Local and Regional Spatial Analysis of Plant Virus Disease Epidemics with Geographic Information Systems (GIS) and Geostatistics

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التحليل الزمني لأمراض النبات الفيروسية الوبائية محلياً وإقليمياً بواسطة أنظمة المعلومات الجغرافية والاحصاء الجغرافي

ميريت م.ن نيلسون ت. ق. اورم

الخلاصة: لقد قدمت التطورات الحديثة في جهاز الحاسب الآلي الشخصي والتقدم السريع في برامج تشغيله الخاصة بالتحليل الزمني بما يعرف بصديق مشغلي الحاسب الآلي الشخصي قدمت نوعاً من الوسائل التي يمكن استعمالها في تحليل أمراض النبات وخاصة الأمراض الفيروسية المعقدة، وذلك نسبة للتعقيد الذي يلازم الدورة الحياتية للفيروسات التي تنتقل للنبات بواسطة الحيوانات ، وتمثل هذه الأمراض أقصى التحديات لتطبيق تقنيات التحليل الزمني. بينما تركز التحليل الكمي التقليدي على التحليل الزمني في الحقل، فإنه غالبا ما يشتمل على صيغ لأوصاف حسابية، ووسائل التحليل الزمني الحديثة هي الأصلح في مجال تعددت فيه الأمراض الوبائية على المستوى الإقليمي . لقد كان الناتج لكثير من برامج التحليل الزمني صورة مرئية للعديد من الأمراض الوبائية التي تحوز على استحسان مديري المؤسسات الزراعية بقوة. وقد اشتملت تطبيقاتنا حتى الآن على الأمراض الفيروسية التي تصيب الطماطم، الفلفل والقطن في كل من أريزونا، المكسيك وباكستان. هذا بالإضافة إلى تطبيقاتنا له في الأمراض التي يسببها على البطاطس والطماطم، الفطر *Phytophthora infestans* على البطاطس والطماطم Aspergillus *flavus* على القطن والمشكلات التي تسببها الحشرات للطماطم والقطن.

ABSTRACT: Recent advances in personal computer hardware and the rapid development of spatial analysis software that is user-friendly on PC's has provided remarkable new tools for the analysis of plant diseases, particularly ecologically complex virus diseases. Due to the complexity of the disease cycle of the animal-vectored plant virus, these diseases present the most interesting challenges for the application of spatial analysis technology. While traditional quantitative analysis of plant diseases concentrated on within-field spatial analysis, often involving rather arcane mathematical descriptions of pattern, the new spatial analysis tools are most useful at the dimension where many disease epidemics occur, the regional level. The output of many of the programs used in spatial analysis is a highly visual picture of a disease epidemic which has a strong intuitive appeal to managers of agricultural enterprises. Applications by us, thus far, have included tomato, pepper and cotton virus diseases in Arizona, Mexico, California and Pakistan. In addition, this technology has been applied by us to *Phytophthora infestans* in potato and tomato, *Aspergillus flavus* in cotton, and regional insect problems of tomato and cotton.

Simple management strategies are not effective in suppressing infection when dealing with ecologically complex plant virus diseases. Ecologically complex virus diseases are characterized as having dynamic aerial vectors, widespread but discontinuous alternate hosts of the virus and the vector, and genetically diverse virus variants. They often occur in temperate, tropical or desert regions where host plants and the vector may be present year round. Because of genetic diversity of the viral pathogens, breeding for resistance either by traditional or biotechnology approaches is difficult and positive results obtained only after a long development period.

Management of such virus diseases may be approached by a series of actions that focus on known information about their epidemiology. The principle focus of such actions should be on preventing introduction of the virus into the crop. This involves the identification of the hosts or habitats that are most likely to be a source of virus and vectors during the early part of the cropping season, and an understanding of the spatial relationships of these components in reference to disease incidence and severity. While complex virus diseases may come from many different groups of viruses, the whitefly transmitted geminiviruses (WTG's) of many temperate, desert and tropical food and fiber crops are among the most common. The diseases caused by these viruses have become particularly important in the past two decades in temperate areas of the world and include very serious diseases of cotton, tomatoes, squash, melons, peppers and others.

A very good example of a WTG is cotton leaf curl virus (CLCuV). This virus disease has had a major impact on the cotton economy of Pakistan during the last decade. Of critical importance in this type of disease are the proximal effects of the components of the epidemic on the seriousness of the disease. Technology to measure these proximal relationships is now available through the integration of geographic information systems (GIS), geostatistics and global positioning systems. Use of these technologies in the spatial analysis of plant virus epidemics such as those incited by cotton leaf curl virus provides a quantitative estimate of the spatial relationships of epidemic components required to cause serious crop losses which may provide background information for a successful management program. An important component to be focused on in the upcoming work with cotton leaf curl virus in Pakistan is the spatial analysis of cotton and alternate hosts surviving during the off season. Spatial analyses will overlay observations during the off-season with early season assessments of incidence.

