing water zones and adults emerging from other locations in NWROC2k did not differ (P = 0.473).

Table 2. Mann-Whitney U comparison of mean number of *T. myopaeformis* recovered from traps in standing water zones and traps in other areas of the fields. P-values below 0.05 indicate a significant difference.

Location	Count of traps in other areas	Count of traps in standing water zones	Rank Sum (other areas)	Rank Sum (standing water zones)	Mann-Whitney-U Statistic	P
NWROC99	53	13	1968.5	309.5	483.5	0.035
WAG99	62	16	2653.5	427.5	700.5	0.011
NWROC2K	62	12	2373.5	401.5	420.5	0.473
ELDRED2K	33	12	837.5	197.5	276.5	0.044

DISCUSSION

In all fields where emergence was influenced by topography (NWROC99, WAG99, & ELDRED2k) the standing water zones within the fields occupied a small area but accounted for a considerable proportion of the overall topographic difference in the field. The difference in relative elevation from the lowest level in the field to the standing water's edge was greater than 2/3 of the overall variation in topographic elevation in all fields. The standing water zones within these fields were mostly drainage ditches that failed to drain because of water backup from the larger ditches bordering the fields. The within field drainage ditches are dug so that they have relatively steep slopes.

The effect of within-field topography on the successful pupation and emergence of adult *T. myopaeformis* was associated with the presence of standing water through the pupal development of the insect. The general patterns of emerging adult flies reflect the changes in relative elevation within fields. The lack of a direct relationship between within field relative elevation and adult fly emergence was expected, as was the lack of a direct linear relationship between soil moisture and adult fly emergence. Previous research indicated that only very low or very high soil moistures inflict mortality (MacRae & Armstrong 2000). So, rather than linear effects, extreme soil moistures seem to be operating as mortality thresholds. Conditions of very low soil moistures (<5% soil moisture by weight) would exist in the Red River Valley only in drought conditions and did not occur in any of the fields during the trial years. Consequently, the only expected pattern was a decrease in adult fly emergence in the standing water zones of the fields, i.e. those areas that held standing water in excess of 10 days.

The definitive evidence for the association of topography and successful emergence is provided by the Mann-Whitney U test. Results indicated that, in all fields that held standing water, within field topography (i.e. low areas in the field) had a significant negative impact on the ability of *T. myopaeformis* to successfully emerge. While soil type at each sample location was not described, and this may have been a contributing factor, this is not a confounding issue. Regardless of soil type, the analyses indicate that the population distribution is associated with areas of standing water.

Based on laboratory research (MacRae & Armstrong 2000), this probably reflects the influence of high soil moisture. Low soil moisture (<5% soil moisture by weight) increased larval mortality (Anderson et al. 1990, McBride et al. 1990, MacRae & Armstrong 2000) while high soil moisture causes increased mortality in pupae (MacRae & Armstrong 2000). Attempts were made to extract *T. myopaeformis* larvae and pupae from soil samples in an effort to assess pupal versus larval mortality but these efforts were not successful. Because soil moisture did not drop below 10% in any of the fields, pupal mortality was assumed to be the mechanism causing reduced adult emergence in standing water zones.

Currently, *T. myopaeformis* is monitored seasonally by placing sticky stake traps adjacent to sugarbeet fields and the results are used to predict the following year's population (e.g. Boetel et al. 2001). The sticky portion (the garden stake coated with Tanglefoot) of these traps is placed higher on the stake than those used in this study and may, therefore, sample a larger area. Their rate of capture may be influenced by the pattern of adult fly emergence from neighboring fields planted into sugarbeet the previous year. These neighboring fields, planted into sugarbeet the previous year, are likely to be the source of adult *T. myopaeformis* entering current sugarbeet fields. If traps are located next to lower areas in these source fields, they may erroneously report lower populations than are present. Therefore monitoring should be done away from low areas in neighboring fields that held sugarbeet in the previous season.

ACKNOWLEDGEMENTS

This work was supported with funding from the Sugarbeet Research and Education Board of Minnesota and North Dakota. I would like to thank Dr. Larry Smith of the University of Minnesota NWROC and Gary Wagner for providing land and delaying herbicide treatments until data was collected, Matthew Carroll for critical review of the manuscript, and Matt Kent, Heidi Rock, Anne Marie Hanson for assistance with data collection. I would also like to acknowledge and thank Dr. Alan Dexter and two anonymous reviewers for their valuable suggestions.

