GEOGRAPHICAL DISTRIBUTION OF *PEDIOBIUS FOVEOLATUS* IN NEW JERSEY SOYBEAN FIELDS TO CONTROL THE MEXICAN BEAN BEETLE POPULATION

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BIOLOGICAL CONTROL OF THE MEXICAN BEAN BEETLE POPULATION

Geographical Distribution of *Pediobius foveolatus* in New Jersey Soybean Fields to Control the Mexican Bean Beetle Population

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Geographical Distribution of *Pediobius foveolatus* in New Jersey Soybean Fields to Control the Mexican Bean Beetle Population

Abstract

This thesis provides an initial look at potential movement predictions of the *Pediobius foveolatus* for controlling the Mexican bean beetle population. It is commonly known in the entomology world that this wasp is very effective in controlling the population of this soybean pest, but most studies of this insect stopped around 1960. Since then, the rise of geographic information systems has allowed for a renewed interested in this species' movement patterns.

The use of commonly applied geostatistical analysis to create prediction surfaces is examined. Both Kriging and Inverse distance weighted are used to try and predict the percent parasitism levels of the wasp. This experiment shows that common geostatistical methods of inverse distance weighted and Kriging can be used to predict movements, but cannot say which method is better over the other. Further research is needed in this subject.

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ACKNOWLEDGMENTS

I would like to thank the New Jersey Department of Agriculture for all there help and guidance they provided me throughout the study. I would also like to thank my wife, for without her, I would still be procrastinating.

List of Abbreviations

MBB – Mexican bean beetle

IDW – Inverse distance weighted

NJDA – New Jersey Department of Agriculture

RMSE – Root Mean Square Error

MSE - Mean Squared Error

MAE - Mean Absolute Error

CHAPTER 1

INTRODUCTION

It is rare that an organism does not have a natural enemy. Natural enemy populations have a unique ability of being able to interact with their prey or host populations, and regulate them (DeBach 1974). Biological control is a set of methods to control a pest organism by using natural ecological interactions, including predation, parasitism, and competition (Botkin & Keller 2003). It is believed that if biological control is used more extensively, then it will benefit the environment more than pesticides (Purslow 2004).

From an ecological standpoint, biological control is the regulation of natural enemies of another organism's population density (DeBach 1974). The best way to encourage biological control practices is to show economic benefits. In the future there will be more advances in biological control and greater economic benefit. An example of this is in Australia with the attempts to control Noogoora burr. This plant was introduced to the rest of the world from the United States, and it is believed that there is no sterility barrier between species (Van Klinken & Julien 2003) so it spreads rapidly. Starting in 1926, the Noogoora burr was declared as noxious weed, and a comprehensive biological control program was started. About eighty insect species are found in the USA that attacks this burr, but only a few were found in India (Van Klinken & Julien 2003). After laboratory testing, only the seed-feeding fly was considered sufficiently host-specific, but the program was terminated due to World War II. In 1953, the problem was re-examined and this time they tried the pathogenic route to control the burr. Scientists rejected this method, but noted that the rust fungus controlled a strain of the burr in Europe (Van Klinken & Julien 2003). The problem in Australia is the fact that in the region where the Noogoora burr exists, it is a desert-like climate, and the bio-control agents cannot adapt to the heat (Van Klinken & Julien 2003). What Australia needs is a host-specific insect that will be able to inflict a sufficient amount of damage to the current population of the burr in an acid hot climate. Australia has not yet found a proper control agent, but when they do, the benefits will be greater than spraying herbicides because the biological control will be better for the environment, and cheaper in the long run.

The use of biological control agents is better than insecticides. They can reduce the amount of pesticides farmers' use, which in turn saves them money and reduces soil and water pollution. The only way that this research will continue, is either if the government supports funding for scientists, or if large corporations see the potential to gain profit from these techniques.

This is another example of biological control, at a much smaller geographical extent and requires much less resources. The Mexican bean beetle, *Epilachna varivestis,* is a daunting pest that winters over among the hedge rows in New Jersey and emerges around late May to feed on soybeans (Stevens *et al*. 1975). Large populations develop quickly and inflict serious damage on the crop. Two complete generations and one partial generation of the Mexican bean beetle occur in the soybean fields in one growing season. Growers tend to treat with chemical applications that are harmful to the environment and can have long lasting effects (Stevens *et al*. 1975). The Mexican bean beetle suppression program (Robbins *et a*l. 2006), developed by the New Jersey Department of Agriculture (NJDA), is an example of a very successful biological control effort. *Pediobius foveolatus* is a tiny wasp (about 1/9 inch in length) that is a parasitoid of Mexican bean beetle larvae and squash beetle larvae. By analyzing the effectiveness of the Mexican bean beetle parasitoid, *Pediobius foveolatus*, the department can use better strategies in deploying the wasp, resulting in the reduction of costs of field plots, staff needs, and time spent on soybean farms.

Research Objectives

The purpose of this research is to show the spatio-temporal spread pattern of the parasitic wasp, *Pediobius foveolatus,* seeking out Mexican bean beetle larvae.

The Mexican bean beetle is a common pest of snap beans, lima beans, and soybeans in the central and eastern parts of the United States. The parasitic wasp, *Pediobius foveolatus,* is an effective natural bio-control agent used to combat this pest, but the area which 9,000 wasps can cover is not known. The damage from Mexican bean beetle has been controlled under harmful economic levels since the first release of this parasitic wasp in New Jersey (Robbins *et al*. 2006). It is believed that the wasp can travel greater than one mile in a single generation, but the field staffs and entomologists at the New Jersey Department of Agriculture (NJDA) have data showing that the release populations might only be effective in areas less than one mile from the release point (Dorsey 2007). This study will monitor where and when the parasitic wasp infects the bean beetle with parasites and will attempt to better understand the geographical distribution pattern of *Pediobius foveolatus*. By having a better understanding of the geographical distribution of the parasitic wasp after its release, we can successfully foster a better control program.

Study Area

The study area was conducted in and around Assunpink State Park, which is located in Upper Freehold Township, New Jersey, as shown in figure 1. This area is rural region of New Jersey with a vast variety of crops being grown in the region. The farmland used in this study is owned by a private farmer, so every guarantee had to be made in order to ensure that his crops would not be negatively affected.

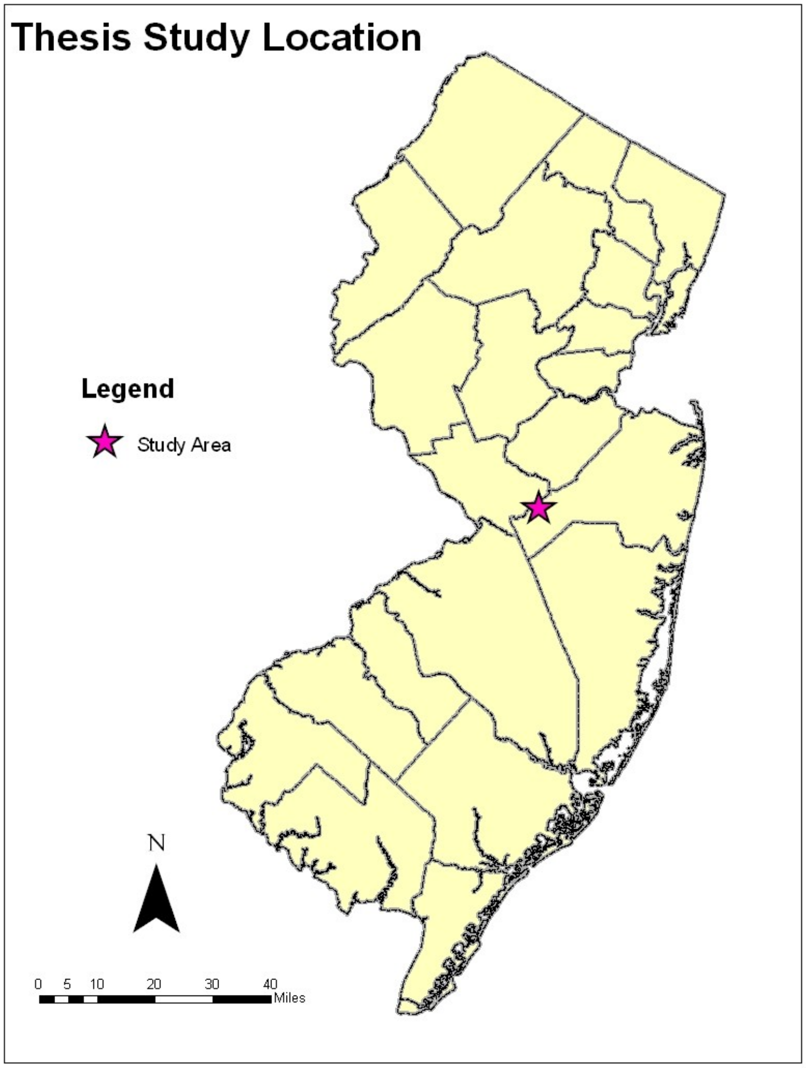


Figure 1: The Study Area

CHAPTER 2

LITERATURE REVIEW

Biological Control Overview

In general, the science focuses on three major groups of bio-control organisms: predatory, parasitic, and pathogenic (Hunter 1971). The first group of natural biological controls is predatory species, which covers a wide variety of taxonomical groups. One problem in using predatory species for pest control is that they lack the highly specialized adaptation seen in parasitic species (DeBach 1974). For example, only in certain stages of life, will the predatory insect be able to feed on the pest. The predators in general have stronger and sharper mouthparts than the plant-eating insects (Swan 1964). The praying mantis, *Mantis religiosa*, is an example of a predatory insect.

The *Coleopteran* is a group of beetles, which tend to be predaceous in nature. Principal *Coleopteran* families include *Coccinellidae* (ladybird beetles), *Silphidae* (carrion beetles), *Staphylinidae* (rove beetles), *Histeridae* (clown beetles), *Lampyridae* (fireflies), *Cleridae* (checkered beetles), *Meloidae* (blister beetles), *Carabida*e (ground beetles), and *Gyrinidae* (whirligig beetles). The *Coccinellidae* and the *Carabid* are the most important *Coleopteras* in biological control (DeBach 1974). The *Coccinellidae* (ladybird beetle) is very important, because almost every species in the family is predaceous. They feed on everything from aphids, mealy bugs, whiteflies, and scale insects to the eggs of other insects. It has been noted that *Coccinellidaes* (ladybird beetles) never seem to be satisfied; they tend to eat constantly (Swan 1964).

The second groups of natural biological controls are parasitic insects, which include two major orders, *Hymenoptera* (bees, wasps, ants) and *Diptera* (flies) (DeBach 1974). Some species within these groups lay their eggs on or inside the host and the larva devour it from the inside out (Hunter 1971). The important thing about the parasitoids is that they only eat non-essential organs so the host will not die until the parasites larvae are ready to emerge from the host (Swan 1964). In adult form, most parasites feed on pollen, which is quite different from the larvae stage.

Parasites are considered to be more advanced than their predator counterparts because they develop faster (Swan 1964). Though parasites (e.g., *Pediobius foveolatus*) mainly feed on larvae (Mayer 2002), they have been known to feed upon eggs, pupae, and rarely adults (Swan 1964). Females of most parasitic wasps lay their eggs inside the host using an ovipositor. This organ is placed into the host, and eggs are deposited inside of them (Swan 1964). Once inside, the parasite eggs hatch into larvae that slowly feed, finally kill the host when the parasite larvae are ready to hatch (Hunter 1971).