The rationale for the application of spatial analysis technology to plant virus disease problems lies in the fact that agricultural ecosystems are patchy in most variables that matter for crop protection and production. Virus disease incidence and severity is regulated by the differential distribution (patchiness) of the main components of virus disease epidemics, the crop host, and the alternate hosts of the virus and vector. Habitat composition and pattern in uncultivated areas as well as spatial arrangements between and within fields can have profound effects not only on the severity and frequency of plant diseases, but also insect pests, and weeds. A combination of these factors can lead to recurring regional patterns of disease severity from which conclusions about source of infection may be made and from which spatial analysis may be initiated. Such disease epidemics as well as insect pest infestations are thought of by landscape ecologists as disturbances across heterogeneous landscapes (O'Neill et al, 1992). Agricultural ecosystems may be thought of as heterogeneous landscapes based on the pattern of crops and associated non-crop areas. In addressing ecologically complex virus epidemics, spatial analysis should focus on the disease at the regional, not the field level. The modern software being applied in this project permits the highly visual display of the spatial relationships that result in serious disease. The information contained in the maps and graphs illustrating these relationships will stimulate regional planning to control disease using cultural management strategies based on risk assessments.

Landscape ecologists emphasize the effect of pattern on process and as such provide a theoretical framework for the use of risk management in crop protection based on spatial analysis (O'Neill et al, 1992). Geographic information systems (GIS) and the associated tools of geostatistics and global positioning systems (GPS) make it feasible to apply an understanding of spatial patterns in the management of crop diseases and pests. The applications of spatial analysis technology in agriculture has ranged from land suitability analysis at the continental scale (Canadian GIS) to risk management on a regional scale to site specific farming within fields. The ongoing challenge is to give meaning to spatial data, to understand the spatial patterns, and to interpret the information for disease and pest management purposes.

Spatial Analysis

Before going into specific applications of spatial analyses in plant disease management, a brief introduction to the key technologies of GIS, geostatistics, and GPS is in order. Prior to the rapid development and availability of personal computers, spatial analyses frequently involved rather arcane mathematical descriptions of pattern. This situation has changed dramatically in the past decade and spatial analysis now involves interactive graphic displays with an great intuitive appeal. GIS software has become a large commercial arena with many software products available. Applications in plant disease management can take advantage of these rapidly changing technologies.

Geographic Information Systems (GIS).

Geographic information systems are designed to store and analyze information about entities whose location has been recorded. According to Star and Estes (1990), the first modern GIS was developed by the government of Canada in 1964 for the identification and rehabilitation of marginal agricultural lands. GIS, therefore, has had applications in agriculture from the beginning. Whereas initially, GIS was only available to large institutions, such as the government of Canada, this technology is now available to anyone who has access to a recent model personal computer and the appropriate recently developed commercial software. GIS capability is within the reach of researchers, extension agents, and farmers. It should be noted that although attractive graphical displays are frequently the end result, GIS's are basically databases and behind every effective GIS is someone or some group that is paying attention to the ordinary details of database management.

There are two basic kinds of GIS data structures: raster and vector (Star and Estes, 1990 and Liebhold et al, 1993). In raster based systems, space is divided into an array of cells identified by rows and columns in a matrix. All of the information is stored and manipulated as matrices. There is a separate matrix for each variable. In the development of a raster based application, one needs to decide how many rows and columns will be used to span the study area. This will determine the area represented by each cell in the matrix. One also needs to come up with conventions for assigning values to each cell in the matrix. The precision of raster systems is limited by the size of the cells, so if a small cell size is required to have separate cells for closely spaced observation points, and if the study area is large, then the matrices can become very large. There are a number of applications in which raster systems are preferred. For example, satellite image data are usually in raster format. Also, raster organization of data is convenient for spatial modelling and image processing that involves algebraic manipulations of matrices.

Vector data structures organize the data in tables of relational database management systems rather than in matrices. Features such as points, lines, and polygons are given id numbers and the spatial relationships among the features are defined by coordinate lists in database tables. Feature attribute tables allow the user to assign numerical or text information to entities based on the feature id number. For example, in a regional agricultural study, each field in the study area can be represented by a point defined by coordinates of the center of the field. A corresponding point attribute table would consist of a column for the field id's and columns for a number of attributes such as field size (in hectares), crop name, variety, date of planting, harvest date, estimated disease severity, and yield. An important early phase in the development of a vector structured GIS application is decision-making about what geographic entities to represent as points, lines, or polygons and what attributes to associate with each type of entity. In the example above, one might have chosen to represent fields as polygons rather than as points. Because vector systems are based on coordinate lists, precision is not limited by cell size and graphic images produced from vector systems are not jagged. Vector database structures are more efficient in storing attribute information and for data queries based on the attribute data, but are less efficient in spatial analysis procedures designed for matrices. Many GIS programs are capable of using both raster and vector data structures.