LITERATURE CITED

Anderson, A.W., Dregseth, R., and R.B. Carlson. 1990. Control of the sugarbeet root maggot in the Red River Valley. Sugarbeet Res. & Extension Rep.. 21: 137-148.

Armstrong, M. 1998. Basic Linear Geostatistics. Springer-Verlag, Berlin.

Bechinski, E.J., McNeal, C.D. and J.J. Gallian.1989. Development of action thresholds for the sugarbeet root maggot (Diptera: Otitidae). J. Econ. Entomol. 82 (2) p. 608-615.

Bechinski, E.J., Everson, D.O., McNeal, C.D. and J.J. Gallian. 1990. Forecasting peak seasonal capture of sugarbeet root maggot (Diptera: Otitidae) with sticky-stake traps in Idaho. J. Econ. Entomol. 83 (5): 2078-2085.

Boetel, M.A., R.J. Dregseth, A.J. Schroeder, and L.J. Smith. 2001. Biology and control of the sugarbeet root maggot in the Red River Valley – 2001. Sugarbeet Res. & Extension Rep.. 32: 232-245.

Campbell, L.G., A.W. Anderson, R. Dregseth, and L.J. Smith. 1998. Association between sugarbeet root yield and sugarbeet root maggot (Diptera: Otitidae) damage. J. Econ. Entomol. 91(2): 522-527.

Cassel, D.K, and D.R. Nielson. !986. Field capacity and available water capacity. IN: Klute, A. (ed). Methods of Soil Analysis. Part 1 – Physical and Mineralogical Methods. 2nd ed. Am. Soc. Agron. Inc & Soil Sci. Am. Inc. Madison, WI. 1188pp.

Clark, I, and W.V. Harper. 2000. Practical Geostatistics 2000. Ecosse N. Am. Columbus, OH. 390 pp.

Isaaks, E.H., and R.M. Srivastava. 1989. An Introduction to Applied Geostatistics. Oxford Univ. Press, New York.

Jensen, R.E. 1998. Climate of North Dakota. National Weather Service. North Dakota State University, Fargo, North Dakota. Jamestown, ND: Northern Prairie Wildlife Research Center Home Page. http://www.npwrc.usgs.gov/resource/othrdata/climate/climate.htm (Version 02APR98).

Krajewski, S.A., and B.L. Gibbs. 2001. Understanding Contouring – A Practical Guide to Spatial Estimation Using a Computer. Gibbs Assoc. Boulder, CO. 92 pp.

Liebhold, A.M., R.E. Rossi, and W.P. Kemp. 1993. Geostatistics and geographic information systems in applied insect ecology. Ann. Rev. Entomol. 38: 303-327.

MacRae, I.V., R. Carlson, A. Anderson, and R. Ellingson. 1999. Improving predictive population models for the sugarbeet root maggot. Sugarbeet Res. & Extension Rep.. V. 29: 229-236.

MacRae, I.V., S.A. Armstrong. 2000. High soil moisture effects on pupation of sugarbeet root maggot, *Tetanops myopaeformis* (Roder), (Diptera: Otitidae). J. Sugar Beet Res. 37(2): 33-40.

McBride, D.K., Dregseth, R. and A.W. Anderson. 1990. Insects affecting sugarbeets in North Dakota. North Dakota State University Bulletin E-695, rev. Fargo, N.D. 7 p.

Miller, P.C., D.K. Poole, and P.M. Miller. 1983. The influence of annual precipitation, topography, and vegetative cover on soil moisture and summer drought in southern California. Oecologia, 56(2/3): 385-391.

Neter, J., W. Wasserman, and M.H. Kutner. (1990). *Applied Linear Statistical Models*. Irwin: Homewood, IL, 3rd edition. 1181 pp.

Prax, A. 1991. Soil moisture content in connection with topography. Dev. Agric. Manage. For. Ecol. V. 15:335-354.

Schwert. D. 2001. Fargo Geology – Geology of the Fargo-Moorhead region. http://www.ndsu.edu/fargo_geology/index.htm Dept. of Geol., NDSU.

Whitfield, G.H. 1984. Temperature threshold and degree-day accumulation required for development of postdiapause sugarbeet root maggots (Diptera:Otitidae). Environ. Entomol. 13 (5): 1431-1435.

Whitfield, G.H. and B. Grace. 1985. Cold hardiness and overwintering survival of the sugarbeet root maggot (Diptera: Otitidae) in Southern Alberta. Ann. Entomol. Soc. Am. 78 (4): 501-505.