One important factor in selecting a parasite is to look at the timing of when the insect will or is able to lay its eggs inside a host (Browne & Withers 2002), thus the threshold for acceptance of a host decreases as time goes on. In the case of *Pediobius foveolatus*, this parasitic wasp prefers to lay its eggs during the third and fourth instars, or life stage (Mayer 2002). When the parasites' hosts' life cycles do not line up, and there is no other host the parasite can use, it almost makes it impossible to set up a permanent presence of the parasite (Swan 1964).

The final major category of biological control is pathological. The most common diseases in insects are caused by bacteria, fungi, viruses, protozoa, and nematodes (DeBach

1974). Only a few pathogens are known compared to the number of parasitic and predaceous insect species that are known. *Bacillus thuringiensis* (a Gram-positive, soil dwelling bacterium, under the trade names such as Dipel and Thuricide), and the fungi, such as *Entomophthora sphaerosperma*, *Beauveria bassiana*, and *Metarrhizum anisopliae*, attack a large range of host species. These pathogens have spectacular effects when it comes to natural control, and are most effective during large insect outbreaks (DeBach 1974). The major problem with pathogenic biological control is that insects develop resistances to the diseases. This forces scientists to constantly develop new strains of the pathogens.

Pest Management

When it comes to pest management programs, the two most essential components are host (e.g. soybean) consumption by the pest (e.g., Mexican bean beetle) and the development rate of the pest (McAvoy & Smith 1979). Economic injury levels can be determined by using the feeding rates and development rates of the pests on soybeans. To completely understand the potential of damage caused by the pest, it is essential to understand the feeding rates and developmental rates of the insect in laboratory conditions.

McAvoy and Smith (1979) conducted a laboratorial experiment to observe the life cycle of Mexican bean beetle, *Epilachna varivestis*. Larvae and adults of Mexican bean beetle were raised between 20º ± 2ºC and 26º ± 2ºC. These temperatures represent the average minimum and average max temperature for the months from June to September in the Northeast (Kauffman *et al*. 1985). Eggs were collected from a field in Suffolk, Virginia, and each set of egg masses was placed in the conditions mentioned above. After hatching, the larvae were placed on the York soybeans. The leaf surface area consumed was measured by using a grid sheet, 30 by 30 cm sheet with each grid cell equal to .0161 cm^2. Each leaflet was placed over the grid, and each grid that corresponded to feeding damage was counted and multiplied by .0161. This gave the leaflet area consumed relative to the total leaflet area. The dry weight was later found from multiplying the surface area consumed by the unconsumed leaflet dry weight ($g/1.26\ cm^2$), which is calculated from unconsumed leaves. This gave the dry weight consumed by the larvae each day.

Total bean beetle larval development time was between 23 to 31 days and varied on temperature (McAvoy & Smith 1979). Figure 2 shows the life cycle of Mexican bean beetle. The 4th instar larvae stage consumed the most foliage, between 76% - 68% of the total food consumed. Total larvae consumption was between 88 to 97 mg varying on temperature. Adult consumption was between 2.7 - 3.8 cm^2/day.

Figure 2: Life Cycle of Mexican Bean Beetle (source: http://www.purdue.edu)

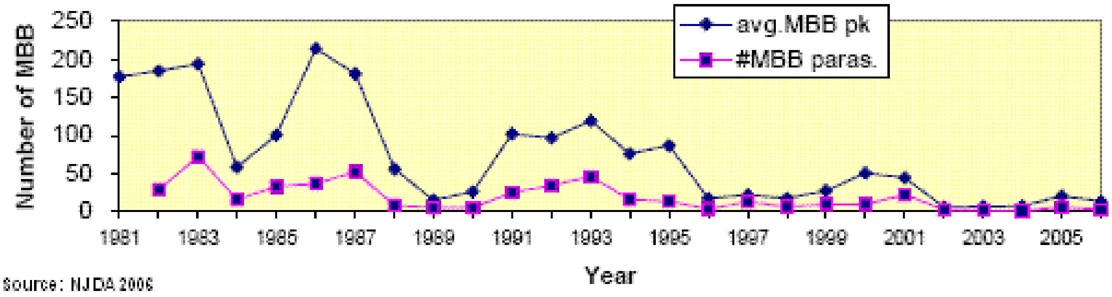
The parasitic wasp, *Pediobius foveolatus* is found to parasitize the larvae of the Mexican bean beetle (Lall 1962). Studies of this insect were conducted in the early 1960s to determine the effectiveness of the parasite, and to examine its biology. The adult *Pediobius foveolatus* mate as soon as they emerge from the host body. Mating lasts between 15 to 20 seconds (Lall 1962). The fertilized female parasite then seeks out a host and deposits the eggs inside. The life cycle of the parasite can vary from 10 - 30 days depending on the weather conditions (New Jersey Department of Agriculture 1980), with the wasp going through five stages of development from egg to adult (Lall 1962).

Tests were run on the percent parasitism of the wasp from October to March in India. The 3rd and 4th instar larvae of the Mexican bean beetle were released in cages and examined in week intervals. The highest percentage of parasitism was found in October, 37.8 % (Lall 1962). Each parasitized Mexican bean beetle (mummy) releases 4-27 new wasps with a male to female ratio of 1:2.

Wide area suppression studies began in Maryland in 1972 – 1974 (Stevens *et al.* 1975). These studies were based on research performed by Lall in 1962. Lall (1962) showed that the average life cycle of the parasite, *Pediobius foveolatus*, is between 10 - 30 days depending on environmental conditions. The *Pediobius foveolatus* were grown in Maryland using specimen from India. The results of these field studies showed that program was most successful in areas where a trap crop was planted to attract pest. As a result, the later programs have adopted the trap crop method to draw in the over-wintering populations (Mayer 2002). Figure 3 shows the effectiveness of the parasite on the Mexican bean beetle population in New Jersey from 1981 to 2006.

Parasitism data is dependent on the ability of the NJDA personnel finding parasitized mummies. In an uncontrolled open environment, if parasitized beetles are on bean leaves that have abscised and fallen to the ground, it becomes very difficult to find them. As a result, parasitism data is underrepresented and the parasitism is probably greater than what is shown in the figure 3 (Robbins *et al*. 2006). By creating the project in a controlled caged environment, this study expects to show that the percentage of parasitism or the effectiveness of the wasp to find and kill the prey is very high at closer distances versus greater distances from the wasp release point.

Table 1 shows a summary of various counties that participated in the Mexican bean beetle suppression program. Six out of a total twenty-one counties participated in the program. In Mercer County, where this experiment took place, one release was made, and the Department of Agriculture estimates that the *Pediobius foveolatus* had a 50% parasitism rate of Mexican bean beetle.



Source: NJDA 2006

Figure 3: Mexican Bean Beetle Population and Parasitism 1981 - 2006
(source: New Jersey Department of Agriculture)

Table 1: Nurse Plot Summary by County 2006
(source: New Jersey Department of Agriculture)

County	Total No. of Plots	Total No. of Parasites Released	Average No. of *P. foveolatus* Released per Plot	No. of Plots with *P. foveolatus* Releases	Percent of Plots with *P. foveolatus* Releases	Average Percent Parasitism	No. of Plots with Egg Releases Only	No. of Plots with Trigger Releases
Burlington	4	10000	2500	2	50	5.7	0	2
Cumberland	17	68000	4000	11	64.7	11.4	3	8
Gloucester	7	20000	2857	5	71.4	10.9	3	2
Mercer	2	6000	3000	1	50	5	0	1
Monmouth	8	24000	3000	4	50	12.6	1	3
Salem	17	46000	2705	10	58.8	8.9	5	5
Total	**55**	**174000**		**33**			**12**	**21**
Avg Levels			**3010**		**57.5**	**11**		

<u>Interpolation Methods</u>

Interpolation is the procedure of estimating unknown values from a set of known values. The objective of this study is to estimate the spread pattern of parasitic wasp seeking out Mexican bean beetle larvae based on the sampled cages, which means the spatial interpolation, is the fundamental geographic analysis technique in this study. The assumption of interpolation is based on Tobler's first law of Geography, "everything is related to everything else, but the near things are more related than distance things." (Tobler 1979) In other words, things are close together tend to have similar characteristics. Inverse Distance Weighted (IDW) and kriging are the common spatial interpolation procedures in commercial GIS.

IDW estimates the unknown values by averaging the values of sample data points in the vicinity. The closer the sampled point (known value) to the estimated point (unknown value), the more influence it has in the process. It assumes that the variable being estimated decreases in influence with distance from its sampled location. IDW control the significance of known values upon their distance from the estimated point. By defining a higher power, more emphasis is placed on the nearest points, and the resulting surface will have more detail (less smooth). Specifying a lower power value will give more influence to the points that are further away, resulting in a smoother surface. The characteristics of the interpolated surface are also controlled by the number of sampled points that can be used for calculating the unknown value. The number of involved sampled points can be defined by specifying the search radius from the estimated point (fixed search radius as used in ArcGIS by ESRI, Environmental Systems Research Institute) or by specifying the minimum number of required sampled points (variable search radius as used in ArcGIS by ESRI).

Several factors influence the precision of IDW. They range from the closeness of the sample to the radius picked by the interpreter. Distance between points for IDW plays a major role in predicting the values (Mitchell 2005) The nature of weighted distance means that the farther away something is, the less influence it has on that object. Equation (1) shows the general form of the IDW weighted equation is entirely depended on the distance as

$$W_{ij} = 1 / d_{ij}^{p} \tag{1}$$

where d_{ij} is the distance and p is the power variable. The inverse distance shows how distance modifications to the IDW equation can greatly affect the predicted outcome.

Inverse Distance Weighting (IDW) is a quick deterministic interpolator with very few decisions to make regarding the model parameters (Mitchell 2005). This method is considered a good way to take a first look at an interpolated surface, however, there is no assessment of prediction errors, and IDW can produce isolated predictions around data locations. Another benefit of IDW is that there are no assumptions required of the data

(Mitchell 2005). Given that there are no assumptions on the data, allows for the interpolation of the percent parasitism without worrying about equal distribution around the surface.

Kriging is a geostatistical procedure that creates an estimate of the surface from a set of scatter points with certain values (Oliver 1990). Kriging is based on the regionalized variable theory that assumes that the spatial variation in the phenomenon represented by the z-values is statistically homogeneous throughout the surface. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface (Oliver 1990). In general, kriging is a multi-step process that includes: exploratory statistical analysis, variogram modeling, creature a surface, and exploring a variance surface. Kriging is most appropriate when you know there is a spatially correlated distance or some forms of directional bias (Oliver 1990).

Kriging is considered a moderately quick interpolator, which can be exact or smooth depending on the measurement error model (Mitchell 2005). It is very flexible and allows you to investigate graphs of spatial autocorrelation. Kriging uses statistical models that allow a variety of map outputs including predictions, prediction standard errors, probability, etc. The flexibility of kriging can require a lot of decision-making. Kriging assumes the data come from a stationary stochastic process, and the kriging method chosen assumes that there is an unknown constant trend (Mitchell 2005).