Good worldwide web sites for an introduction to GIS include the GIS Master Bibliography Site of the Ohio State University Department of Geography: **http://thoth.sbs.ohio-state.edu/osugisbib/wais.html**, the GIS WWW server of the Department of Geography at the University of Edinburgh: **http://www.geo.ed.ac.uk /home/gishome.html** and two commercial sites: **http://www.esri.com/**; and **http://www.mapinfo.com/**.

GEOSTATISTICS: Geostatistics is a branch of applied mathematics that makes use of spatial information about variables and helps describe the spatial continuity that is characteristic of many variables in natural systems (Isaaks and Srivastava,1989). Geostatistics provides tools to analyze and work with variables that have spatial autocorrelation. Spatial autocorrelation occurs when nearby points are similar in value. Many variables will show spatial autocorrelation at more than one scale (distance over which nearby values are similar). A number of studies in plant pathology have used geostatistics simply to help describe the spatial autocorrelation (Johnson et al, 1991, Todd and Tisserat, 1990). On the other hand, one of the more popular geostatistical techniques is called kriging. Kriging refers to a group of linear regression techniques that use models of the spatial autocorrelation to estimate values at unsampled locations (Myers, 1991, Isaaks and Srivastava, 1989, Nelson et al, 1994). Kriging is sometimes referred to as a surface interpolator. Some GIS packages offer a number of surface interpolators including inverse distance weighing (IDW). Kriging provides a much more comprehensive approach to surface interpolation than IDW because it involves a model of the spatial autocorrelation and takes into account clustered data locations. On the other hand, for some users, IDW is the only available option. Because we have found most virus disease incidence variables at the regional level to be spatially autocorrelated, IDW would, in most cases, be preferable to an unweighted moving average in the absence of a geostatistical analysis. For ongoing discussions of these and other issues relating to geostatistics, there is an excellent WWW page and list serve moderated by Grégoire Dubois, Joint Research Centre Environment Institute, Environmental Monitoring Unit TP 321,I-21020 Ispra (Va) Italy, at **http://java.ei.jrc.it /rem/gregoire/index.html** with an excellent page on Frequently Asked Questions on Geostatistics by Syed Abdul Rahman Shibli at **http://java.ei.jrc.it/rem/gregoire/ai-geostats_faq.html#4a**.

One of the most important applications of geostatistics in regional analyses of plant disease is the use of indicator kriging to handle binary data and so-called "soft-data". Soft data are qualitative data and can be based on subjective experience. This is particularly valuable when used in connection with well-disciplined and trained observers. In indicator kriging, a variable is scored 0 or 1 according to the presence or absence of a factor or according to whether or not another variable is above or below a cutoff value. The indicator variable is assessed at many locations with known coordinates and the spatial structure is modeled using the same techniques as spatial modeling with continuous variables. Using an appropriate variogram model of the spatial structure, the indicator variable is then kriged to provide a probability map of the region associated with that variable (Isaaks and Srivastava, 1989, Journel, 1989, Shibli @ **http://java.ei.jrc.it/rem/gregoire/ai-geostats_faq.html#4a**). Indicator variables can also be combined using Boolean algebra to create a multiple variable indicator transform that incorporates a combination of factors into a probability map of a region (Nelson et al, 1994).

Results of kriging can be displayed as contour maps or as shaded cells overlayed on a map with other features using a GIS. Block kriging is a smoothing algorithm and emphasizes broad patterns rather than local variability (a face with no wrinkles). Conditional simulation (Rossi et al,1993 Shibli @ **http://java.ei.jrc.it/rem/gregoire/ai-geostats_faq.html#4a** extends kriging to produce a series of equally probable maps that give a feel for the local variability (a face with the wrinkles emphasized). Whether or not it is important to incorporate local variability depends upon the application (Rogowski, 1994). Geostatistics have been widely applied in geology during the last three decades but recently many applications have been developed in other fields including ecology, entomology, and plant pathology (Rossi et al, 1992, Liebhold et al, 1993, Kemp et al, 1989, Lecoustre et al, 1989).