Kriging is similar to IDW by way of it being able to weight the surrounding measured to derive a prediction for an unmeasured location. Equation (2) is the general formula for both interpolators formed as a weighted sum of the data:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \tag{2}$$

where $Z(s_i)$ is the measured value at the i^{th} location, λi is an unknown weight for the measured value at the i^{th} location, s_0 is the prediction location, and N is the number of measured values (Schloeder *et al*. 2001). Another important property of both IDW and kriging is that the estimated value will not exceed the maximum or the minimum values of the sampled points. Since this study utilizes percent parasitism as its primary variable, this means that the values will not exceed 1 or go below 0.

CHAPTER 3

METHODOLOGY

The primary objective was to observe the spread pattern of the parasitic wasp, *Pediobius foveolatus,* seeking out Mexican bean beetle larvae in the real world not just in laboratorial environment. However, due to the difficulties to collect data and obtain permission from the farm owners, some types of controlled mechanism must take place in the field study.

Figure 4 illustrates the overall research framework of this study. The first step was to locate the field study area, which contained larger areas of farm fields to provide food source for Mexican bean beetle. The parasitic wasps, *Pediobius foveolatus,* needed to be released from the center of the field study area to insure there is no bias of movement direction. The beetles were caged in order to provide a controlled method of tracking the live pest, and because the beetles are released on a production farm, where the owner won't allow the loose beetles to damage the crop. These cages were placed in the farms in the study area with the owner's permission. A daily field count survey of each cage provided the percentage rate of parasitized beetles in sample point. A final spatial analysis created an estimated surface of wasp spread pattern for each day.

Figure 4: Research Framework

Location of Study Area and *Pediobius Foveolatus* Release

The field study took place in Upper Freehold Township around Assunpink State Park in central New Jersey, with a total of 9 fields within a one mile radius. Figure 5 shows the soybean fields the farm owners planted in early May 2007. The size and location of the fields vary based on the availability of open land in this region of New Jersey. The release point was calculated based on the center of all fields using the mean center by the ESRI ArcGIS mean center tool. This tool utilized the Euclidean distance to identify the geographic center from a set of features. Table 2 listed the coordinates in New Jersey State Plane projection for the centroid of each field and the release point.

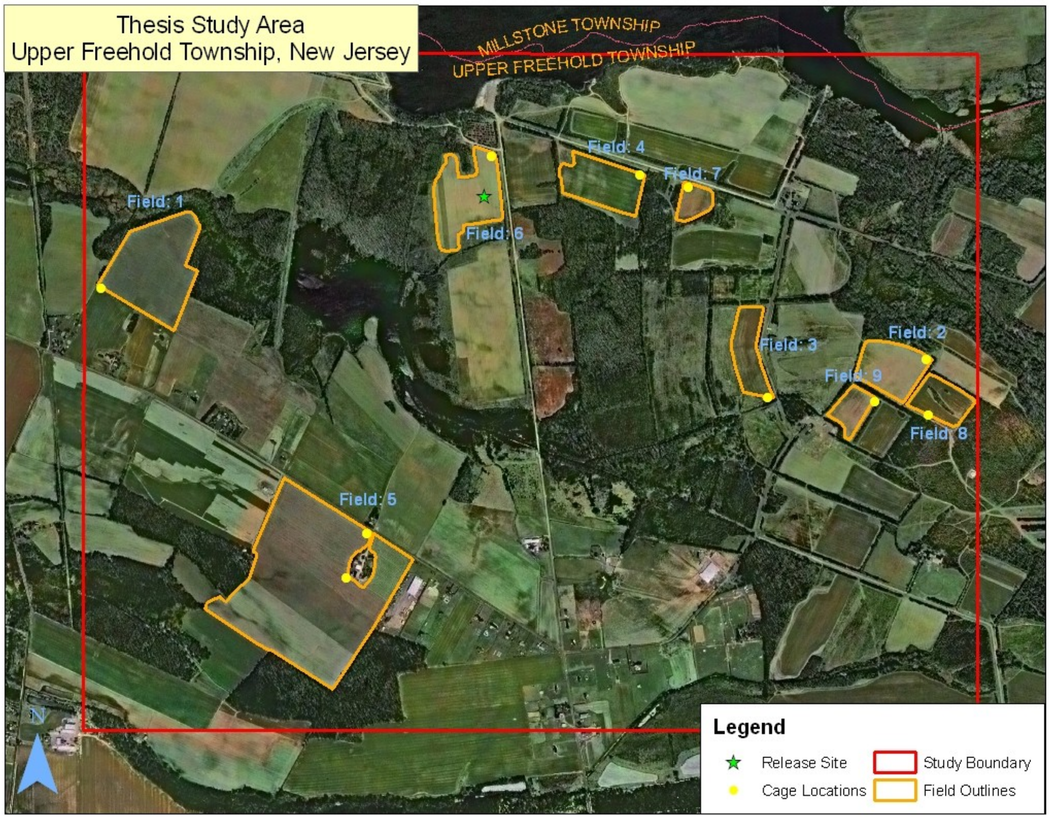


Figure 5: Field survey area

Table 2: Centroid of Fields and Release Location Coordinates in State Plane

Description	X – Coordinate	Y - Coordinate
Field 1	483256.69	501214.29
Field 2	492483.07	499968.42
Field 3	490699.05	500166.31
Field 4	488859.84	502272.06
Field 5	485217.81	497232.25
Field 6	487153.44	502096.05
Field 7	490003.26	502042.94
Field 8	493111.88	499550.09
Field 9	491986.30	499440.31
Release Site	487386.07	502113.54

Release was made on the first day of the field study. Ten thousand parasitic wasps were released from the central release point. The wasps came packaged in 5 containers containing 2,000 wasps per container. The population was kept at a cool temperature in order to easily release the insect into the wild. The population was placed on the ground in the sun in order to fully revive them quickly.

Cage Placement

The cages used to house the Mexican bean beetle were 2 by 2 by 1 foot in size. These cages consisted of a wooden cube shaped box, covered with a screen mesh to prevent the bean beetle larvae from escaping, but allowing the parasite to easily enter to lay their eggs (see figure 6). This concept was developed with the help of the New Jersey Department of Agriculture.

The target was to house 45 larvae in these cages, based on the recommendation of Tom Dorsey, the State Entomologist (2007). This recommendation led us to believe that based on the feasibility of transporting the cage and the feeding rate of the larvae, a small cage size with a few larvae would suffice. The dimensions of the cage allowed for the cage to be easily placed over the top of soybean plants and it could be easily moved from one section to another if larvae populations digest the plants entirely.

The original design of cage placements was to have cages distributed evenly distributed within the fields. However, the farm owners only allowed one cage to be placed at the edge of each farm. Therefore, each field had one cage placed on them except for field 5 (see figure 5), which had the owner's permission to place two cages in it.

There were totally 10 cages placed in the field study area. Cage placement was based on three criteria.

1) By what crop was being grown in each field. In this region, corn and soybeans are the two primary crops. Cages were placed in soybean fields.
2) Where the farmers allowed the cages to be placed. The farmers in this region only allow 1 - 2 cages per field, and it must be on the perimeter of the fields because of the herbicide spray schedule, and the inability to see the cages while on the tractor.
3) The distance from the central release point. From distances of 0 - 3000 feet there were 5 cages and distances > 3000 feet there were 5 cages.

These cages were placed at the two distance bands based on the availability of soybean fields in this region of New Jersey. Figure 7 illustrated the radius distance of 3000 feet from the wasp release point to the cages locations.

Figure 6: Bean Beetle Cage

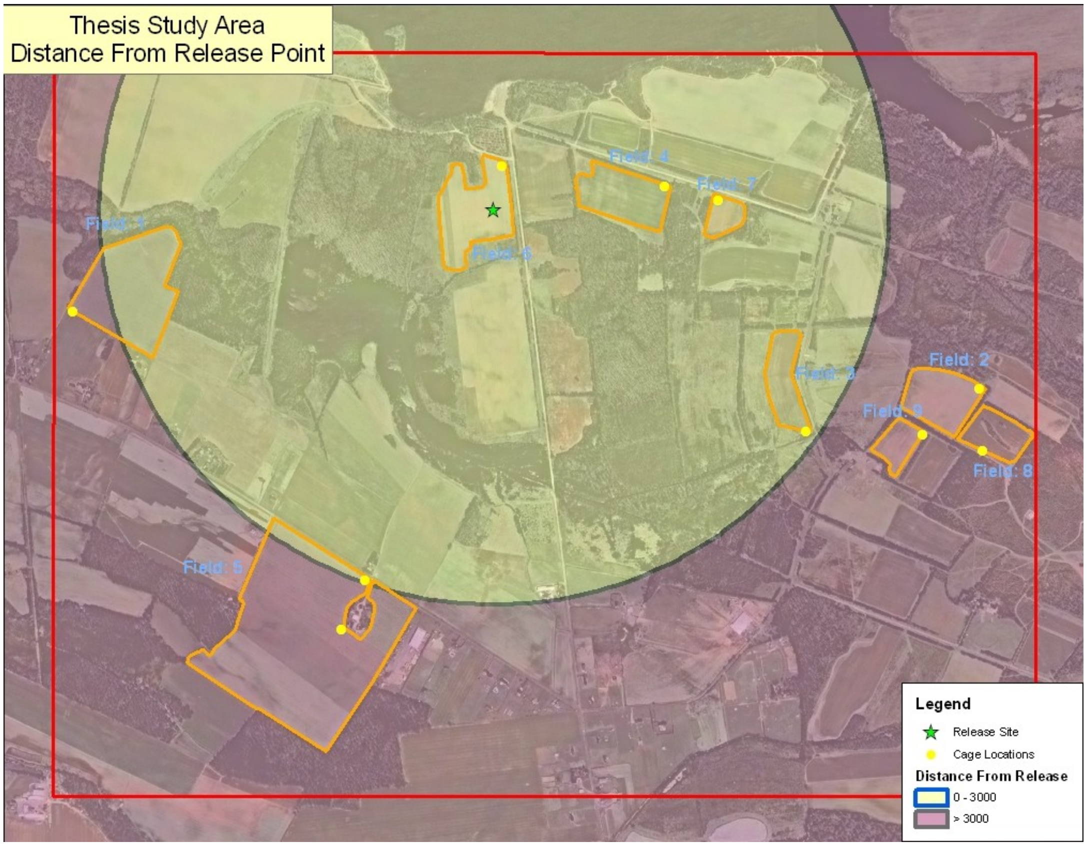


Figure 7: Distance from Release Point to the Cages in Feet

Field Collection

When performing field collection using GPS, two parameters were established to ensure that all data was obtained with ± 2 meter accuracy. By establishing a minimum number of satellites (five) and differential correcting the data files upon return, there was an assurance that field data was as accurate as possible, for the equipment used. Another parameter to enable averaging of point data, using 20 points that was averaged for each location before the latitude and longitude is recorded. These parameters reduced errors and ensured a higher standard of accuracy.