GLOBAL POSITIONING SYSTEMS (GPS): Global positioning systems (GPS) are based on navigation satellites launched and maintained by the United States Department of Defense and Department of Transportation. The satellites contain very high precision clocks and broadcast radio signals with the time information. Time is used as a proxy for distance in the calculations of position because radio signals travel from the satellite at the speed of light (a constant). GPS receivers calculate position by triangulation based on distance from the satellites. The United States Department of Defense dilutes the precision of the satellite information so that unprocessed coordinates have a precision of about 100 m, a condition known as selective availability (SA). The precision, speed, connectivity to accessories, and cost of GPS receivers varies greatly and the choice of GPS equipment will depend heavily on the application. Inexpensive handheld devices (unable to correct for SA) can provide coordinates with a precision of 100 m or better. Such precision is sufficient to identify field coordinates for regional analyses. For greater precision a process known as differential GPS (DGPS) is used. DGPS relies on two GPS units (a base station and a rover) with sufficient memory to store a great deal of satellite information. The base station is fixed in location at known coordinates while the rover is moved to positions of interest. The coordinates of the rover are determined by differencing using data from the base station. The higher precision is obtained by post processing the rover and base station data on a computer (precision usually in the 2 to 5 m range). Real time DGPS is possible when the rover can receive and analyze base station information broadcast by radio (precision within 10 m). Real time DGPS is the basis for site specific farming technology. As site specific farming technology develops, DGPS linked to GIS will be increasingly integrated into some farming operations. Spatially referenced databases on important within-field variables such as yield and soil fertility can be maintained. Crop disease, insect pest, and weed information can be incorporated into the GIS along with the agronomic data. In its most optimistic outcome, GIS would provide the tools needed to meet the need foreseen by Odum (1989) for input management of agricultural production systems in order to reduce the use of environmentally damaging agricultural materials.

Spatial Analysis in Plant Disease Management

The tools of GIS, geostatistics, and GPS can be used at any scale ranging from within a single field to a region of hundreds of square kilometers. Within-field applications of GIS and geostatistics are common in plant pathology/ nematology and form the basis of "precision farming" and "site-specific farming". The application of this technology on a regional scale is less common and requires a different "mind-set" than that used in within-field applications. Figuratively speaking, regional applications look for a pattern of the forest rather than the condition and identity of individual trees. Many plant disease epidemics, especially those in the category of ecologically complex virus diseases, are best understood at the regional scale. To form a basis for analysis at this scale, data collection techniques need to be simplified and disciplined so that an adequate number of locations throughout a region can be sampled. It is important not to dwell on unnecessary detail or unrealistic precision at a given sample location. Between the within-field scale and the regional scale is the local scale. The local scale (10 - 100 so. km.) can be very important, because that is the scale at which many individual farmers and farm managers operate. Regional analyses by institutions and agencies can provide a context for local scale decisions by farm managers.

Our own work in spatial analysis initially focused on plant virus diseases of cotton, cucurbits, tomatoes, and peppers. We conducted field experiments measuring the spatial distribution and spread of aphid-transmitted viruses in cucurbits and, at a different time of year, similar experiments on a geminivirus disease of cotton. What these experiments showed us is that most virus movement is from plant to plant for whitefly- and aphid-transmitted viruses and the patterns of spread are indistinguishable. This has also been shown independently for a leafhopper-transmitted virus in Central America (Power, 1992). The results of these studies encouraged us to simplify data collection within a field, not dwell on differences in virus biology/identity, and concentrate on larger scale processes between fields and between non-crop habitats and fields. It also encouraged us to develop simplified field evaluation techniques to allow us to collect from an adequate number of field locations as is mandated by the spatial analysis approach to disease assessment regionally (Nelson et al, 1994). While the virus work continues, our interests have expanded and now include an analytical look at the regional distribution of genetic variants of *Phytophthora infestans* in a mixed potato, tomato culture in northwestern Mexico (Jaime-G. et al, 1996) as well as the strain composition of the aflatoxin fungus, *Aspergillus flavus*, in Arizona cotton (Orum et al, 1997). We have also been involved in insect population monitoring programs including one to map whitefly development based on weekly data from about 1000 yellow sticky trap sites near cotton fields across Arizona. Another project involved mapping tomato pinworm population development in the tomato crop in the state of Sinaloa, Mexico based on a regional array of pheromone traps for the adult moth. In addition, we have assisted in the analysis of spatial data in a whitefly migration project (Byrne et al, 1996). Throughout this involvement, computer software for spatial analysis has been rapidly changing and the prospects for further practical applications continue to improve.

Many farmers will receive their first introduction to GPS and GIS in the popular press through descriptions and promotions of technology related to precision farming (also known as prescription farming and site specific farming). Precision farming is made possible by a combinations of technologies including real time DGPS, on-the-go yield monitors, soil sensors, and variable rate applicators of fertilizers and pesticides. All of this information is handled by a GIS - usually with a user-specific interface designed by the developer of the product. Precision farming is in a stage of development where there is a creative, chaotic mix of enterprise ranging from very small businesses to giant corporations. Because the field is developing so rapidly, the best way to track on its progress is through the Internet. The following www sites currently provide information on precision farming: **http://dynamo.ecn.purdue.edu/~biehl/SiteFarming/,** The Electronic Precision Farming Institute, Purdue University, West Lafayette, Indiana USA; **http://www.silsoe.cranfield.ac.uk/cps /default.htm,** Centre for Precision Farming, Cranfield University, Bedfordshire, England; and **http://precision.agri.umn.edu/,** Precision Agriculture Center Online, University of Minnesota, St. Paul, USA.

Examples of Regional Plant Virus Management Using Spatial Analyses

THE TOMATO VIRUS PROGRAM IN SINALOA, MEXICO: A management program based on a regional approach supported by GIS was implemented successfully by the tomato paste processing industry in the Del Fuerte Valley of Sinaloa Mexico between 1990 and 1996. Results of the first two years of the program have been published (Nelson et al, 1994). The design of plant virus management programs is often based on specific biological characteristics of a virus. This approach is useful when the principal problem is a single virus with an easily managed weak link in the disease cycle. From a biological standpoint the tomato virus diseases identified in the Del Fuerte Valley were a diverse group. They included the aphid-transmitted tobacco etch virus (TEV), pepper mottle virus(PeMV), cucumber mosaic virus(CMV), thrips transmitted TSWV, whitefly transmitted geminiviruses (including yellows and leaf curl types), and tomato mosaic virus (TMV). The tomato viruses in the Del Fuerte Valley presented a typical ecologically complex virus disease situation. Consequently, a cultural management approach was needed in which a series of actions are taken that collectively delay infection and suppress disease spread. A classic model for a cultural approach using multiple management actions is the leafhopper transmitted curly top in California (Duffus, 1983).

The Del Fuerte Valley agricultural area is approximately 60 km by 110 km with two principal cities, Los Mochis in the north and Guasave in the south. There are many smaller villages scattered throughout the valley with a concentration around the two cities mentioned. The Los Mochis area is by far the most extensive urban area in this valley. The program focused on processing tomatoes - approximately thirty per cent of the tomatoes grown in the valley. The tomato crop is planted from September through January in normal years with the most serious virus infections occurring in the September plantings. During September, the whitefly vectors of the geminiviruses were associated primarily with the maturing soybean crop and various weed species that start to become

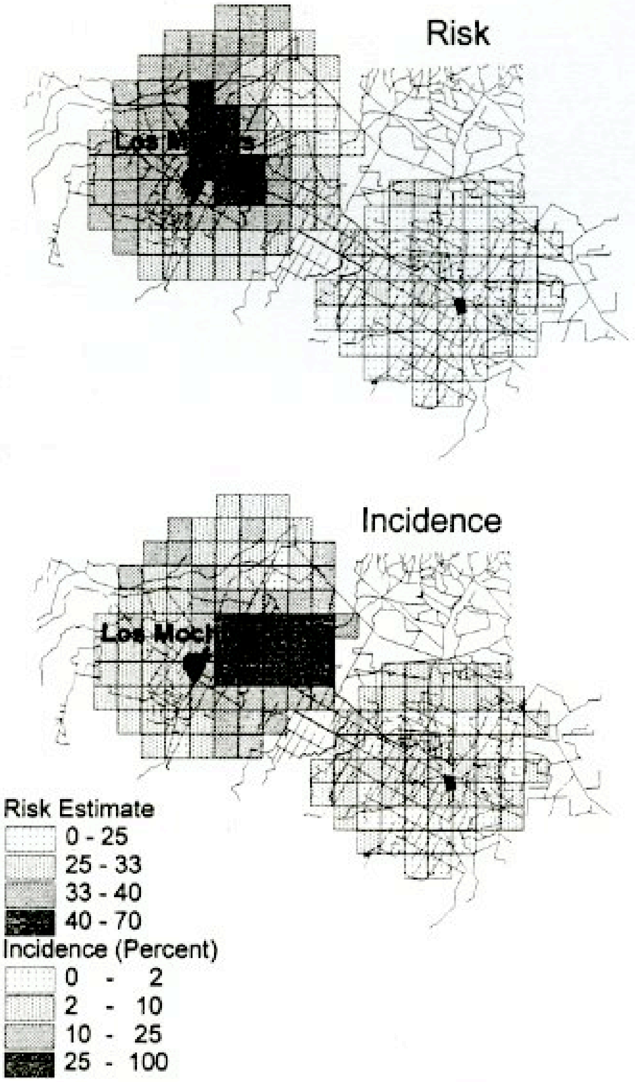

Figure 1. Regional spatial pattern of risk and incidence of tomato viruses in the Del Fuerte Valley, Sinaloa, Mexico during the 1991-1992 growing season

senescent when tomatoes are first planted. In certain areas and during some seasons, the combination of abundant vectors and virus sources (weeds, summer peppers, abandoned tomato fields, and urban plantings) result in early and heavy virus infection. A program was developed to assess risk of virus infection for fields immediately prior to the planting of tomatoes. This program of risk assessment was based on the general hazards for virus infection immediately surrounding the field. Later, virus disease incidence was assessed in the same fields. Regional maps identified areas of highest risk and incidence (Figure 1). The areas became the focus of attention in subsequent years.

Field evaluators visited each of the fields to assess the risk of virus disease at the time of transplanting. The adjacent fields and ditches in each direction were evaluated for weeds, potential vectors, plants with virus symptoms, and crops (such as soybeans or peppers) that might harbor either virus(es) or insect vectors.