All 10 cages were examined daily, with each cage being lifted off the designated survey area, and the population counted. The number of dead, un-parasitized, and parasitized Mexican bean beetles was recorded. Since this study was performed on newly planted soybeans, and due to the fact that the bean beetle population eats large quantity of food, there was a need to constantly move the cages, so the population did not migrate out of the cages to obtain other food sources. Another reason to check daily was to record the natural death of the bean beetle and to determine when the parasitic mummies appear. It helped to determine how effectively the population was parasitized or if the population was lost due to environmental constraints.

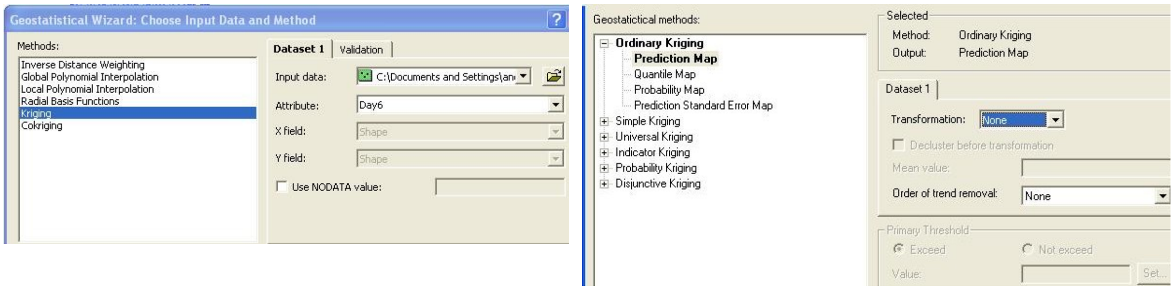
Geographical Analysis

ESRI ArcGIS Geostatistical Analyst Extension was used to analyze the field data. The objective of this study was to show a simulation of wasp distribution patterns to help derive a guideline for future release procedures of the parasitic wasp. To create the wasp movement simulation two methods of interpolation were compared. Inverse Distance

Weighted (IDW) and Ordinary Kriging (with Gaussian distribution assumption) techniques were used to interpolate the percentage parasitism within the study area. The goal was to show how the wasps seek out and parasitize Mexican bean beetles larvae over a specific distance and time.

The Geostatistical Analyst wizard provided a friendly interface for both IDW and kriging interpolation procedures. Figure 8 illustrated the steps through the kriging interpolation process. After opening the extension, the wizard asked for a dataset (figure 8a). Next, select a statistical method (figure 8b). The Geostatistical Analyst provided multiple forms of each spatial interpolation. When the users selected kriging interpolation method, the wizard allowed for examination of the semivariogram surface, and allowed for the changing of key parameters such as: lag size, search direction, and type of method (figure 8c). Searching neighborhoods was the next step. Figure 8d allowed for the user to select the desired number of points and to declare the least number of points to include in the statistical calculation. Figure 9 showed the examination of the error, export the cross validation, and created the prediction surface.

This study utilized the fixed point method (variable search radius) for defining the search neighborhood, values of 4, 5, and 6 points for IDW and default, 7, 8 and 9 for Kriging. Kriging required a larger minimum amount of points to work in ArcGIS. The output cell size was four meters because that was the highest positional accuracy that the GPS unit could obtain without differential correction.



Input data: C:\Documents and Settings\an

Attribute: Day6

X field: Shape

Y field: Shape

☐ Use NODATA value:

Selected

Method: Ordinary Kriging

Output: Prediction Map

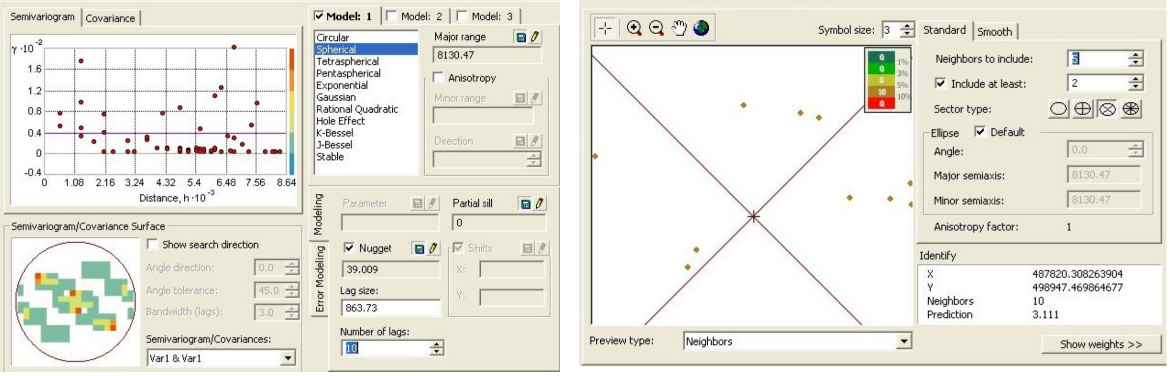
Transformation: None

☐ Decluster before transformation

Mean value:

Order of trend removal: None

(a): Choose Input Data and Method (b): Select Geostatistical Method



☑ Model: 1 ☐ Model: 2 ☐ Model: 3

Major range: 8130.47

☐ Anisotropy

Partial sill: 0

☑ Nugget: 39.009

Lag size: 863.73

Number of lags: 10

☐ Show search direction

Angle direction: 0.0

Angle tolerance: 45.0

Bandwidth (lags): 3.0

Semivariogram/Covariances: Var1 & Var1

Symbol size: 3

Neighbors to include: 5

☑ Include at least: 2

Sector type:

☑ Default

Angle: 0.0

Major semiaxis: 8130.47

Minor semiaxis: 8130.47

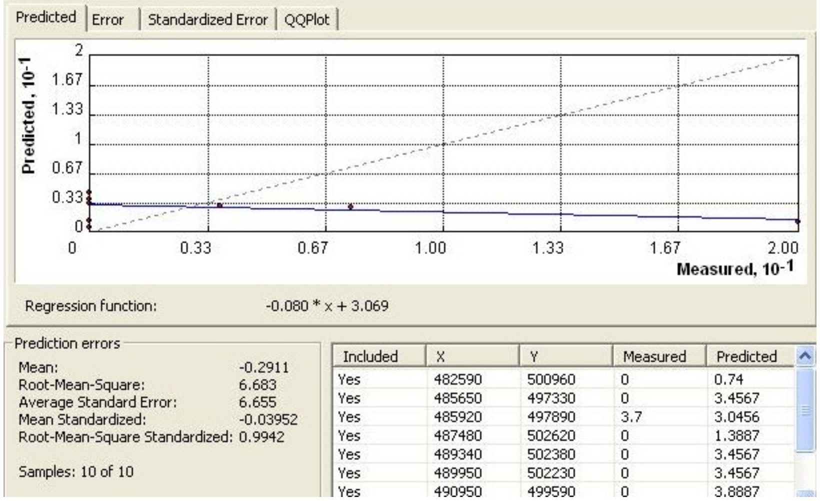
Anisotropy factor: 1

X	487820.308263904
Y	498947.469864677
Neighbors	10
Prediction	3.111

Preview type: Neighbors

(c): Semiveriogram Examination (d): Select Number of Points

Figure 8: The Interpolation Process in ArcGIS



Regression function: -0.080 * x + 3.069

Prediction errors

Mean: -0.2911

Root-Mean-Square: 6.683

Average Standard Error: 6.655

Mean Standardized: -0.03952

Root-Mean-Square Standardized: 0.9942

Samples: 10 of 10

Included	X	Y	Measured	Predicted
Yes	482590	500960	0	0.74
Yes	485650	497330	0	3.4567
Yes	485920	497890	3.7	3.0456
Yes	487480	502620	0	1.3887
Yes	489340	502380	0	3.4567
Yes	489950	502230	0	3.4567
Yes	490950	499590	0	3.8887

Figure 9: The Interface of Prediction Errors

Mean Squared Error (MSE) and Mean Absolute Error (MAE) measures were used to compare different interpolated surface. MAE was calculated by

$$\text{MAE} = \frac{1}{N}\sum_{i=1}^{N} | f_i - y_i | \qquad (3)$$

where f_i is the prediction and y_i is the true value. MSE was calculated by

$$\text{MSE} = \frac{1}{N}\sum_{i=1}^{N} (F_i - A_i)^2 \qquad (4)$$

where F_i is the predicted value, A_i is the target measurement, and N is the number of data.

MSE is the measure of the sum of the squared residuals, and MAE is the measure of the sum of the residuals (Schloeder *et al*. 2001). The goal was to have a low MSE and MAE. The MAE and the MSE can be used together to examine the variation in the errors in a set of prediction. The MSE should always be larger or equal to the MAE. The greater difference between the two types of error, the greater the variance in the individual errors in the sample.

CHAPTER 4

ANALYSIS RESULTS

Description of Data

The dataset was collected in Upper Freehold Township around Assunpink State Park in central New Jersey over 20 days. The cages were marked using a Trimble Geo XM GPS receiver. Post processing of field data (post-time differential correction) was used on all dataset to obtain positional accuracy between 2 - 4 meters. A total of 10 cages were monitored during this time frame in various locations over a 1 by 1 mile study area (figure 5). Figure 10 was the field picture that shows the cages in the soybean fields.

Weather conditions from the month of April 2007 caused the normal planting time for soybeans to be delayed. Heavy rains and colder weathers caused many of the farmers to either plant late or not plant their fields at all. In Upper Freehold Township, this was no exception. The soybean fields were planted in late April to early May. This

Figure 10: Cage in the Field

late planting caused a lack of food source for the bean beetle larvae, adults, and eggs to be eventful. Therefore, it triggers a negative impact on all cage survey results. Another hindrance on the results is the interference of the natural wildlife. The wildlife in this area, such as raccoons and skunks, caused a constant problem because they would break into the cages. It resulted in the need to constantly repair or replace materials in the cages.

Prediction Procedures

Table 3 showed the complete survey data collected in this study. 10 cages were surveyed during the study, and 2 out of the 10 cages had unexpected results. Cages 8 and 9 have abnormal percent parasitism rates. Cage 9 had no parasitism due to animal interference. The cage had the screens broken and the hosts escaped. To deal with this issue, a common pesticide was used to eliminate any remaining hosts. Cage 8 had unusually high percent parasitism rates due to the natural deaths occurring due to lack of vegetation in this area. Low heights of the soybean plants could not sufficiently protect the bean beetle larvae from the rain and other elements.