Risk variables were derived from a numerical scoring system based on observations of adjacent fields and ditches (within 50 m to 100 m) in each direction from the field including the corners (eight directions). During the first three years of the study, scores were assigned as follows (score in parentheses): clean fallow - no crops, no weeds (1); crops present - no symptoms (2); crops present - virus symptoms (4); weeds present - no symptoms (2); weeds present - virus symptoms (4); aphids, whiteflies, or thrips present (2); small village or dwelling nearby (2). These scores were combined in various ways. The most used variable, "Risk-total", was computed by adding the scores for all eight directions. A critical issue was to design a program that was useable by field men who make decisions about when and where to plant tomato fields. Forms were drawn up to aid in the recording of data. The risk assessment lead to two possible subsequent actions. Either the particular field in question was judged to be a bad risk for early planting because of virus infection hazards that could not be modified or the decision was made to modify risk by removing weeds, or if appropriate, terminate a problem adjacent crop under control of the grower earlier and reduce risk so that early planting could proceed.

Virus incidence was evaluated by scoring approximately 1000 tomato plants in each field for the presence or absence of four categories of virus symptoms: chino and golden mosaics (geminiviruses), mosaics (TEV, CMV, and TMV), TSWV, and virus-like symptoms but type uncertain. Plants from all categories were used in the final analysis to determine percent incidence. Fields were divided into nine blocks (usually on a 3 x 3 grid) for survey purposes. Within each block, between 100 and 120 consecutive plants were evaluated for virus symptoms. Fields were evaluated for incidence at early fruit set (about 60 days after transplanting). Because the overall incidence of virus disease was the primary focus of the study, the field specialists did not dwell on subtle differences in symptom type. However, their prior professional experience as well as testing during the diagnostic phase of the project in 1988 and 1989, provided background that allowed them to recognize certain symptom types as dominant. This was the first application of this technology, and detailed data were taken because of the availability of skilled manpower. In subsequent virus projects we have decided that such detailed data are unnecessary for spatial analysis. For broad regional analyses, we have concluded that only two questions need be asked. Are virus symptoms present in the field and is the incidence high or low? Field observation skills can be developed to adequately standardize the response to these questions. Geostatistics, through indicator kriging (explained above), provides a methodology to analyze such binary variables. Of course, in other projects involving fungi and insects, laboratory analysis is sometimes necessary depending on the goals of the research. Of critical importance is the number of data points and their spatial distribution throughout the region. We recommend a minimum of 100 locations. The more points and the better the distribution, the more accurate the analysis.

Commercially available topographic maps (1:50000) produced by the Instituto Nacional de Estadistica Geografia e Informatica (Mexico City, Mexico) were obtained and digitized using ARC/INFO (ESRI, Redlands, CA) and a Calcomp 9500 digitizer (Calcomp Digitizer Products Group, Scottsdale, AZ). Map features were assigned Universal Transverse Mercator (UTM) coordinates. Thirteen detailed maps were developed with a 1 km by 1 km grid in such a way that UTM coordinates of the center of the fields could be estimated within approximately 200 m. After 1993, GPS units were used to facilitate estimates of the field coordinates and improve accuracy. GeoEAS (USEPA EMSL-LV, EAD, Las Vegas, NV) was used for a standard geostatistical analysis of the risk and incidence variables (Myers, 1991). Because the distributions for the incidence variables were highly skewed, indicator variogram models and indicator kriging were also used to produce block estimates. For the first two years, a multiple variable indicator transformation (MVIT) of the variables Dayseas and Risk-total was scored 1 if planting date was prior to November 1 and Risk-total was greater than 33; otherwise 0. Kriged maps of the MVIT were prepared for both growing seasons. Kriged maps of incidence were prepared for the entire region through the 1993-94 season and for the Los Mochis area through the 1995-96 season. The PC version of ARCVIEW (ESRI, Redlands, CA) provided interactive access to the GIS database and hard copy printout of maps.

Sample variograms and variogram models for risk and incidence of virus disease showed that these variables are spatially dependent with a range of 20 to 25 km. Indicator kriging revealed that the area east of Los Mochis was higher in both risk and incidence than the area around Guasave from 1990-91 through 1993-94. Incidence peaked during the 1991-92 growing season (regionally: mean 11.5%, median 6.3%), but the regional spatial pattern of incidence was similar during the first four years of the program. By 1993-94 incidence was sufficiently low (well under 1%) in the Guasave region, that data on incidence were not taken in subsequent years, though the risk assessment and risk mitigation efforts continued. Efforts were focused on the area east of Los Mochis where incidence continued to drop from a local area average incidence of 30% in 1991-92 to under 3% in 1995-96.