Only 10 cage sites were used in this study, this was due to environmental factors, and because this was the minimum amount of sites to have to perform IDW and Kriging (Mitchell 2005). 10 cages were supposed to be the base amount of points for each day in the study, with random survey sites adding additional parasitism information. The lack of additional survey points was caused by greater than normal rainfall, preventing the farmers from planting the field at the normal time. This late planting produced a lack of food and shelter for the bean beetle larvae, adults, and egg laying sites. The result caused

Table 3: The Complete Survey Data in Percentage

Trap ID	1	2	3	4	5	6	7	8	9	10
6/12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6/13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6/14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6/15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6/16	0.00	0.00	0.00	0.00	3.33	10.00	10.00	0.00	0.00	0.00
6/17	0.00	3.70	0.00	7.41	0.00	20.00	0.00	0.00	0.00	0.00
6/18	0.00	4.55	10.00	9.09	0.00	28.57	0.00	0.00	0.00	13.64
6/19	0.00	4.55	11.76	9.09	0.00	28.57	0.00	0.00	0.00	25.53
6/20	10.00	5.00	11.76	13.33	0.00	28.57	25.00	100.00	0.00	23.53
6/21	10.00	5.00	13.30	20.00	16.67	40.00	25.00	100.00	0.00	31.25
6/22	12.00	5.00	13.30	20.00	16.67	40.00	25.00	100.00	0.00	43.75
6/23	12.00	6.67	13.30	20.00	16.67	40.00	50.00	100.00	0.00	43.75
6/24	12.00	6.67	13.33	20.00	16.67	40.00	50.00	100.00	0.00	43.75
6/25	12.00	6.67	13.33	20.00	16.67	40.00	50.00	100.00	0.00	70.00
6/26	15.00	13.33	42.86	25.00	33.33	40.00	50.00	100.00	0.00	70.00
6/27	15.00	13.33	42.86	25.00	33.33	40.00	50.00	100.00	0.00	70.00
6/28	15.00	13.33	42.86	25.00	33.33	40.00	50.00	100.00	0.00	70.00
6/29	15.00	13.33	42.86	25.00	33.33	40.00	50.00	100.00	0.00	70.00
6/30	15.00	13.33	42.86	25.00	33.33	40.00	50.00	100.00	0.00	70.00
7/01	15.00	13.33	42.86	25.00	33.33	40.00	50.00	100.00	0.00	70.00

the native population not emerging from these overwintering sites and producing no viable extra survey locations. If this study went beyond a proof of concept, then 10 points would not suffice, but since the study meets the minimum criteria for IDW and Kriging, it can still be held as a valid proof of concept.

The data were examined by both Inverse Distance Weighted and Ordinary Kriging (with Gaussian distribution assumption) utilizing ArcGIS Geostatistical Analyst toolset. The results were investigated numerically to see which results produced the best results.

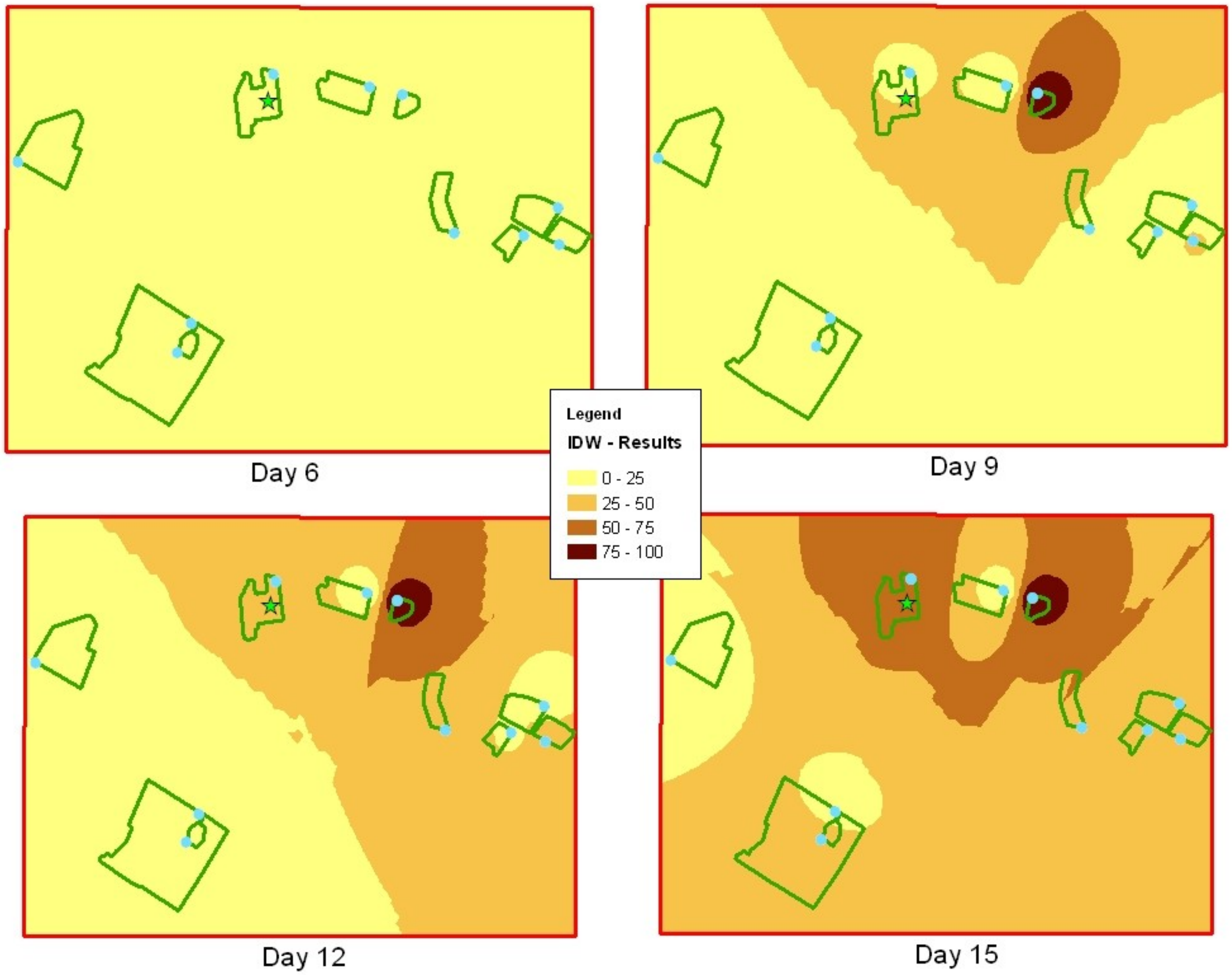
The variable examined in this study is the percentage of parasitism. The sampled value of the percent parasitism is calculated by taking the infested population divided by the total living population (see table 4). Distance is the controlled variable used with the geostatistical analysis. Total population will be varied due to natural deaths caused by environmental factors. Both weather and size of the soybean plants played a major role in the survival of the host insect, the Mexican bean beetle. During the study period, wetter than normal conditions prevented farmers from planting soybeans at their regular time, thus adversely affecting the caged population's food source. This caused many of the introduced population to die, due to lack of protection, and prevented the natural population from emerging during this study. The lack of natural population greatly reduced the number of sample points available for this study to 10. If natural population was taken into consideration, the sample points per day would have been greater than 10 and could have helped in reducing error in all models.

For this study, the exponent parameter *p* of inverse distance weighted interpolation was assumed to be 1 because during evaluation, p's of 1, 2, 3 are investigated with no noticeable change based on visual examination. To get a base comparison, the default method was used which examines all 10 neighbors and a power value of 1. The base comparison of Kriging model uses a default value of lag 12.

Table 4: The Field Data Used for Interpolation

Cage #	Day 6	Day 9	Day 12	Day 15
1	0%	10%	12%	15%
2	3.7%	5%	6.67%	13.33%
3	0%	11.76%	13.3%	42.86%
4	7.41%	13.33%	20%	25%
5	0%	0%	16.67%	33.33%
6	20%	28.57%	40%	40%
7	0%	25%	50%	50%
8	0%	100%	100%	100%
9	0%	0%	0%	0%
10	0%	23.53%	43.75%	70%

The comparisons of interpolation results are day 6, 9, 12, 15 of survey. All cages are included in the study, but it should be noted that cage 9 never had any parasitism during the study period. These days are picked out because they show the greatest overall change in percent parasitism from one day to the next. By day 15, the survey percent parasitism reaches peak percentages for the whole study. Figures 11 – 18 illustrate the simulated of estimated percentage parasitism spreading through time using different interpolation procedure. Figures 11 – 14 show the IDW results, as points are added to each successive model; there is a clear trend that shows how individual hot spots have less influence on the overall results. An example of this is shown by examining Day 9 of figures 11 – 14. Figure 11 shows a hot spot of parasitism in the upper right hand side of Day 9, but as more points are added to the model, the predicted values for Day 9 become smoother and high percent parasitism values have less influence on the overall model. For Day 12, the opposite appears to be happening, as more neighbors or points are considered in the predictive process, the greater influence higher values have on the predicted values. For the IDW model with 4, 5, and 6 points there is a clear break in predicted values shown on Day 12, but when examining the 10 point model, the values predicted seem to be more uniform across the whole study area, not producing a clear cut boundary. Day 15 for the IDW produces some of the most drastic visual difference between all the models. The actual values obtained from the field vary greatly, which can mean that the more neighbors included, the less influence large variations will have on the predicted values. IDW including 4 points shows specific 2 clear regions of hot spots, but as the model includes more neighbors in the IDW prediction process, the hot spot areas shrink and are ultimately eliminated with the inclusion of all 10 points.