Our results suggested that tomato virus disease incidence had two principal sources: hazards immediately surrounding the field, represented by the risk variables, and area-wide landscape features conducive to virus persistence, observed but not quantified. In the 1991-92 growing season, incidence was high and the regional pattern of risk was similar to the regional pattern of incidence (Figure 1). There was a positive correlation between risk assessment and incidence for each field. This supported the conclusion that reducing the hazards immediately surrounding a field was important. Area-wide landscape features probably interacted with the hazards surrounding the fields to produce the regional recurring spatial patterns of virus disease incidence observed. Qualitative observations revealed that the landscape in the Guasave area differed from the Los Mochis area. The Guasave area has larger fields (150-300 ha vs. 20-150 ha), more grain fields, fewer vegetable fields, and fewer embedded rural homesteads than the Los Mochis area. The more urban Los Mochis area is more likely to contain suffretescent pepper and tomato plants in home gardens to carry viruses from one year to the next as well as small plantings of peppers and tomatoes for the local market. In general, irrigation and drainage ditches in the Guasave-Bamoa area are lined with concrete, whereas in the Los Mochis area they are not. GIS analysis was not required for the implementation of standard good management practices, but rather provided a unifying perspective to encourage efforts throughout the region and focus on hot spots. By focusing attention on the high incidence/high risk areas, classical virus management strategies could be more efficiently and effectively promoted. These strategies included the control of alternate hosts near fields, delayed plantings in high risk/incidence areas, avoidance of major hazards such as maturing pepper fields, control of volunteer or surviving tomato plants during the off-season, etc. We observed that after the 1991-92 season, the producers did not plant tomatoes in the area of highest risk the following season.

Furthermore, anywhere where field risk assessments were high, mitigation efforts were taken to eliminate weeds prior to planting. Regional cultural management strategies were also put into place. Producers put pressure on the National Water Commission to clean the weedy vegetation along irrigation canals and ditches in the Los Mochis area. The Water Commission also required a deposit from farmers to insure the tomato crop residue was destroyed (plowed under) at the end of the season. This was initiated after the spatial analysis work with the tomato

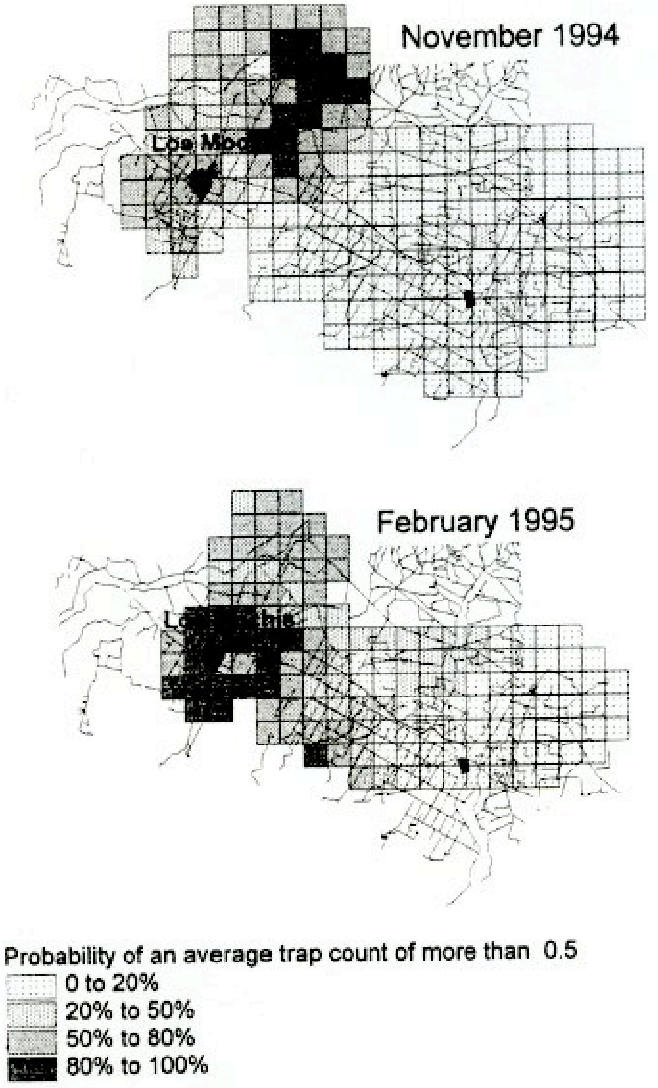

Figure 2. Regiaonal spatial pattern of adult tomato pinworm moths in the Del Fuerte Valley, Sinaloa, Mexico