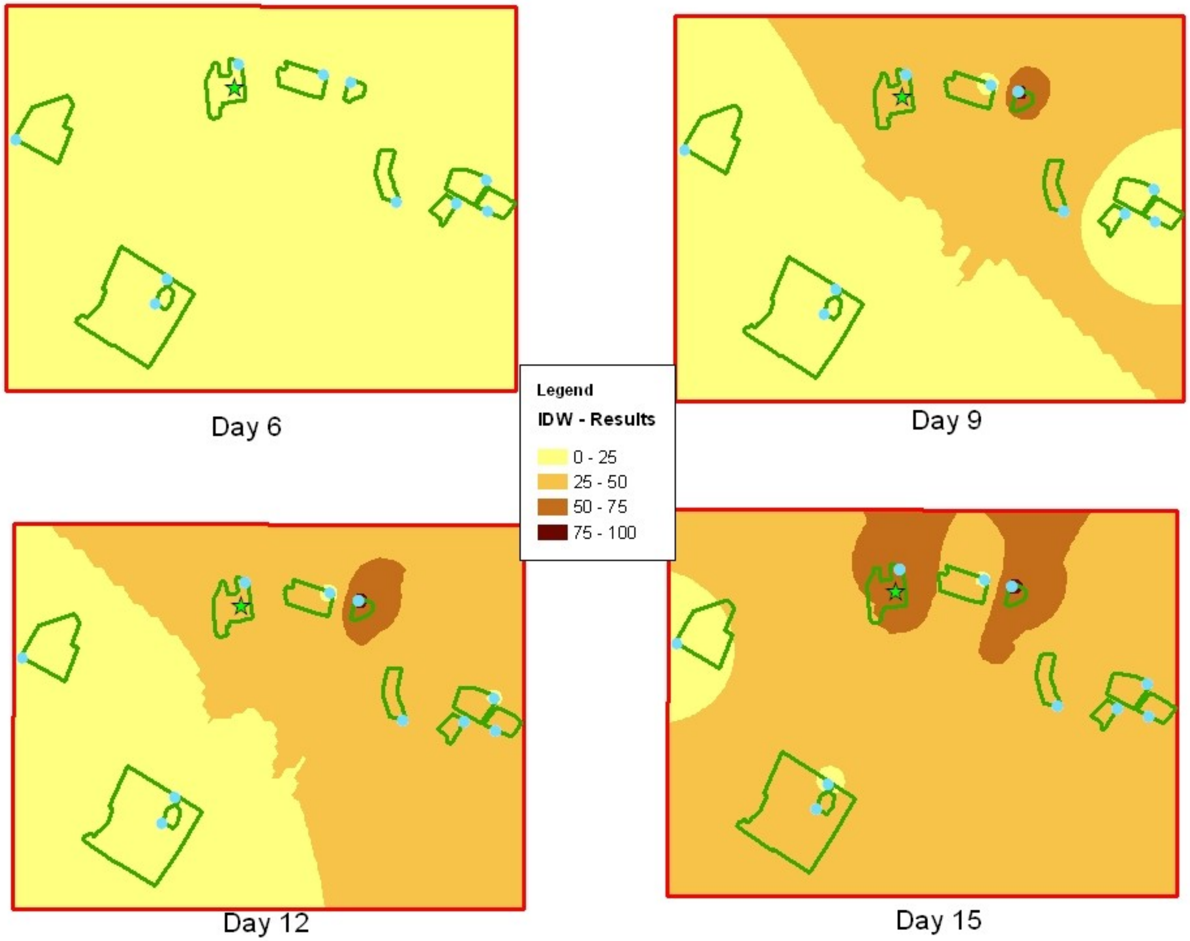
Day 6

Day 9

Day 12

Day 15

Figure 11: IDW – Four Points search Radius with power of 1



Day 6

Day 9

Day 12

Day 15

Figure 12: IDW – Five Points search Radius with power of 1

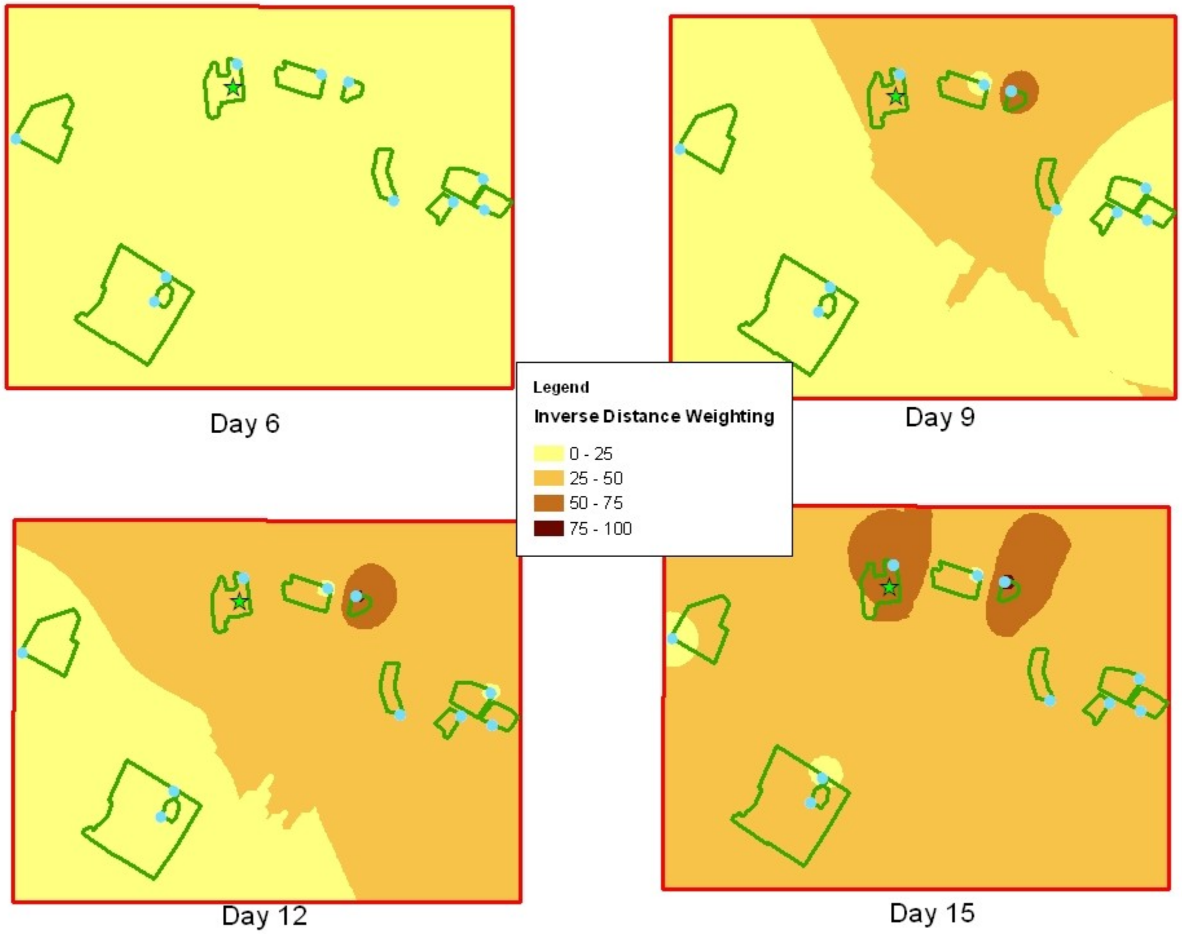
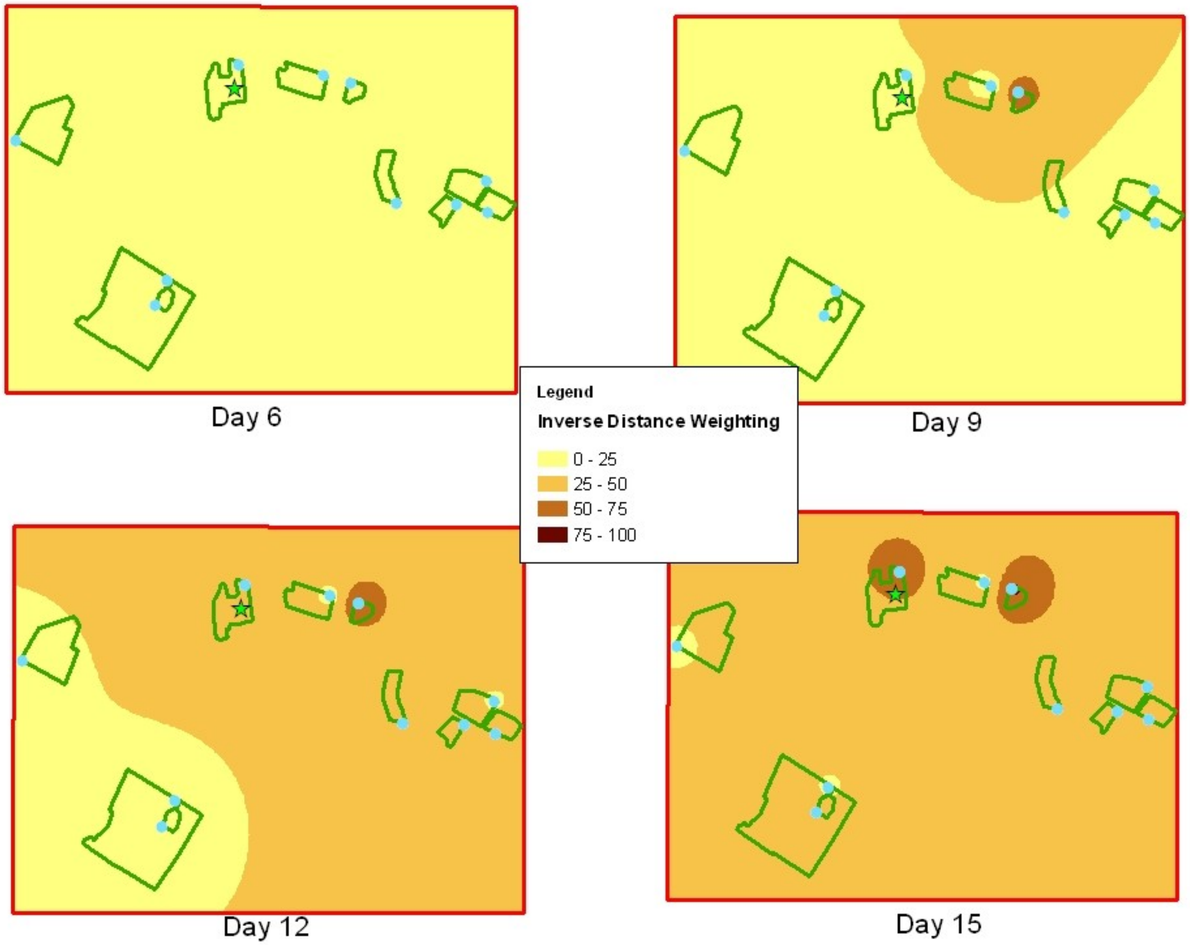


Figure 13: IDW – Six Points search Radius with power of 1



Day 6

Day 9

Day 12

Day 15

Figure 14: IDW – Ten Points search Radius with power of 1

Lag is the vector that separates any two locations and it has both a distance and direction. In an effort to uncover a variogram's structure, similar lags are grouped together into bins or groups. Lag size is the distance of the bins into which these vectors are grouped (Mitchell 2005). Figure 15 – 18 shows the visual Kriging results. The Kriging results, compared to the IDW, produce an image that is not as smooth. Day 9 results show visual variation from the adjustment of the lag variable. Lag size 7, 8, and 9 produce similar predictive surfaces compared to lag size 12 for all the days. Day 9 produces two zones of higher percent parasitism on the left and right side of the study area for lays 7, 8, and 9, but lag 12 produces a very different result. The image produced show the fields falling mainly within the 0-25% result. Day 12 produces a predictive surface for lag 7, 8, and 9 produce a similar predictive surface, but as the lag increases the area of the 25-50% becomes larger. For lag 12 on day 12, the surface is almost completely covered as the 25-50%, except for field 5. There appears to be a sharp drop off in predicted values for this surface that appears to be directly influenced by having the two sample point (points 2 and 3) near each other with low values. Day 15 lag 8, 9 and 12 produces a constant surface with the predicted value being between 25-50%. Lag 7 produces large varying surface with high predicted values compared to the other models for day 15. The shape of the prediction is similar to the predicted surfaces of day 9 lags 7, 8, and 9. This lag predicts the highest values for any kriging method and appears to stress closer neighbor values greater than the one farther away.