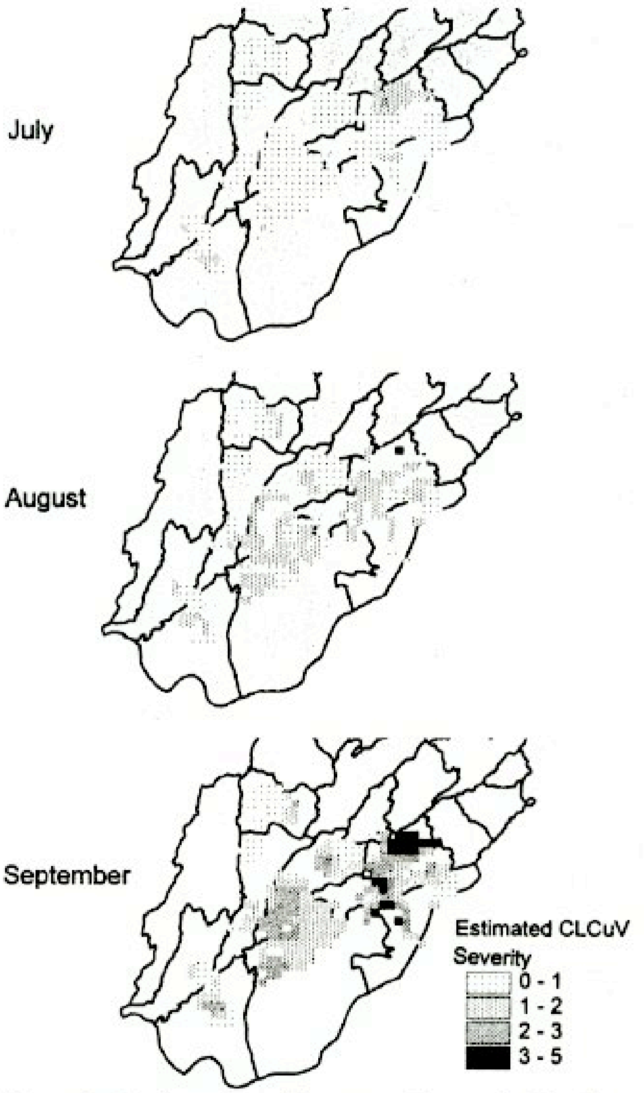

Figure 3. Regiaonal spatial pattern of cotton leaf curl virus severity in Punjab, Pakistan in 1996

pinworm showed similar patterns to the viruses, reinforcing the common perception that abandoned tomato fields were a source of pathogens and pests. Most importantly, the gathering and presentation of information by the spatial analysis technology stimulated remedial actions that have helped suppress both virus diseases and pinworm in the Del Fuerte Valley by reducing the amount of inoculum carried through the off-season. Changes in summer plantings may have reduced whitefly population levels helping the overall virus picture. The combination of efforts and factors has resulted in a much reduced virus incidence, especially in the previously high risk area east of Los Mochis.

The program has another beneficial effect - a major reduction in the use of pesticides. The combination of classical virus management strategies with the focus provided by the GIS analysis was used by one producer to completely eliminate pesticide spraying for the control of vectors as part of an integrated pest management strategy (Bolkan and Reinert 1994). It is well-accepted that insecticide control of vectors is not an effective tool in virus disease management when applied directly to the crop at risk, even in high incidence areas (Gibbs and Harrison, 1976), but without easily communicated alternatives, it can be difficult to convince growers to resist pressure to use insecticides for virus control. Because the GIS infrastructure of map data and trained personnel was in place for the Del Fuerte Valley, we were able to develop data on tomato pinworm for the area as well. Pheromone traps for the adult tomato pinworm moth were placed throughout the region and spatially referenced using a GPS unit. A geostatistical analysis of tomato pinworm data revealed a pattern similar to the virus incidence pattern (Figure 2).

THE COTTON LEAF CURL VIRUS PROGRAM IN PUNJAB, PAKISTAN: Of immense current importance is the leaf curl disease of cotton. This disease is a whitefly transmitted gemini virus and has created havoc for the economy of the country of Pakistan.

This disease was first observed in Pakistan in 1967 but it was not until the period of 1989-91 that it became a major cause of low productivity of the cotton crop. The disease has been known in Africa for more than eighty years. A similar though less severe disease, leaf crumple, is a problem for cotton in the western hemisphere (Nadeem, Weng, Nelson, and Xiong 1997).

Currently, a cooperative project between the Central Cotton Research Institute (CCRI), Multan, Pakistan and the Department of Plant Pathology, University of Arizona is applying spatial analysis technology to this problem. Initial GIS, geostatistical analysis has illustrated the highly structured distribution of the leaf curl virus in the Punjab Province of Pakistan (Figure 3). The objectives are to identify consistent landscape features that are responsible for the observed patchiness and to use this information to develop virus management programs to reduce losses to the cotton crop in Pakistan. Current efforts to develop resistant varieties by traditional breeding methods are providing some positive results. Biotechnology approaches are also being employed and show promise for the long term. The long term contribution of GIS/ geostatistical technology to the problem will be to moderate the level of infection so that the resistant varieties as they are developed will be protected from the remarkable biological variation that is showing up in different collections of the virus from the cotton areas of Pakistan.

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