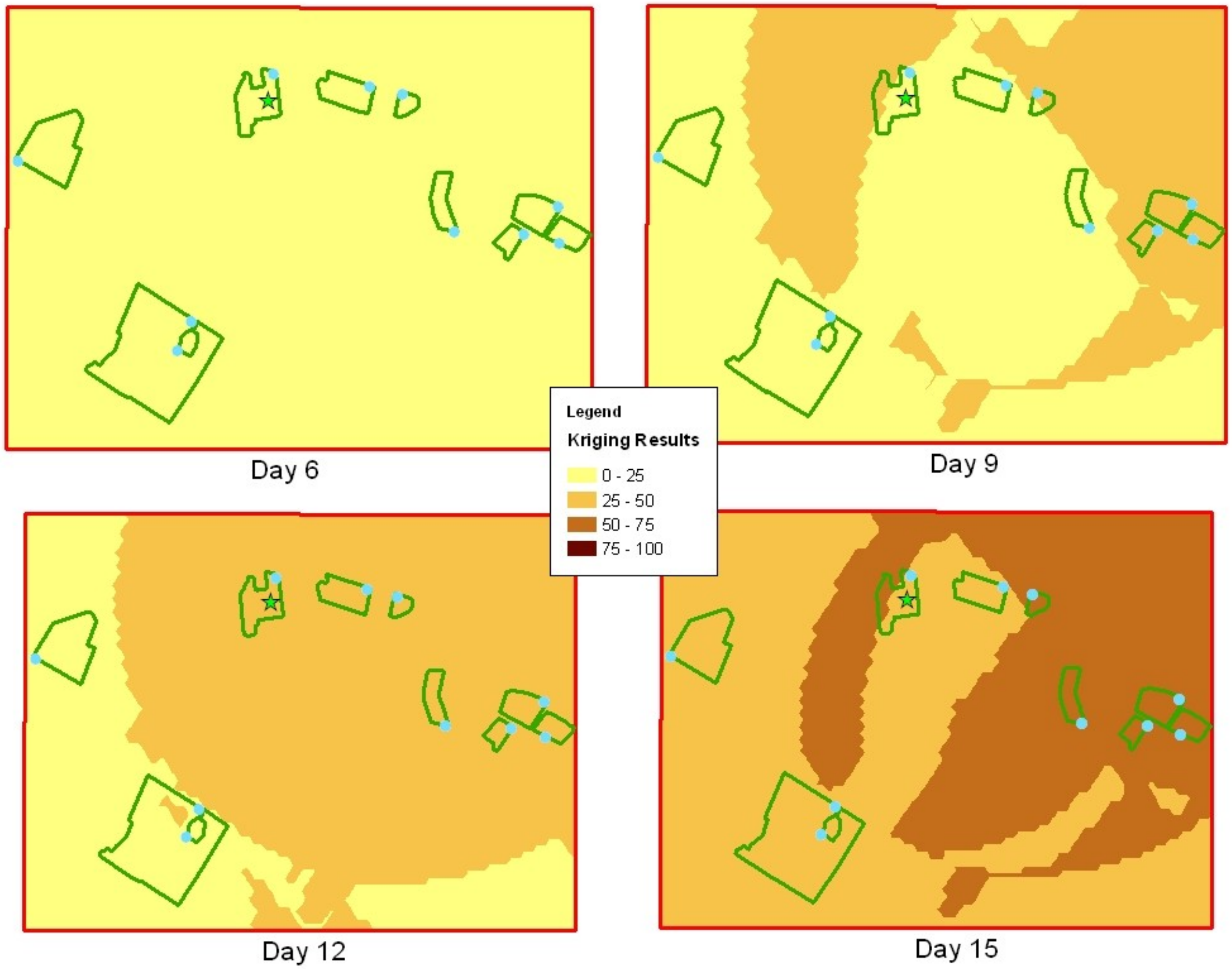


Figure 15: Kriging – Lag 7

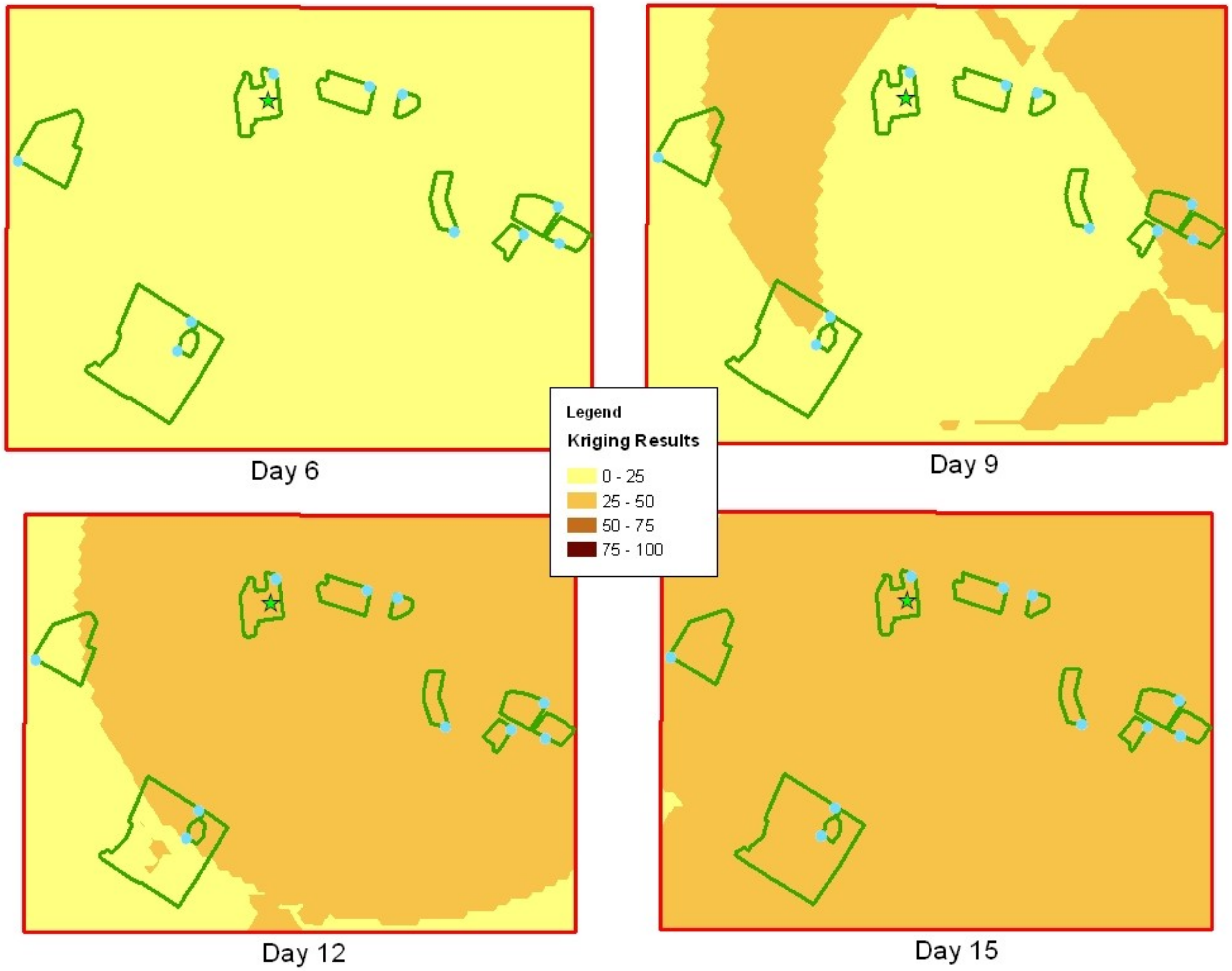


Figure 16: Kriging – Lag 8

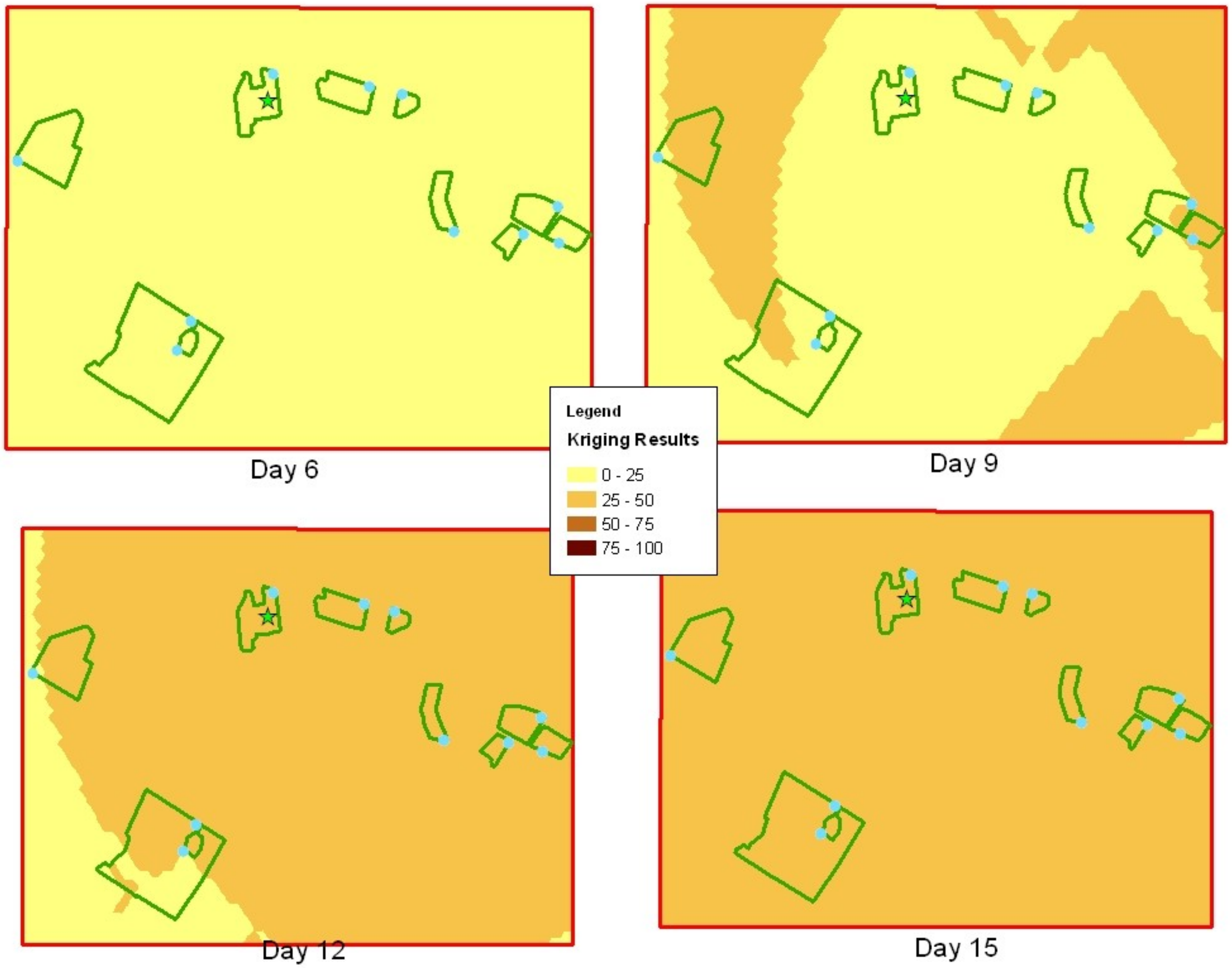


Figure 17: Kriging – Lag 9

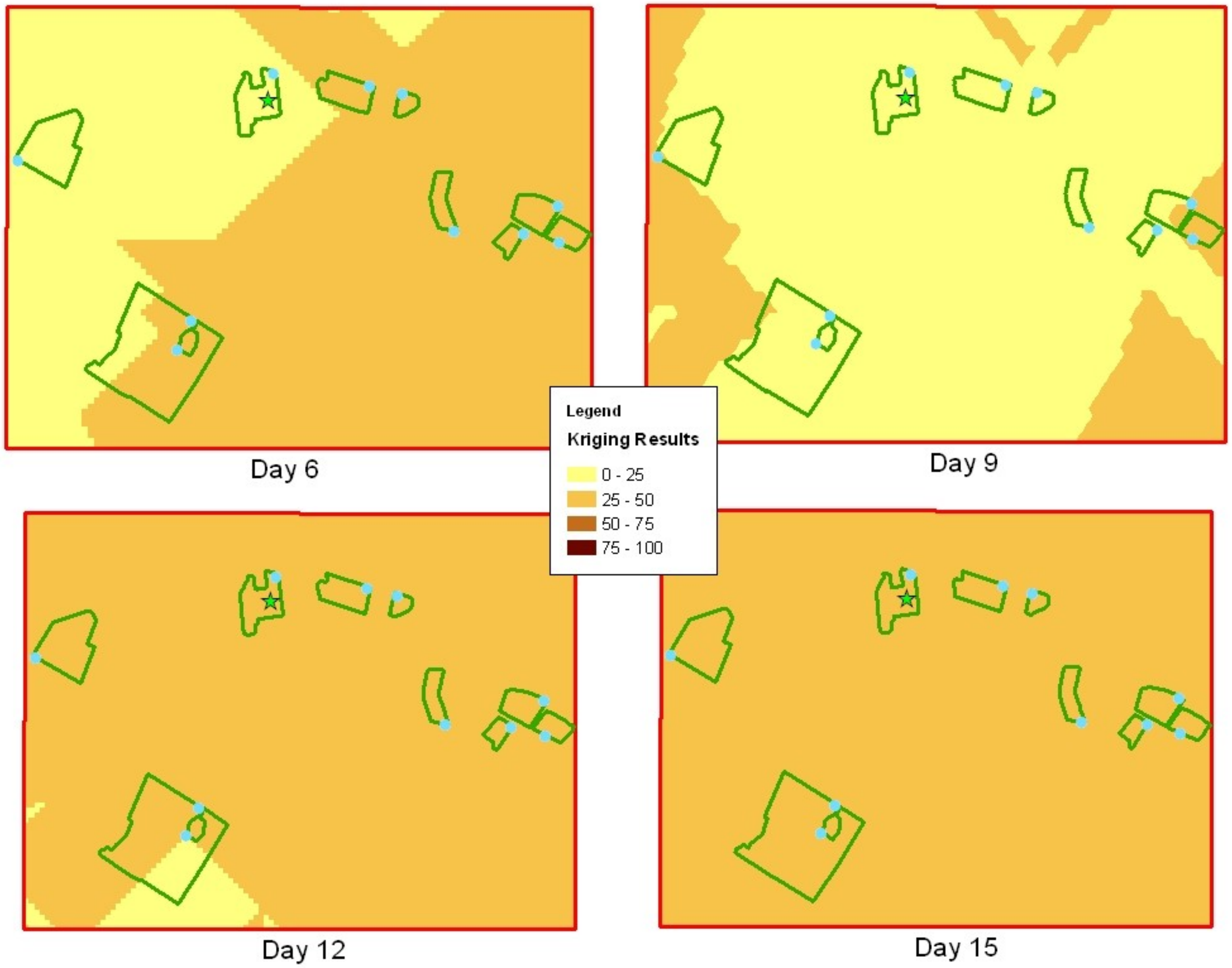


Figure 18: Kriging – Lag 12

Evaluation Method

There are several valid methods suitable for comparing the accuracy of the interpolation results. For this experiment MAE and MSE will be used. The MAE values range from 0 to infinity and the lower the value, the better. Though this value does not indicate the direction of the deviation, MAE can be used to assess the model. Table 5 shows the results of the MAE comparison between the different interpolation procedures for days 6, 9, 12 and 15. Table 4 shows the result of the MSE comparison between different interpolation procedures in day 6, 9, 12, 15 of survey. Like the MAE, it does not indicate the direction of the deviation. Compared to the MAE, the MSE gives greater weight to large errors than to small errors in the average. It is therefore a more appropriate statistic to use when large errors are particularly undesirable. Its sensitivity to large errors also means that it may not give stable estimates of error if small samples are used.

For all Kriging models, the MSE values are greater than MAE, but the variation between the two measurements is slightly smaller than the IDW results. Just like the Kriging results, IDW have the values are greater MSE than MAE. The IDW 10 point model has the lowest MSE variation and Kriging lag 9 has the lowest MSE value. The differences between MSE and MAE for Kriging and IDW on day 6 have no significance difference between the models. When days 9 to 15 models are compared, the Kriging models result in a lower MSE value. When looking at the MAE for all the results, the best model would be Kriging lag 9, but the variation in MAE overall between both IDW and Kriging is relatively small and more sample points would be needed to determine which method of analysis would be best.

Looking directly at the MSE verse the MAE, this will give an indication of the error variance. If the MSE is much greater than MAE this would show that there is an indication of high error variance. Though there is no set rule on how to evaluate the difference of error in model, the MSE and MAE results for the models do show small differences between Kriging and IDW. Though the Kriging model produces lowers MSE and MAE values all around, the difference between the two models in not significant. This means that the variance of error is not significant for the models.

Table 5 Mean Square Error (MSE) of the Interpolation Results

Day	IDW 4-point p = 1	IDW 5-point p = 1	IDW 6-point p = 1	IDW 10-point p = 2	Kriging Lag7	Kriging Lag8	Kriging Lag9	Kriging lag 12
6	7.42	7.33	7.29	7.26	6.75	6.67	6.64	6.78
9	42.93	42.70	42.40	41.92	30.59	31.64	31.42	30.87
12	43.24	43.19	43.00	42.59	29.50	31.58	31.08	31.25
15	46.05	46.18	45.86	45.37	30.19	31.56	30.43	31.04

Table 6 Mean Absolute Error (MAE) of the Interpolation Results

Day	IDW 4-points	IDW 5-points	IDW 6-points	IDW default	Kriging Lag7	Kriging Lag8	Kriging Lag9	Kriging lag12
6	4.93	4.83	4.84	5.00	4.79	4.55	4.32	4.84
9	26.04	26.79	26.59	26.12	17.93	20.35	19.52	20.45
12	28.16	29.18	29.30	29.20	23.12	25.17	23.92	25.06
15	33.76	34.59	34.35	34.03	24.22	25.87	24.26	24.03

CHAPTER 5

CONCLUSION

The purpose of this research is to show the spatio-temporal spread pattern of the parasitic wasp, *Pediobius foveolatus,* takes to seek out Mexican bean beetle larvae. The Mexican bean beetle is a common pest of snap beans, lima beans, and soybeans in the central and eastern parts of the United States. The wasp, *Pediobius foveolatus,* is an effective natural bio-control agent used to combat the Mexican bean beetle, but the area which a fixed wasp population can cover was in question. This parasitic wasp, since its first release, has been able to control the levels of the Mexican bean beetle to under harmful economic levels (Robbins *et al*. 2006). This study attempted to monitor where and when the parasitic wasp infect bean beetle larvae with parasites, and attempted to better understand the geographical distribution pattern of *Pediobius foveolatus*.

The results show the spread pattern of the parasitic wasp generally started from the released area and gradually reach the entire field. The bull-eye effect area in Day 9 of IDW pattern is caused by cage 9 (in field 4) due to the natural deaths because lack of a food source. This sharp drop in population caused the IDW and Kriging results to have a

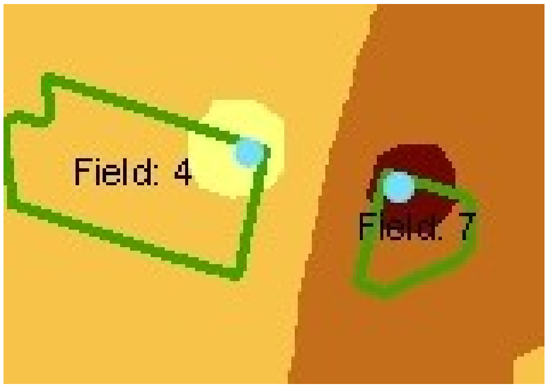


Figure 19: Cage 8 and Cage 9

sharp jump in the generated predictive surface. Cage 8 (in field 7) had extremely high percent parasitism due caused by high mortality rates, which resulted in a limited number of hosts to be parasitized. Just like in cage 9, there was a lack of food and shelter available for the host. The fact that cages 8 and 9 were very close to each other amplified the results of both the IDW and Kriging predictive surfaces. The output results clearly reflect this by showing a hot spot in cage 8, and quick drop off at cage 9. These two cages had a dramatic effect on the results, and they affected the overall results of the whole experiment.

Limitations of Study

The small sample effect had a dramatic effect on the results. By adding more points, errors could have been reduced, and smoother predictive surfaces could have been produced by the geostatisical procedures. Though this study only showed proof of concept of the wasp's spread, it also showed how important sample size is to the study. The 10 sample points did not to completely describe the area, and in future studies, a better sampling method needs to be developed.

Weather played a major role in this study. Any study that involves the outdoors always has some factors that cannot be controlled. In this study, the weather acted as a major source of trouble. In the weeks following the experiment, the increased levels of rain prevented the farmers from planting there crop on time. As a result, the soybean crop was not as mature as desired. This caused a host of problems: lack of food source, lack of protection, and a lack of native population.

Animal interference caused problems in some of the cages. Small mammals, such as skunks, caused a constant source of frustration. The cages in areas that were near dense forest hedge rows would have to be constantly repaired. The fact that animals would interfere with the study never was anticipated, and this factor needs to be included in any future study in order to get a better test result.

Suggested Future Study

This experiment results show that the IDW and Kriging models can be used as a base for further prediction of *Pediobius foveolatus* parasitism. Further study is needed to determine which model is a better predictor. To help reduce the error in the models, fine-tuning is needed to incorporate other weighted factors such as time and wind direction. This could make the estimation equation as follows:

Figure 20: Sparse Vegetation at Cage 9

$$E_c = \alpha * E_t + \beta * E_s + \gamma * E_d \qquad (5)$$

Where E_c is the estimated value, E_t is the temporal interpolation method, E_s is the spatial interpolation, E_d is the wind direction factor, and $\alpha + \beta + \gamma = 1$.

Another factor that will help reduce error is introducing more cages or survey sites. The 10 points used in this study was the minimum amount of survey locations needed to complete the study. A sample size of 10 points is considered small, and over a large area cannot fully model all the variations over the surface area. The initial goal was to incorporate additional sites by utilizing the native bean beetle population, but due to poor weather, this could not happen. Even without these parameters, it is interesting and encouraging that results can be derived with only one factor. Increased study points would improve the overall modeling process, and as a result, could help to reduce the MSE and MAE levels of error.

Cage placement could also have been improved. Though in this study we were limited by where the farmer would let us place the field, a more ideal condition would have been to create a more unified placement process that would better describe the study area. Also, decreasing the study area might be beneficial to fully understand how the wasp moves through a single field. A better understanding of how the wasp moves in a single field would help better understand how the wasp moves in a multi-field environment.

A central release might better suit this study. Though the study used a mean center release point, using the study area release point could reduce weight from one area to another. A central release point would better show if the spread is uniform or random in nature.

This study only showed the initial analysis of the spatial-temporal spread patterns. Though it is not possible to say which model is the best fit for predicting the spread of the

Pediobius foveolatus, it was shown that the movement can be modeled using geostatistic models. Limitation that arose during the study hampered the results, but the study does provide a foundation which clearly shows this area could produce beneficial information. Further analysis needs to be performed to have a complete understanding of the geographical distribution of the parasitic wasp after its release.

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